S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
vol. LIII–LIV, 2019–2020: 59–84 PL ISSN 0081-6434

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LANDSLIDE EXPOSURE ASSESSMENT UNDER ENVIRONMENTAL CHANGE IN THE ROMANIAN SUBCARPATHIANS

Abstract: This study focuses on one of the most complex petrographic and structural relief units in Romania, affected by significant earthquakes and uplift neotectonic movements, i.e. the Subcarpathian region. The Subcarpathians represent a highly fragmented hilly area subject to various mass movements and erosion processes, frequently affecting settlements, transport infrastructure and environmental values. The paper aims to present a landslide exposure assessment conducted for this region, following three main stages which are addressed in the context of present environmental conditions and their possible future changes: landslide susceptibility, landslide hazard and the exposure of elements at risk. It also intends to address and discuss the associated specific contexts, problems and challenges. By integrating selected landslide hazard scenarios, computed under different precipitation and seismic conditions, and key data on elements at risk (i.e. built-up areas, arable lands, permanent crops and major protected areas) into GIS spatial and statistical analyses, potential current and future landslide risk areas are outlined. Results are quantified at the Local Administrative Unit (LAU; towns and communes) level. The output maps reveal significant regional differences in landslide susceptibility and hazard according to the specific predisposing and triggering factors considered, as well as spatial variations in the landslide exposure in relation to specific land-uses and protected areas in the region. The present study contributes to increasing knowledge on landslide susceptibility, hazard, and exposure in the area and provides a ground for further related investigations. In addition, because of its predictive character, this study may constitute a useful tool for policy makers supporting decisions with regard to where future priorities should be focused.

Keywords: landslide susceptibility, landslide hazard, landslide exposure, environmental change, Subcarpathians, Romania

INTRODUCTION

The Subcarpathian hilly region, with its particular geological characteristics, was seen, at first, as a younger relief formation of the Carpathian Mountains by geologists L. Mrazec (1900) and G. Munteanu Murgoci (1905) as well as by the French geographer E. de Martonne (1902) at the end of the 19th and the beginning of the 20th century. In his work "Research upon the morphological evolution of the Alps of Transylvania (Southern Carpathians)" (de Martonne 1907), distinct chapters on the Subcarpathians are included, highlighting aspects regarding the young age of the relief, the tectonic mobility as well as the slope and riverbed evolution. Research concerning landslides in the Subcarpathians, begun in this period, are credited to Romanian geologists G. Macovei and G. Botez (1923), as well as to E. de Martonne (1907). Some aspects connected with earthquake–triggered landslides, alongside other geomorphological phenomena were described by G. Schüller in the Bulletin of the Romanian Geographical Society (1883).

In the third decade of the previous century, research advanced mostly with regard to the geomorphological divisions of the Subcarpathians, the intense human impact on landforms, and the different areas affected by landslides were described (Popp 1936; Mihăilescu 1939, 1943 etc.).

A new stage in the research of the Subcarpathian relief arose after 1950 along with the reorganization of the Institute of Geography, the publication of some PhD theses on topics related to the Subcarpathians (e.g. Roșu 1967; Badea 1967; Grumăzescu 1973; Brânduş 1981) and the elaboration of synthesis works (IGAR 1992). Regional geomorphological research discussed in the above-mentioned theses pointed out various landslide-affected areas related to lithology, the geological structure and to human activities. Some local landslide events have been outlined in all parts of the Subcarpathians. Synthesis works on present-day geomorphological processes (e.g. Tufescu 1966; Bălteanu, Mateescu 1973; Morariu 1974; IGAR 1983, 1992) show these processes as being particularly intense, extended and mainly represented by a wide diversity of landslides. Quantitative research unfolded, based on repeated measurements and mappings in experimental plots. Geomorphological research carried out at the Pătârlagele Geographical Station (set up in 1968), in the Curvature sector of the Subcarpathians, focused on the mechanisms involved in the onset and evolution of landslides intimately connected with the triggering factors. Investigations were conducted in 38 test-areas through repeated topographic measurements, photogrammetric methods and detailed geomorphological research-works (Bălteanu 1983).

After 1990, the research on the present-day geomorphic processes continued and different regional syntheses have been elaborated (e.g. Dinu 1999; Loghin 2002; Grozavu 2003) which may be seen as precursors of the later susceptibility and hazard assessments (Bălteanu et al. 2012). Investigations enlarged in the last decades to new aspects, such as susceptibility, hazard, vulnerability and risk. Numerous PhD theses were devoted to the subject and varied interdisciplinary research on landslides was undertaken in the framework of European projects (FP6 and FP7) mainly concerned with scenario-based evaluations of climate change effects on the environment and society. Maps of susceptibility to mass movement processes have been drawn for various sectors of the Subcarpathian chain using detailed databases and spatial analysis techniques (e.g. Șandric 2005, 2008; Micu 2008; Micu, Bălteanu 2009; Chițu 2010; Constantin et al. 2011; Armaș 2012; Jurchescu 2012; Mărgărint et al. 2013; Zumpano et al. 2014; Chițu et al. 2015). Later on, pilot studies on landslide triggering and hazard began to be elaborated on a scenario basis (e.g. Șandric 2008; Dragotă et al. 2008; Chițu 2010; Micu 2011; Jurchescu 2012; Chițu et al. 2017) while also considering future climate change projections (Jurchescu et al. 2016, 2017a). Landslide vulnerability and risk analyses have also been recently conducted (Jurchescu et al. 2016, 2017b).

The goal of the current paper is to present a spatial assessment of landslide exposure in the Subcarpathian region as well as the main stages involved in this assessment, while also taking into account environmental changes: landslide susceptibility and hazard analyses, based on elaborations in the frame of the RO-RISK (2016–2018) project (https://gis.ro-risk.ro/site/), and an estimation of the elements at risk and their exposure by making use of several spatial key data. The study does not aim to provide a landslide risk quantification, but rather an image on the spatial distribution and levels of landslide occurrence probabilities in the Romanian Subcarpathians as well on the possible current and future landslide risk areas. It, thus, highlights which Subcarpathian regions will require special attention in view of a future landslide risk assessment.

GEOGRAPHICAL SETTINGS AND ENVIRONMENTAL CHANGE

The Subcarpathians are a 300–900 m high hilly area that stretches along 550 km in the eastern and southern parts of the Romanian Carpathians and are extended over 16,500 km^2 (Fig. 1). The Subcarpathians touch upon the Moldavian Plateau to the East, the Romanian Plain to the South–East and the Getic Piedmont to the South. They consist of folded and faulted Neogene molasse deposits, associated with Paleogene flysch. The relief features alignments of hills and intra-hilly depressions controlled by a lithological diversity, tectonic lineaments and up to 2–4 mm neotectonic uplift movements in the Curvature region (Zugrăvescu et al. 1998). The Subcarpathians display a great diversity of rocks and numerous landslides develop on clays and marls with sandstone and sand intercalations.

