Avalanche risk analysis using airborne LiDAR data

Georgiana GRIGORAS[1], Ioana VIZIREANU*[,1,2], Bogdan URITESCU[1], Andreea CALCAN[1]

*Corresponding author
[1]INCAS – National Institute for Aerospace Research "Elie Carafoli", B-dul Iuliu Maniu 220, Bucharest 061126, Romania, grigoras.georgiana@incas.ro, vizireanu.ioana@incas.ro*, uritescu.bogdan@incas.ro, calcan.andreea@incas.ro
[2]Military Technical Academy "Ferdinand I", B-dul George Cosbuc 39-49, Bucharest 050141, Romania

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Abstract: *Natural and man-made disasters are a justified concern causing life-threats damages, affects existing budgets or disrupts national economic and social development plans. In this paper, a digital terrain model (DTM) and a geographic information system (GIS) are used to identify areas with a high risk of avalanches in the Râmeț mountain area of Alba County. Avalanches are the result of a complex interaction between terrain, weather conditions and snow cover characteristics. The most important factor among those listed is the terrain, being the only constant parameter over time. Therefore, the present study focused in particular on the determination of topographic parameters and the realization of a digital terrain model with a resolution of 0.5 m, which allows the small-scale identification of slope angle variations, which are of great interest for avalanche study. This digital terrain model was generated after processing LiDAR data obtained from a scanning campaign for the analyzed area with the Riegl LMS Q680i LiDAR system, located aboard the Hawker Beechcraft King Air C90 GTx aircraft from INCAS. The result of the analysis consisted in mapping the risk of avalanches in the Râmeț mountain area in Alba County.*

Key Words: *LiDAR (Light Detention and Ranging), Digital Terrain Model (DTM), avalanche risk, geoprocessing model, airborne scanning*

1. INTRODUCTION

Disaster management, as defined in "Internationally Agreed Glossary of Basic Terms Related to Disaster Management" UN, IDNDR, Geneva, 1992 [1], is one of the main worldwide concerns. Due to the significant increase in the number and severity of natural and man-made disasters in recent years, and given that future disasters will reach extreme levels and will present a higher degree of complexity, with far-reaching and longer-term consequences, resulting in particular from climate change and the potential interaction between several natural and technological hazards, an integrated approach to disaster management is becoming increasingly important [2].

Climate changes [3], among others, affects the mountain cryosphere in terms of: the time of occurrence, the height, duration and melting of the snow layer and the water equivalent of the snow layer, leading to changes in the hydro-geomorphological processes [4], [5], which in turn can affect sectors such as agriculture, tourism, hydropower production, etc. Changes in the characteristics of the snow cover in mountainous areas may also intensify the occurrence of spontaneous avalanches, especially those involving wet snow [6].

Avalanches, defined as "rapid and sudden slipping and leaking of usually incoherent and unsorted mixtures masses of snow/ ice/ rock material" [1] are favored by topo-climatic conditions such as: terrain slope, precipitation (especially fresh snow), wind (creates irregular snow deposits with different density or hardness), air temperature (especially sudden changes in temperature contribute to the instability of the snow layer), stratification of the snow layer [7]. Correlations were also made between avalanches and land use changes [8]–[10].

Regarding the avalanches in the Carpathian Mountains in Romania, there are studies that wanted to explain the occurrence of these phenomena, especially in the Southern Carpathians [11], Bucegi [12], Făgăraș [13], [14], Parâng [15], [16].

In these studies, the analysis of avalanches occurrence was based mainly on dendrogeomorphology, a sub-discipline of dendrochronology, a dating technique based on the study of tree ring width variations caused by climate and environmental variations at the time of ring formation.

Avalanches in the Romanian Carpathians are of small or medium category and are formed at altitudes of over 500 m, on lands with slopes greater than 30-40%, but most are triggered on slopes greater than 60% [17].

Although they do not have the magnitude of avalanches that occur in very high massifs such as the Alps, however, over time they have caused human casualties and property damage, thus increasing the concern for optimizing the planning of disaster response operations. To this end, it is necessary to carry out studies, surveys, modeling and development of scenarios to facilitate the exchange of knowledge, good practices and information.