The Subcarpathians are divided in three units: the Moldavian Subcarpathians in the North–East, the Curvature Subcarpathians, which are part of

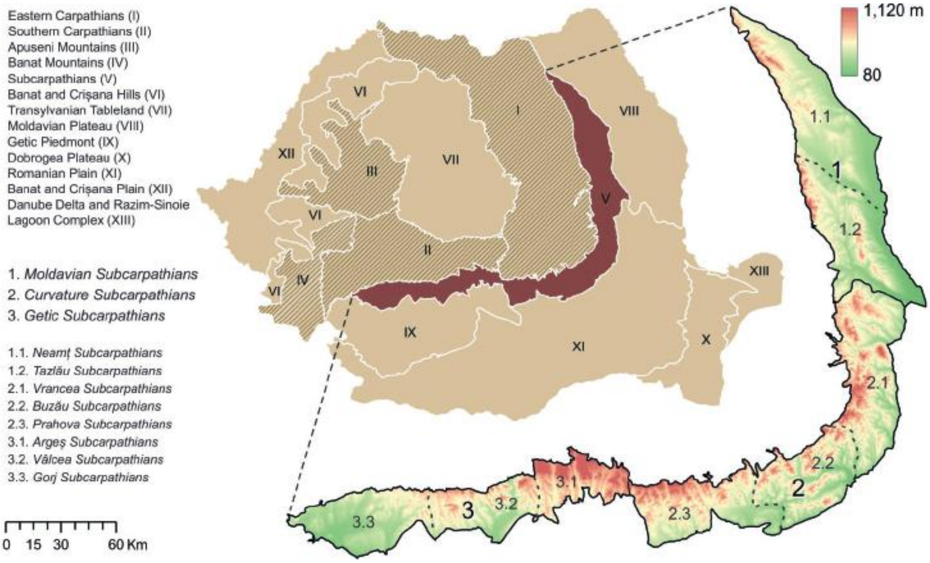

Fig. 1. The Romanian Subcarpathians. Major divisions and subunits (according to L. Badea 2008)

the Vrancea seismic region, and the Getic Subcarpathians in the West. The Moldavian sector extends on a N–S direction, between the Moldova and the Trotuș valleys, and comprises an alignment of Subcarpathian depressions corresponding to synclinoria filled with molasse deposits, which is bordered to the exterior by Subcarpathian hills predominantly built of sandstones. The Curvature Subcarpathians, between the Trotuș and the Dâmbovița valleys, represent the youngest and most dynamic Subcarpathian sector, being composed of two hilly and depressionary alignments with a high tectonic and petrographic diversity. Most affected by landslides are the lithologic complexes made of clays and marls and those formed of sandstones with clayey and salt breccia intercalations. In the region, eight complexes of geomorphic process were established, where mass movement processes (slides, flows, falls) are associated with intense erosion, gullying and piping processes (Bălteanu 1983). The suspended sediment transport reaches values above 25 $t \cdot ha^{-1} \cdot year^{-1}$, while in small catchments the registered amount is of 40–55 $t \cdot ha^{-1} \cdot year^{-1}$ (Diaconu 1974, cited in IGAR 1992). The Getic Subcarpathians, lying between the Dâmbovița and the Motru rivers, are situated in the South of the Southern Carpathians and show different morphostructural features as compared to the previous units. This unit of the Subcarpathians was formed in the Getic Depression which evolved as a foredeep basin starting with the Paleogene (Mutihac, Mutihac 2010). The relief of hills and depressions is developed over thick molasse and Paleogene flysch deposits oriented on a E–W direction. In the western half, both open-pit and underground coal (lignite) mining generated higher slope instability, while salt exploitation at Ocnele Mari was followed by complex processes of falls and landslides.

The climate is temperate continental with annual average temperatures of 9–10°C and 600–800 mm precipitation. It is characterized by the irregular variability of precipitation correlated with the general air mass circulation and the orographic barrier of the Carpathian chain. Long-lasting intervals of heavy and torrential rainfall are specific mostly to the warm season, representing an important trigger of sliding and flowing processes. During the 1969–1973 period, the longest and most intense period with excess rainfalls was registered for the previous century. The maximum rainfall in 24 hours was 150–200 mm (Bogdan 2005). In this century, heavy rainfall was registered in 2005, 2010 and 2014, being followed by floods, flash floods and an extension of landslide-affected areas in the Getic and Curvature Subcarpathians.

Assessments regarding climate change in Romania are based on climate projections of six EURO-CORDEX GCM-RCM simulations, viewed as most adequate in reproducing the current climatic conditions in Romania (Bojariu et al. 2015). According to these, under the RCP4.5, in the Subcarpathian area, a slight increase in summer precipitation is expected to appear in the future period of 2021–2050, being constrained to the North–East, while for the far future, up to the year 2100, this is expected to also affect the southwestern part. A somewhat more enhanced and generalized increase is expected under scenario RCP8.5, extending over the entire eastern part of the Subcarpathians and with slight variations until 2100 (Bojariu et al. 2015).

In the Curvature Subcarpathians, earthquakes are a major triggering factor. The Vrancea seismic region represents the main seismic source (at intermediate depth) in Romania and large parts of the Subcarpathian chain fall under its influence. As reviewed by Micu (2017), apart from the direct damages inflicted by the Vrancea earthquakes, landslides may consistently contribute to the overall damage toll. Occurring in the form of earth slides, rock slumps, rock block slides, rock falls, rock avalanches, co- and post-seismic landslides have been registered as triggered by earthquakes with magnitudes above Mw = 7 (1802, 1837, 1940, 1977) but also by lower magnitude earthquakes, if the occurrence framework is characterized by subsoil water saturation (Micu et al. 2014). Usually, earthquake-triggered landslides occur in the upper sector of steep slopes, in the immediate vicinity of ridges, often on anti-dip slopes, featuring a convex morphography, at times with no apparent initial connection to the river network, and many times in the immediate vicinity of fault lines (hanging wall) (Micu 2017). Overall, in comparison with the Flysch Carpathians which are largely bordering the Moldavian and Curvature Subcarpathians towards the interior, there are important differences. The more gentle topography, featuring lower slope inclinations, shorter slope lengths and less present narrow convex ridges, and the litho-structural environment, marked by the widespread presence of visco-plastic clays and marls, are rendering the Subcarpathians more prone to precipitation-induced landslides, at least in terms of first-time failures.

The Subcarpathians rank among the regions of Romania inhabited since ancient times. Archaeological findings have unearthed some Palaeolithic and Neolithic settlements on the terraces of the main rivers (IGAR 1992). Currently, the Subcarpathians represent one of Romania's most populated regions, numbering approximately 2,000,000 inhabitants. The area hosts 38 towns and about 350 communes, with an average population density of 117 inh.$\cdot$km^{-2}, higher (>200–250 inh.$\cdot$km^{-2}) in the settlements located along the Bistrița valley (Moldavian Subcarpathians), the Prahova and the Ialomița valleys (Curvature Subcarpathians), as well as in the Olt and the Jiu valleys (Getic Subcarpathians). The lowest population densities are found in the northern half of the Curvature Subcarpathians and in the West of the Getic Subcarpathians, mostly in the areas located at the contact area with the Carpathian Mountains (<30 inh.$\cdot$km^{-2}) (NIS 2011).

Agricultural lands in the Subcarpathians experience high denudation rates due to gullying and sliding, of 16.5 t$\cdot$ha$^{-1}\cdot$year^{-1} in the Moldavian Subcarpathians; 17–28 t$\cdot$ha$^{-1}\cdot$year^{-1} in the Curvature Subcarpathians and 11–16 t$\cdot$ha^{-1} $\cdot$year^{-1} in the Getic Subcarpathians (Moțoc 1982).

Wide biophysical diversity and the long history of human activities resulted in a varied spatial pattern of land-use/cover categories (CORINE Land Cover database; EEA 2012), dominated mainly by forests and agricultural lands (Fig. 2a). Vast arable lands stretch out mostly in the Moldavian Subcarpathians, permanent crops (vineyards and orchards) in the Curvature and Getic Subcarpathian ranges, while the Curvature Subcarpathians exhibit a wealth of forests. Significant areas are covered with pastures and natural grasslands favoring slope modeling processes over vast expanses. Built-up areas and heterogeneous agricultural lands are formed especially in depressions and alongside the main watercourses of the Moldavian and Getic Subcarpathians. Regionally and locally, especially in the Getic Subcarpathians, the impact of coal and salt mining activities lead to the emergence of man-made landforms as well as to a higher frequency of human-induced mass movement processes, especially affecting the artificial slopes of quarries and sterile heaps or occurring in correspondence to underground mining galleries (e.g. Cioacă, Dinu 2000). At the same time, the Subcarpathian hills display a remarkable biodiversity and landscapes included in protected natural areas (part of the Natura 2000 European Network; MMAP 2015), which cover about 11% of the overall study area, fully or partly overlapping it (Fig. 2a): e.g. Vânători-Neamț

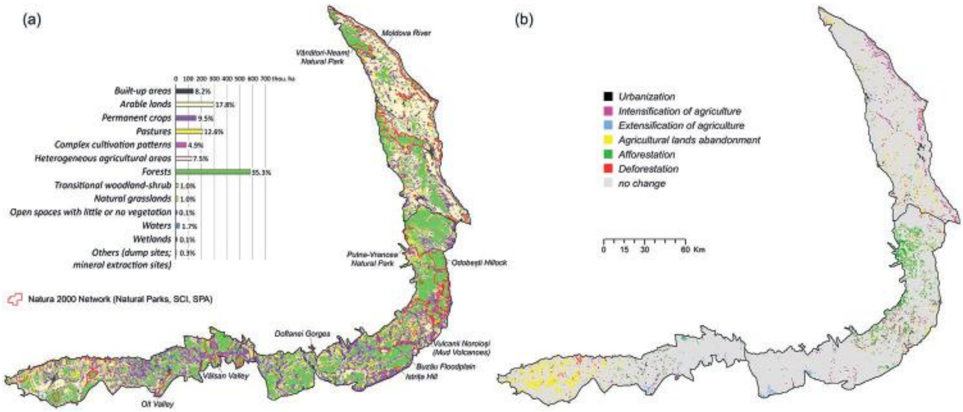

Fig. 2. The main land-use/cover categories (after CORINE Land Cover; EEA 2012) and the Natura 2000 Network (a) and the potential land-use/cover change flows up to 2050 (an extract from G. Kucsicsa et al. 2019) (b)

and Putna-Vrancea Natural Parks, Vulcanii Noroioși (Mud Volcanoes), Buzău Floodplain, Istrița Hill, Doftanei Gorges, Odobești Hillock, the Olt and Vâlsan Valleys, the Moldova River Valley.

Just like everywhere else in Romania, the Subcarpathian territory has, over time, experienced a remarkable land-use/cover evolution. The same went on even after the fall of Communism (1989), a period marked by a series of political, institutional and socio-economic changes. An important part in preparing and/or intensifying landslides could be assigned to the extending arable lands, pastures and natural grasslands and above all to the deforestation on slopes. Moreover, scenarios of future land-use/cover pattern, simulated by the CLUE-S model (The Conversion of Land Use and Its Effects at Small Regional Extent) using the CORINE Land Cover database (Popovici et al. 2012; Kucsicsa et al. 2019), indicate significant potential changes to occur until 2050, with major regional disparities in land-use/cover change flows (Fig. 2b) from one unit to the other.

LANDSLIDE SUSCEPTIBILITY

The Subcarpathians are one of Romania's most representative units in terms of landslide morphogenesis and typology (Bălteanu 1986, 1992, 1997) (Figs 3, 4). Their complexity, expressed in terms of morphology, morphometry and morphodynamic patterns is the result of numerous predisposing, preparatory and triggering factors. The landslide-prone lithology (loose forma-

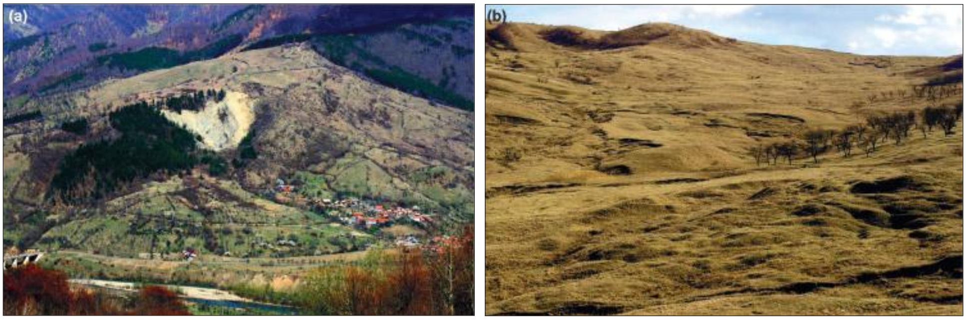

Fig. 3. Deep-seated rock slump (a) and shallow translational earth slides (b) in the Curvature Subcarpathians (Buzău sector). (Photos by M. Micu, 2016)

Fig. 4. The morphology of a typical debris flow and its impact on the river network (Curvature Subcarpathians, Vrancea sector) (a) and a detailed view on the flowing channel (Curvature Subcarpathians, Buzău sector) (b). (Aerial photo source: GeoEye, Google Earth imagery archive; Photo by M. Micu, 2018)

tions of Mio-Pliocene molasse, in which clayey-marly formations alternating with low-cohesion and schistose sandstones prevail) and structure (intensely faulted, narrow folds with diapire – salt and salt breccia – intercalations towards the interior and large anticline-syncline folds towards the exterior) lead to a gentle relief, prone to slope and channel modeling processes. The relief's morphometry reflects the litho-structural conditions, imposing a typological adaptation of landslides accordingly: shallow and medium-seated translational earth slides and earth flows along the large, gentle slopes of the outer sector, as well as along structural surfaces, while rock slumps, rock block slides, falls, and topples are characteristic for the sectors with steep slopes, corresponding mainly to cuesta fronts or sandstone packages caught in the intense folding process (Micu 2017). This landslide occurrence/reactivation potential is enhanced, on a long-term basis, by general features like the active deepening of the fluvial network as a reflex of intense uplift movements, the long-term human intervention in the environment, and, at a regional level (in the Curvature sector), by the active seismicity conditions.

In this complex framework, the evaluation of landslide susceptibility proves of extreme importance for the development of hazard scenarios and for the implementation of risk reduction strategies. The process of landslide susceptibility assessment imposes itself as highly demanding, as governed by extreme complexity in terms of morpho-litho-structural traits, reflected in the high typological spectrum of both landslide processes and forms, many times linked throughout the initiation sequence with complementary erosional processes. A general evaluation of landslide susceptibility at the level of the Romanian Subcarpathians could be thus subject to numerous uncertainties, while regional assessments are able to outline local particularities, imposed, for instance, by the presence of large and elongated flood plains which are marking the relief of the Moldavian Subcarpathians, by the seismicity of the Curvature sector or by the presence of large depressionary areas, hosting extended mining areas, like in the Getic Subcarpathians.