In this paper, data obtained from a flight mission, carried out with the Hawker Beechcraft King Air C90 GTx research aircraft, equipped with the LiDAR Riegl LMS Q680i LiDAR system for topographic scanning of a mountainous area, were processed and inserted with other types of geospatial data, in an application developed on the GIS (Geographic Information System) platform, to obtain the avalanches risk map in the Râmeț area (Cheile Mănăstirii) in Alba County.

Such study results, consisting of risk maps, support public authorities with responsibilities for disaster and/or emergency management with the role of providing faster and more accurate information on decision-makers on the potential for disaster.

2. STUDY AREA AND DATA DESCRIPTION

2.1 Study area

The analyzed area is located in western Transylvania, in Alba County, in the northeast of the Trascău Mountains, and covers part of the "Cheile Mănăstirii" protected area (Fig. 1). The climate of the area is predominantly continental-moderate, generally humid and cold in the high areas with hot-tropical interference in the lower areas. Atmospheric precipitation (snow, rain) can reach up to 1000 mm on massifs and ridges, and the predominant winds are from the west and northwest.

The area chosen for the study covers an area of 28.33 km^2 and has elevation range between approximately 448 and 1292 m, with very steep slopes, up to 90 degrees, thus being suitable for the analysis of the risk of avalanches.

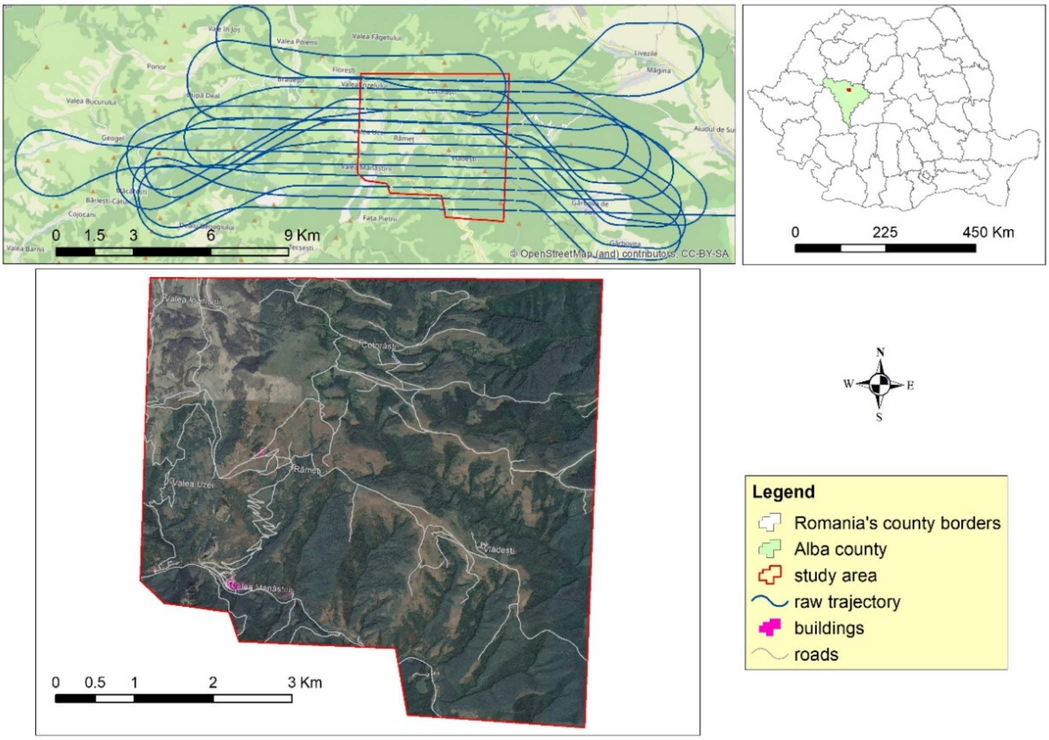

Fig. 1 Location of the study area and the flight trajectory

2.2 Data and methods

In order to generate the map representing the risk of avalanches for the Râmeț region, data were needed on: i) the digital terrain model, ii) surface slopes, iii) land cover classess, iv) geospatial data of the main roads and constructions in the area, v) Euclidean distance from roads and buildings.