The general landslide susceptibility assessments for the Romanian territory, performed by D. Bălteanu et al. (2010) and, more recently, within the RO-RISK project (2016–2018) and presented in-depth in D. Bălteanu et al. (2020) (Fig. 5), gave a representative overview on the distribution of susceptibility classes. The image they provided for the Subcarpathian hills is in agreement with the numerous regional and local studies, which took into detailed analyses sectors from the Moldavian Subcarpathians (e.g. Mărgărint et al. 2013), Curvature Subcarpathians (e.g. Șandric 2005; Micu 2008; Micu, Bălteanu 2009; Chițu et al. 2009; Șandric et al. 2011; Constantin et al. 2011; Armaș 2012; Zumpano et al. 2014; Chițu et al. 2015; Hussin et al. 2016; Prefac et al. 2016) or the Getic Subcarpthians (e.g. Jurchescu 2012). All this regional research outlined the large presence of highly and very highly susceptible areas (up to 40–50% of the entire territory in communes like Bozioru, Odăile, Cozieni, Sărulești, Vintilă Vodă in the Curvature Subcarpathians; Zumpano et al. 2014).

Based on a broad spectrum of approaches (heuristic – expert knowledge, weighted overlay, statistic and probabilistic – weights of evidence, logistic regression, deterministic – numeric modeling), these studies, entirely based on grid cells (20–30 m) as reference units, take into consideration different combinations of predisposing factors (morphometry – altitude, slope, aspect, relief energy, fragmentation density, curvatures, etc.; lithology; land-use/cover; soils). The inventories of landslides on which the approaches are based generally derive from field mapping combined with authorities' reports (Zumpano et al. 2014), aerial (oblique or orthorectified) photos interpretation (Șandric,

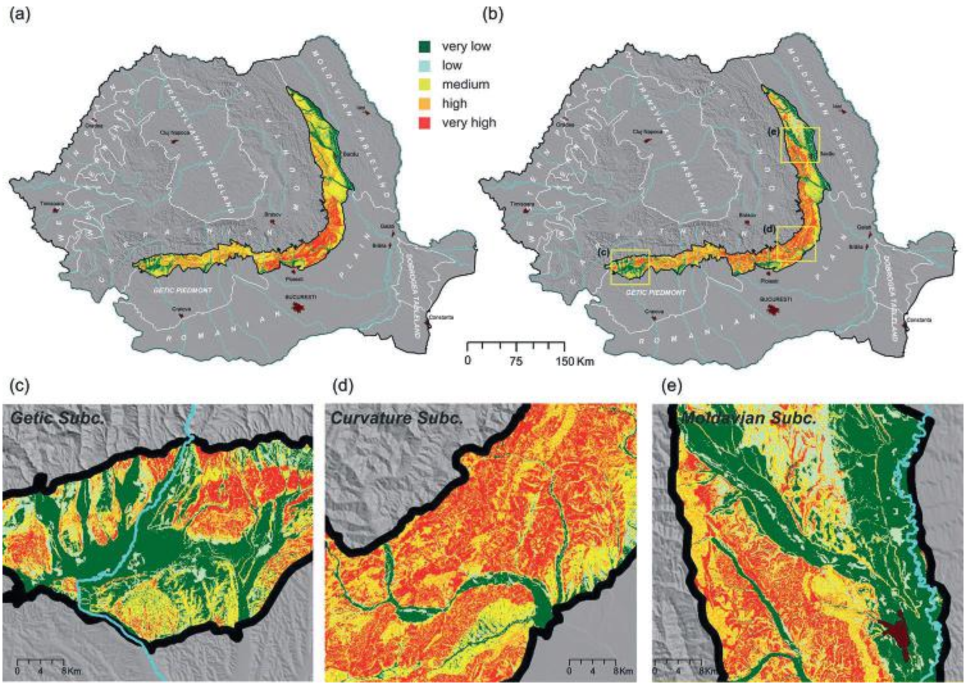

Fig. 5. Landslide susceptibility maps for the Subcarpathians unit, according to D. Bălteanu et al. (2010) (a) and D. Bălteanu et al. (2020) (b), and detailed extracts for the three representative units of the Subcarpathian chain: the Getic (c), the Curvature (d) and the Moldavian (e) Subcarpathians

Chițu 2009; Chițu et al. 2015), radar imagery (Riedmann et al. 2014) or stereoscopic anaglyph interpretation (Damen et al. 2014). The landslide inventories used for modeling the susceptibility are either polygon– or point-based, but in-depth sensitivity analysis (point-polygon representations, differences between depletion-accumulation areas in point sampling, etc.) are largely missing. The validation of the results usually follows the statistical approach, prediction and success rate curves outlining both the robustness of the models and their predictive capacity. The values of AUROC (Area Under the Receiver Operating Characteristic curve of 78–79% in V. Zumpano et al. 2014, 76–82% in Z. Chițu et al. 2015) are generally considered satisfactory taking into account the data availability.

The presence of inherent uncertainties during such a susceptibility assessment is noticed (e.g. Șandric et al. 2019): many times, the processes are not typologically-differentiated and there are almost no references to their multi-temporal dimension; there is a need of arguments concerning the graphic representation (comparisons between point and different-sized polygons); there are accuracy differences in the source material (especially in the case of different-scale maps or mapping sources); the reasons/constraints in the choice of the method; the representativeness of variables and their classification between continuous and categorical; the final classification and the reasoning of its choice, in comparison with others.

Moreover, although often considered a static factor in landslide susceptibility studies, there is increasing confirmation of the influence of land-use/cover changes on landslide susceptibility distribution (e.g. Glade 2003; Promper et al. 2014). Hence, the decrease in permanent crop areas and arable lands abandonment, as well as the expansion of pastures and natural grasslands to the detriment of forests up to 2050 (Kucsicsa et al. 2019) are expected to significantly increase landslide susceptibility in the Romanian Subcarpathians, mainly in the Getic and Moldavian sectors. This shows that, unless appropriate measures are taken to prevent or diminish landslide effects, greater damage to settlements, agricultural lands and communication infrastructure is to be expected, the same being also true for forest areas.

If properly built, the final susceptibility maps could contribute in a significant way to public safety in potentially endangered areas. To the contrary, without a proper informational support of the above-mentioned issues, the susceptibility map itself may act as a major uncertainty within the hazard analysis. The susceptibility zonation maps may be considered a valid instrument for the local authorities, in the process of understanding future landslide distributions at different levels (county/commune, catchment, relief units). In the meantime, the susceptibility maps could represent an important step for future hazard and risk assessments, needed for adequate risk management strategies. Since the quality of the map is largely dependent on the used inventories, it is important to underline that continuous updates (thus improving the predictive capacity of the model and enhancing its reliability) are needed for a complete understanding of the process' severity in terms of possible consequences.

LANDSLIDE HAZARD SCENARIOS

Given the importance of the two triggering factors acting in the Romanian Subcarpathian area, both climatically and seismically induced landslide hazard scenarios are considered relevant. Such scenarios were constructed for the entire extent of the country in the frame of the RO-RISK project and the approaches used are described in M. Jurchescu et al. (2017a; in prep.) and D. Bălteanu et al. (2017).

In order to explore the current state and expected future changes in landslide incidence, rainfall data were provided by the National Meteorological

Administration (NMA), both in the form of observation records and as future climate projections. For the assessment of the climate change impact on landslides in Romania, two EURO-CORDEX GCM-RCM runs have been considered, proposing a wetter (IPSL-INERIS-WRF331F) and a drier (KNMI-RACMO22E) future climate. For each of these, rainfall data were available for two different scenarios, RCP4.5 and RCP8.5, and two main 30-year long periods, namely a reference (1971–2000) and a future one (2021–2050). Correlations between landslide occurrences and precipitation values were investigated to assess landslide hazard under current and future climatic conditions (Jurchescu et al. 2017a).

Precipitation-induced landslide hazard as well as the impact of climate change on landslides in Romania were analyzed in the RO-RISK project and are extensively presented in other papers (Jurchescu et al. in prep.). Here, the discussion focusing on the Subcarpathian area merely refers to the landslide-triggering effect of the duration of the wet spell. More precisely, the extreme event assumed here is the 90th percentile of the maximum duration of wet spells, considered to roughly correspond to a 10-year recurrence period. As a general observation, both scenarios and models exhibit a future increase in the duration of wet intervals in the Moldavian Subcarpathians, with a more evident extension under scenario RCP4.5. The magnitude of the increase varies among the scenario and model combinations, from 5% up to about 40%. Further areas characterized by an increase of this extreme rainfall parameter are located in the Prahova subunit of the Curvature Subcarpathians (with about 5–10%, as shown by the WRF 331F model), and in the Vâlcea and Gorj Subcarpathians (with about 10–20% according to the RACMO 22E model). Given the high and very high predisposition of the Subcarpathian hills to landslides, these future variations in the consecutive number of rainy days are expected to reflect themselves in the landslide hazard. Indeed, all hazard scenarios considered here portray the Subcarpathian hills as dominated by high and very high hazard levels. A very high landslide hazard is expected to affect the Moldavian Subcarpathians, especially the Tazlău subunit. Under most scenario-model combinations, a very high hazard is also projected for the Prahova Subcarpathians. Locally, also parts of the Buzău, Vrancea and Gorj-Vâlcea subunits are threatened by a very high hazard.

Regarding the likely future changes in landslide hazard, overall, increases and decreases are found to be alternating regionally and locally as well as among the different climate simulations. More consistent outcomes appear to be in the case of the Moldavian Subcarpathians, for which almost all RCP and model combinations agree in projecting increases in hazard level, and in the case of the Buzău Subcarpathians, where reductions of landslide hazard seem to be generally expected. Locally, decreases are found in the Argeş

Subcarpathians and the western far reaches of the Gorj Subcarpathians. The most widespread landslide hazard intensification caused by the length of wet spells appears to affect the Moldavian Subcarpathians, sometimes also extending further in the Vrancea Subcarpathians, according to the RACMO 22E model under the RCP 4.5 scenario. The same future simulation also predicts increases in parts of the Getic Subcarpathians. As for the most extensive hazard reduction, this corresponds to the RACMO 22E model under RCP8.5, being mostly encountered in the Curvature area (Prahova and Buzău Subcapathians).

If other rainfall parameters are considered for expressing the landslide triggers, results in terms of landslide hazard evolution trends may be significantly different. However, when considering one specific RCP and model simulation, consistencies in the outcomes can also be observed, such as hazard increases in the Moldavian Subcarpathians and sometimes also in the Curvature area, and some decreases in landslide activity predicted for the Getic unit.

A second type of hazard maps discussed here is related to the occurrence of landslides triggered by earthquakes. The elaboration of earthquake-triggered landslide hazard required seismic hazards maps, which were produced through the joint effort of the Technical University of Civil Engineering Bucharest (TUCEB), the National Institute for Earth Physics (NIEP) and the National Institute for Constructions, Urban Development and Sustainable Land Planning (URBAN-INCERC) (RO-RISK 2016–2018; Bălteanu et al. 2017). Two approaches were used to this end: a probabilistic and a deterministic one. The probabilistic approach took into consideration all the ground shaking movements generated by earthquakes from all identified sources and all possible magnitudes as well as the associated uncertainties. The deterministic analysis estimated the maximum possible values of ground shaking due to earthquakes in a certain seismic area. The resulted maps of seismic hazard give the distribution of the horizontal peak ground acceleration (PGA). Each of these was superposed to the map depicting terrain predisposition to landsliding. Given the highly incomplete character and the low spatial accuracy of the data regarding failures generated during or immediately after the seismic movements, the evaluation of the landslide-earthquake spatial relationship was done based on expert knowledge and considering the little information found in literature. Critical thresholds of seismic parameters were established for landslide occurrence based on the few known historical seismically-induced landslides, assuming a continuous increase in landslide density once the minimum triggering shaking intensities are surpassed. Based on expert knowledge, compensating for the reduced dataset available, a matrix Susceptibility x Magnitude of the triggering earthquake (PGA) was built and qualitative hazard levels were attributed.

Thus, four landslide hazard scenarios resulted (Bălteanu et al. 2017), displaying the probability of landslides as induced by: an intermediate earthquake generated from the Vrancea source with a return period of approximately 1000 (975) years; an intermediate earthquake generated from the Vrancea source with a return period of 100 years; an intermediate major earthquake with a Vrancea source similar to the historic event of March 4, 1977 (M = 7.4, h = 97 km, I_0 = 9), with an approximate return period of 100 years; and an intermediate major earthquake with a Vrancea source similar to the historic event of November 10, 1940 (M = 7.7, h = 133 km, I_0 = 9), roughly corresponding to a return period of 200 years.

For the current paper focusing on the Subcarpathian region, only two of these will be discussed. The landslide hazard map associated to a 100-year return period earthquake can be seen as having a high occurrence probability. The magnitude of the seism is likely to generate landslides within those terrains characterized by an increased litho-structural predisposition. uch areas are highly characteristic in the Subcarpathian region, especially at the Curvature and in the eastern part of the Getic sector. The map displaying the landslide hazard as triggered by a major intermediary earthquake with a Vrancea source similar to the one of March 4, 1977 (M = 7.4, h = 97 km, I_0 = 9) can also be roughly associated to a 1/100-year frequency. Previous studies have shown that such an earthquake could generate debris falls and avalanches and – less frequently – slides, which would occur rather post-seismically (Bălteanu 1983). The extension of the area affected by seismically-induced landslides would especially cover the Curvature Subcarpathians, the southern half of the Moldavian division, as well as the eastern sector of the Getic Subcarpathians (Bălteanu et al. 2017).