These types of data have been introduced into an automated geoprocessing model, created specifically to obtain the avalanche risk. The model is represented as a diagram that links together sequences of processes and geoprocessing tools, using the output of one process as input to another process. The automated geoprocessing model was developed using the Model Builder component of ArcGIS 10.8.1 software.

This model uses the overlapping of several raster thematic layers, assigning to each raster a weight according to its importance, the sum of the weight being 100. Also, before the overlapping of the rasters, the values in each thematic raster were reclassified to a common suitability scale (from 1 to maximum 9, the most favorable situation/location being represented by maximum value).

The weights of each raster cell as well as each raster thematic layer were assigned according to their relative importance determined empirically by the opinion of experts. The weight of each cell in the input raster is multiplied by the importance of that layer, and to obtain the final raster, these values are summed.

Using ArcGIS was necessary in all phases of calculation and risk mapping: data acquisition and processing for preparing the input for the calculation model, interpolating terrain altitudes to obtaining the digital terrain model and querying and overlapping weighted elements which are important in the calculation of risk.

All data and maps were georeferenced and projected in the Universal Transverse Mercator (UTM-34N) reference coordinate system using the World Geodetic System (WGS84) datum.

The primary data source for this research study is the *Digital Terrain Model* which is a LiDAR (light detection and ranging)-derived product generated from an airborne laser scanning data processing. In order to achieve this goal, a Riegl LMS-Q680i LiDAR system was operated from an airborne platform, namely the Hawker Beechcraft King Air C-90 GTx, that belongs to the National Institute for Aerospace Research “Elie Carafoli” (INCAS-Bucharest).

Due to the substantial height differences observed in the terrain topography, a special and meticulous flight planning was prepared. In the planning process, the proposed area was analyzed, the chosen solution being kept within the safety limits of the aircraft operation. Therefore, the research flight with a duration of 6 hours and 45 minutes was carried out in the leaf-off season and took place in favorable weather conditions, the cloud ceiling being located at an altitude of 1800 m.

The flight strategy of the LiDAR scanning consists of 17 parallel flight lines, performed at a flight altitude of 700 m above the ground and an average flying speed of 66 m/s, thus resulting an average point density of 8 points per square meters which is suitable for generating a high-resolution digital terrain model.

The main result obtained during the research flight is a three-dimensional time-tagged point cloud, that contains attributes like planimetric and altimetric coordinates (X, Y and Z), reflectivity and intensity level through which additional information can be obtained about the texture and morphology of the scanned surfaces.

It is worth mentioning that in order to correct the point cloud data which can be distorted by systematic errors and to finally reach a highly accurate Digital Terrain Model, a LiDAR system calibration was performed, the misalignment parameters being recovered as follows: Roll [deg] = 0.44415, Pitch [deg] = -0.24317 and Yaw [deg] = 0.00574. These parameters will be further used in the LiDAR data preprocessing step represented by strip adjustment.

Usually, a certain surface or object is scanned two or more times, being included in at least two adjacent strips.

Although the calibration procedure was successfully done, the measurements are still affected by a number of systematics and random errors, hence discrepancies between adjacent strips will result.

This means that a certain object on the ground can be positioned differently, depending on the strip on which is located.

Thereby, the strip adjustment is considered important in the whole LiDAR processing workflow. Once these differences are corrected or minimized using a dedicated software (in this case, the Riegl software was used), the automatic classification of point cloud that has a major influence in Digital Terrain Model derivation, can be started.

Errors appeared in the final product can be minimized by applying a suitable point cloud classification method.

In a broader sense, the classification process includes a series of methods for identifying similar properties of objects, which are subsequently classified into specific classes using a classification model.

Therefore, the Digital Terrain Model will be obtained by interpolating and rasterization of all the points that belong to the Earth’s surface.

The methodology scheme for LiDAR data acquisition and processing in order to obtain the Digital Terrain Model is presented in Figure 2.