LANDSLIDE EXPOSURE

In order to identify where possible landslide risk areas would lie within the Romanian Subcarpathians, four spatial data were used as elements at risk input layers, namely built-up areas, arable lands and permanent crops (vineyards and orchards), derived from the CORINE Land Cover database (EEA 2006), and the major protected areas (National and Natural Parks, Sites of Community Importance-SCI, Special Protection Areas-SPA) integrated in the Natura 2000 Network (MMAP 2015). From the existing hazard assessments, four landslide hazard raster layers were selected (Fig. 6): i) landslide hazard induced by a maximum duration of wet spells with a 10-year return period under current climatic conditions, ii) landslide hazard induced by a maximum duration of wet spells with a 10-year return period under future

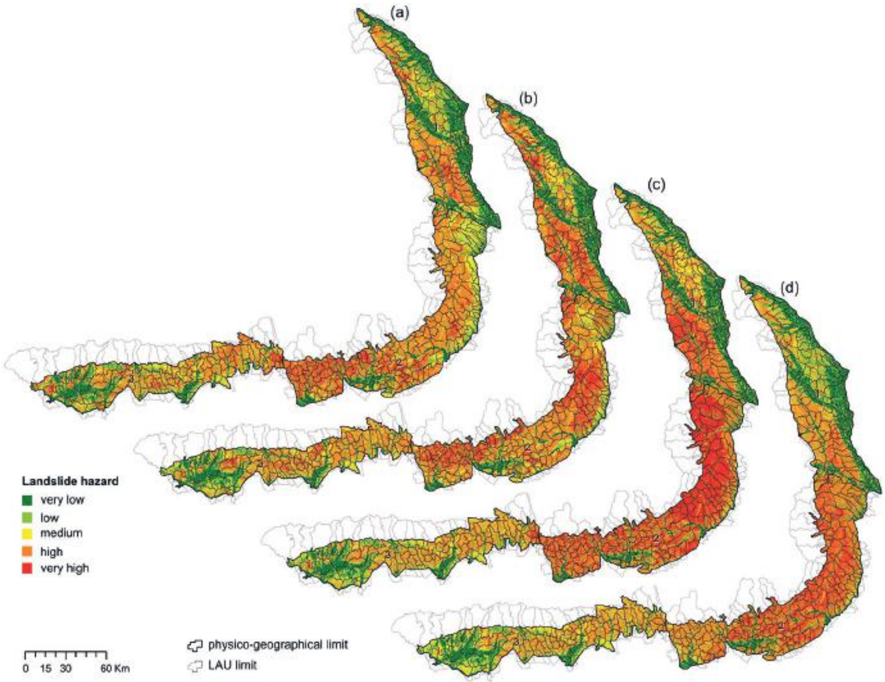

Fig. 6. Selected landslide hazard scenarios: precipitation-induced landslide hazard associated to a maximum duration of wet spells with a 10-year return period under current climatic conditions (a); precipitation-induced landslide hazard associated to a maximum duration of wet spells with a 10-year return period under future climatic conditions (b); seismically-induced landslide hazard associated to a major intermediary earthquake with a Vrancea source similar to the one of March 4, 1977 (c); seismically-induced landslide hazard associated to a 100-year return period earthquake (d). (Numbers refer to the main Subcarpathian divisions: 1 – Moldavian, 2 – Curvature, 3 – Getic)

climatic conditions (as simulated by the RACMO 22E model under RCP4.5), iii) landslide hazard triggered by a major intermediary earthquake with a Vrancea source similar to the one of March 4, 1977, and iv) landslide hazard map associated to a 100-year return period earthquake.

For the spatial assessment of landslide exposure, the considered vector data representing the elements at risk were converted into raster data and then overlaid with the selected landslide hazard maps. This procedure can be mathematically expressed as:

$$LE_{ei} = LHS_i \cdot e, \quad \text{(Eq. 1)}$$

where LE_{ei} is the estimated landslide exposure for the considered element at risk e and under the hazard scenario i; LHS_i is the landslide hazard corresponding to the specific scenario i; e is the analyzed element at risk.

Three out of the five classes of hazard were taken into account in the present study to identify the exposure of elements at risk, namely very high, high and medium. Sixteen spatial exposure indicators resulted from the spatial overlay: exposure of settlements, arable lands, permanent crops and protected areas to the landslide hazard under each of the different scenarios (precipitation-induced – current and future conditions; seismically-induced – conditions similar to the historic event of 1977 and corresponding to a 100-year return period). In order to obtain relevant municipality-level statistics, we used the map of the Local Administrative Units (LAUs) to quantify the potentially affected area (in ha) for each town and commune. Figure 7 shows the schematic workflow explaining the methodology used to evaluate the landslide exposure in the study region.

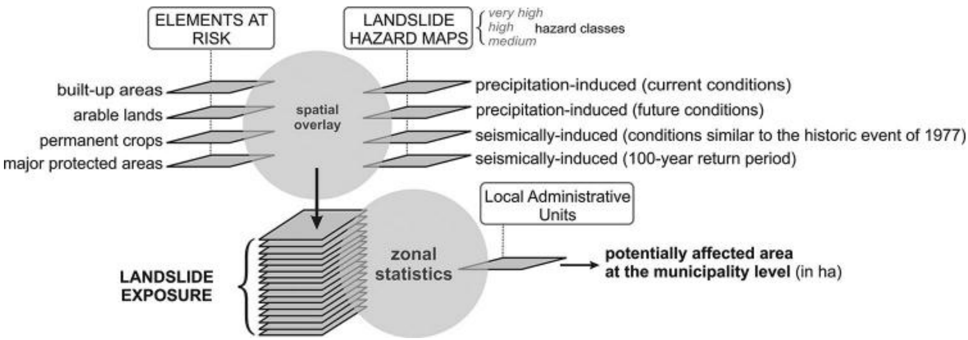

Fig. 7. The flowchart of the methodology used to evaluate landslide exposure in the Romanian Subcarpathians

The resulted maps (Figs 8–11) clearly delineate some areas that apparently form landslide risk hotspots in the study area. Hence, all scenarios indicate large built-up areas (>100–200 ha/LAU) potentially affected by landslides, mainly in the Curvature Subcarpathians and in the southern part of the Moldavian Subcarpathians (Fig. 8), where population density registers approximately 120 inh.$\cdot$km^{-2}. Particularly, potentially affected areas larger than 300 ha/LAU resulted for towns such as Comarnic (about 22% of the total built-up area), Breaza and Slănic (about 9% for each), and Băicoi (about 8%), located in the Curvature Subcarpathians, as well as for the communes Telega (about 9%), Cozieni (about 7%), Dumitrești, Scorțoasa and Bezdead (about 5% for each), located in the Curvature Subcarpathians, and Strugari (about 6%), located in the Moldavian Subcarpathians.

In terms of arable lands, larger areas potentially affected by landslides are indicated mainly in the LAUs comprised in the Moldavian Subcarpathians (Fig. 9). Thus, values higher than 800–900 ha/LAU resulted for most of

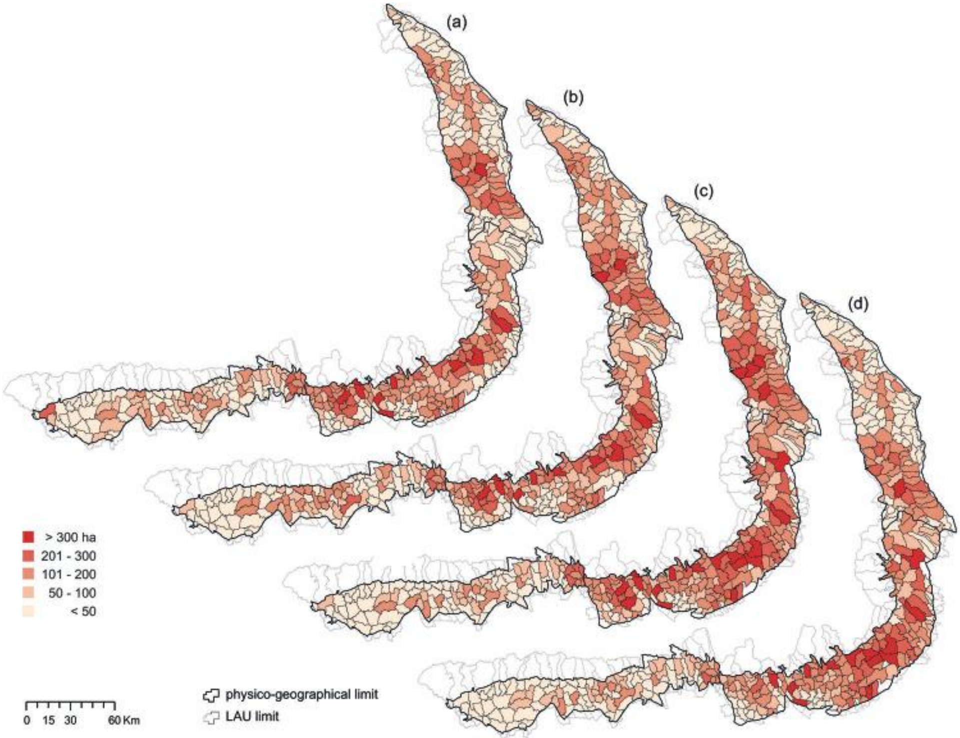

Fig. 8. Landslide exposure of built-up areas under different hazard scenarios: precipitation-induced – current conditions (a); precipitation-induced – future conditions (b); seismically-induced – conditions similar to the historic event of 1977 (c); seismically-induced – 100-year return period (d)

the communes located along the Trotuș and Bistrița valleys (e.g. Strugari, Berești-Tazlău, Gura Văii, Mărgineni, Solonț, Poduri, Români, Pârjol and Girov).

Regarding the exposure of permanents crops, the maps show a significant potential of exposure to landslides in the central Curvature sector and the eastern part of the Getic Subcarpathians (Fig. 10), where some of the most important wine- and fruit-growing regions of Romania are extended. Specifically, high exposure was mainly estimated for the communes Dumitrești, Vizantea-Livezi, Posești, Drajna, Năeni, Cozieni, Calvini, Vintilă Vodă, Chiojdeni, Runcu, Beceni (Curvature Subcarpathians) and Mioarele, Corbi, Stoenești, Poienarii de Muscel, Tomșani, Albeștii de Argeș, Mușătești, Valea Danului and Brăduleț (Getic Subcarpathians), with more than 1,000 ha of exposed lands in each of them.

The study-area does not include large areas under protective measures (only about 11% of the total area), however numerous protected areas, some of them with unique values, are extended mainly in the Moldavian

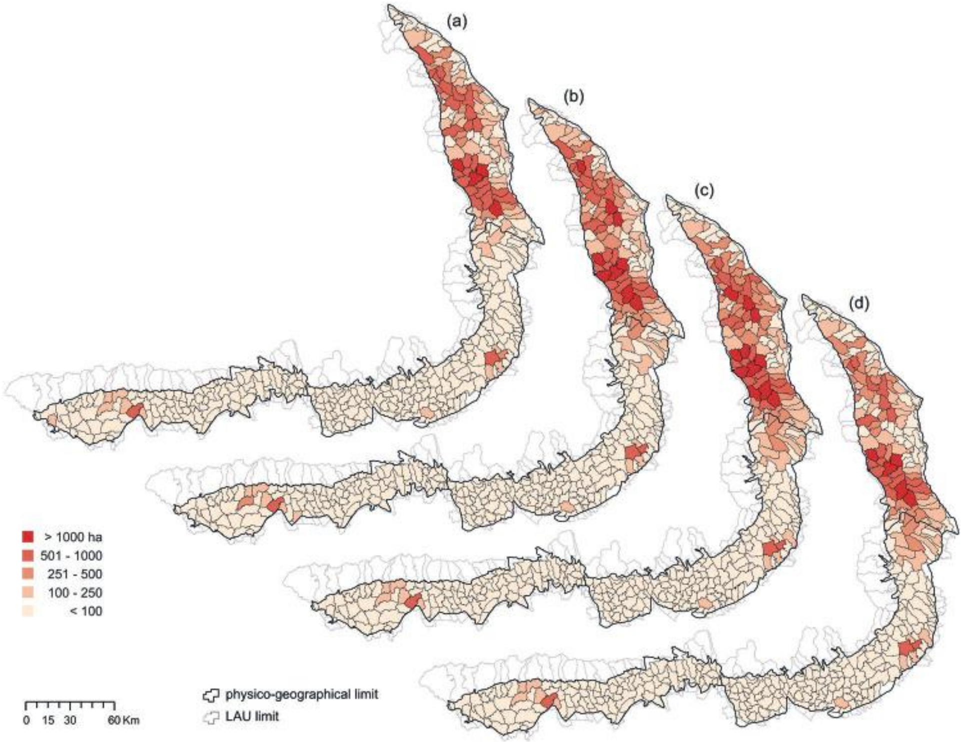

Fig. 9. Landslide exposure of arable lands under different hazard scenarios: precipitation-induced – current conditions (a); precipitation-induced – future conditions (b); seismically-induced – conditions similar to the historic event of 1977 (c); seismically-induced – 100-year return period (d).

Subcarpathians and the northern half of the Curvature Subcarpathians, where the hazard maps display a high occurrence potential for landslides. Thus, the communes that overlap with the protected areas Vânători Neamț (Natural Park) and Piatra–Șoimului Scorțeni–Gârleni (SPA), located in the Moldavian Subcarpathians, with Odobești Hillock (SPA), the Vrancea Subcarpathians (SPA) and Soveja (SCI), located in the Curvature Subcarpathians, as well as with the Vâlsan Valley (SCI) and Argeș Hills (SCI), located in the Getic Subcarpathians, seem to be most exposed to landslides (Fig. 11).

Overall, our investigation found that the exposure to landslides increases in the settlements located in the Neamț and Tazlău–Cașin depressions (Moldavian Subcarpathians), the Ialomița and Prahova subunits (Curvature Subcarpathians) and in the Vâlcea subunit (Getic Subcarpathians). In these settlements, built-up areas are well developed, the population density exceeds 100–150 inh.·km^{-2} and arable lands have considerable extensions.

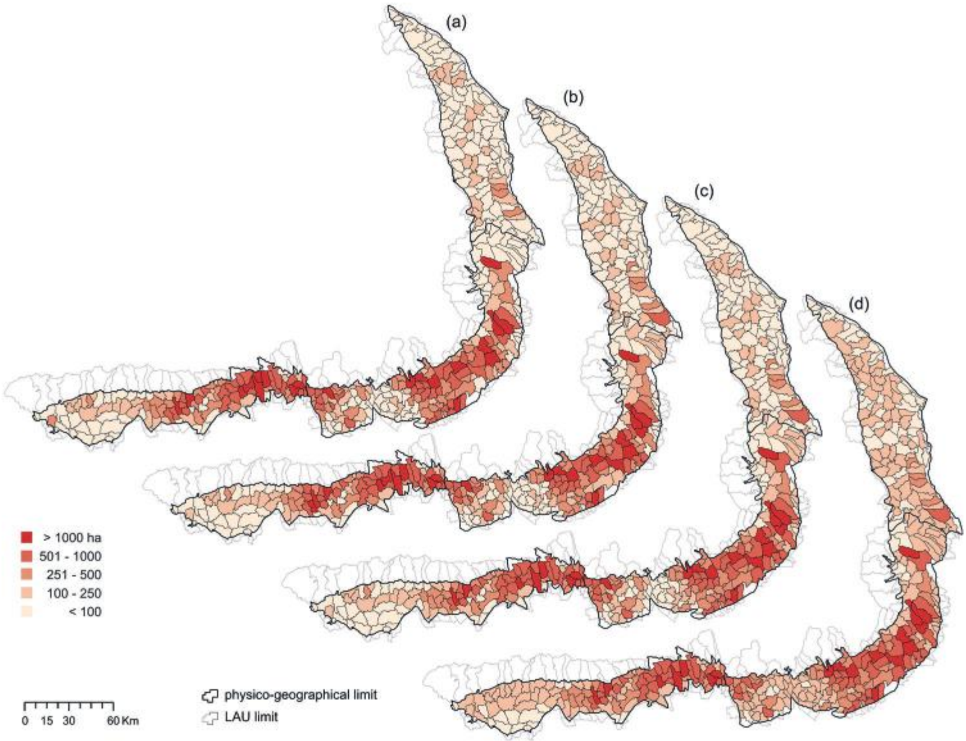

Fig. 10. Landslide exposure of permanent crops under different hazard scenarios: precipitation-induced – current conditions (a); precipitation-induced – future conditions (b); seismically-induced – conditions similar to the historic event of 1977 (c); seismically-induced – 100-year return period (d).

The analyzed hazard maps, however, reveal a high potential for landslide occurrence also in case of other settlements, located in the Neamț subunit and the Pietricica ridge (Moldavian Subcarpathians), the western reach of the Vâlcea subunit (Getic Subcarpathians) or in the Vrancea and Buzău subunits (Curvature Subcarpathians), but where, nonetheless, less developed built-up areas, lower population densities as well as the prevalence of pastures among the agriculturally-used lands lead to lower landslide exposures.

CONCLUSIONS

The present paper represents a synthesis on landslide susceptibility, hazard and exposure in the Romanian Subcarpathians, one of the most significant regions in Romania in terms of landslide occurrence and complexity.

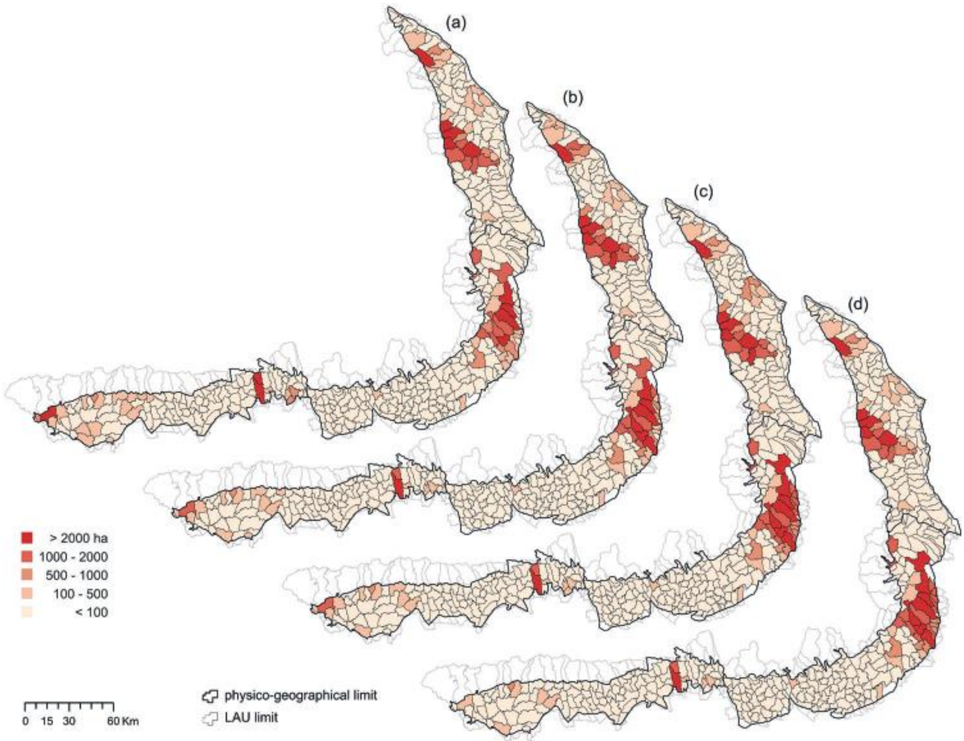

Fig. 11. Landslide exposure of protected areas under different hazard scenarios: precipitation-induced – current conditions (a); precipitation-induced – future conditions (b); seismically-induced – conditions similar to the historic event of 1977 (c); seismically-induced – 100-year return period (d).

The diverse typology and morphogenesis of landslides is the result of combining numerous predisposing, preparatory and triggering factors that reflect the natural features (morphometry, lithology, seismicity, climate, soils) as well as the anthropic ones (land-use/cover, human activities).

The landslide susceptibility map, the basis of the analysis performed in this study, offers an overview of susceptibility classes distribution in the Subcarpathians, outlining the presence of high and very high landslide susceptibility areas, in some areas reaching up to 50% of the territory. With all limitations related to data availability and quality, the landslide susceptibility map may be seen as a useful instrument for the local authorities in the proper management of the region in terms of risk reduction and territorial planning at the administrative unit level.

The study is a step towards landslide risk analysis, through the development of landslide hazard scenarios, derived from considering climate and seismic factors. From all precipitation-induced landslide hazard scenarios taken into analysis, one may infer that high and very high hazard classes are specific for the Subcarpathian regions, mainly in the eastern part and locally in the Curvature and southern parts. For the future timeframe (2021–2050), both increases and decreases of the landslide hazard are expected, more studies being needed to accurately indicate the changes at the local level. In terms of earthquake-triggered landslide hazard scenarios, affected areas especially correspond to the region of the Curvature Subcarpathians, the southern part of the Moldavian unit and the eastern reach of the Getic sector.

The paper also evaluated possible current and future landslide risk areas at the LAU level, based on several elements at risk (built-up areas, arable land and permanent crops and protected areas), outlining different degrees of landslide exposure in the Subcarpathian sectors. Caution is, however, recommended when interpreting the output maps, results being considered as indicative only. While not claiming to offer comprehensive risk estimates, since not considering all the aspects proper to a risk assessment, this study nevertheless allows to highlight which Subcarpathian areas will require special attention in view of a future landslide risk assessment. Therefore, identified potential landslide risk hotspot areas could serve as an indication for both researchers and policy makers with regard to where future priorities should be concentrated.

ACKNOWLEDGEMENTS

The presented work was conducted partly in the framework of the *RO-RISK* (*Disaster Risk Evaluation at National Level*) Project (2016-2018) – *SIPOCA 30,* coordinated by the Romanian General Inspectorate for Emergency Situations (GIES) and supported by the European Social Fund (ESF) through the Operational Programme "Administrative Capacity" (OPAC) 2014–2020 (https://gis.ro-risk.ro/site/), and partly under the research project *The National Geographic Atlas of Romania* (*Landslide Risk Assessment* section) of the Institute of Geography, Romanian Academy. The authors wish to thank GIES and the partner institutions involved in the landslide research: the Technical University of Civil Engineering (TUCEB), the National Institute for Research and Development in Constructions, Urban Planning and Sustainable Spatial Development (URBAN-INCERC), the National Institute for Earth's Physics (NIEP) and the National Meteorological Administration (NMA). The entire team of personnel involved in the different parts of the assessment is also thanked.

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