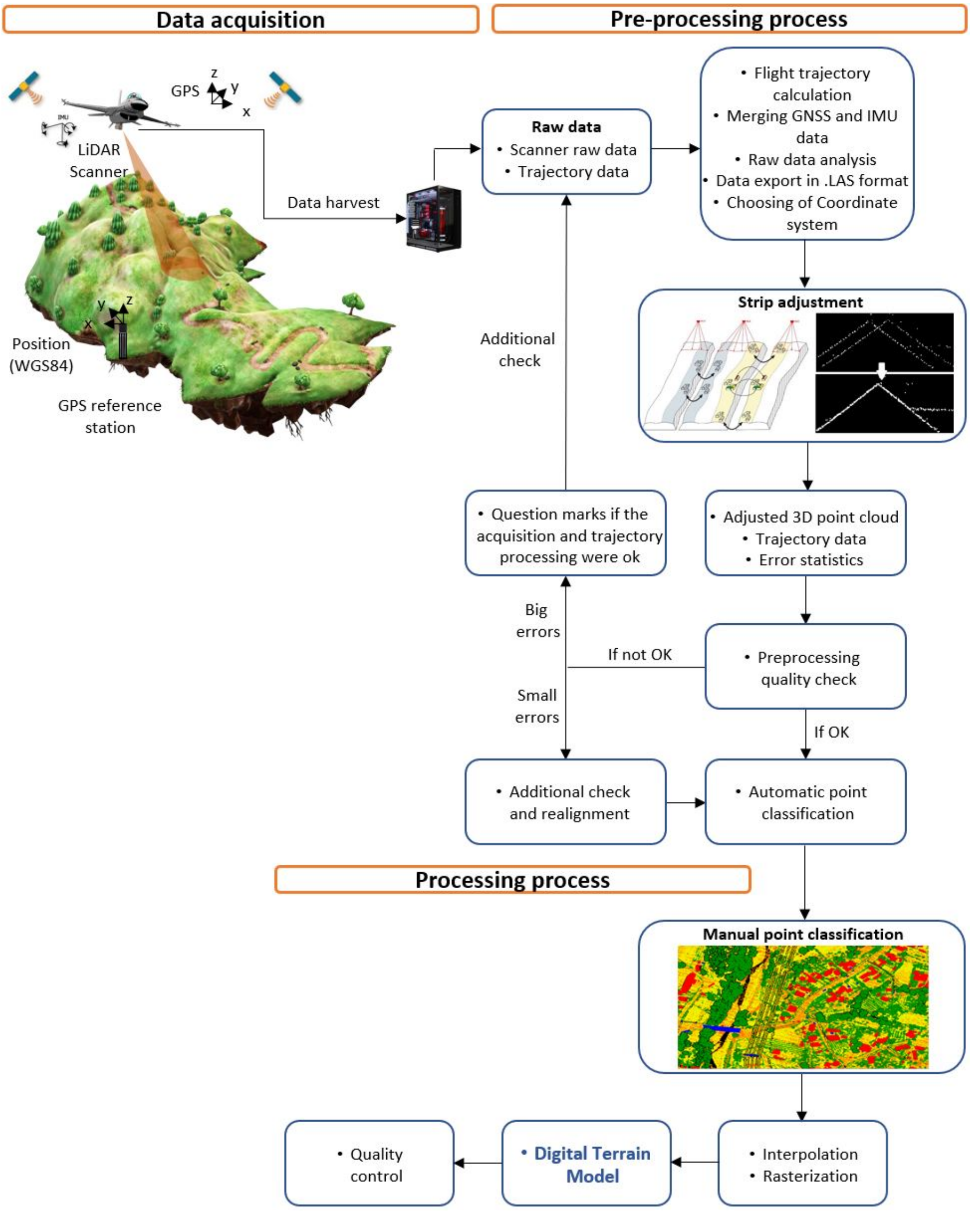

Fig. 2 LiDAR data processing flowchart

Terrain slopes were calculated from the digital terrain model using the ArcGIS software [18].

Land use cover was obtained from Corine Land Cover (CLC) data. These are a set of reference data for land use categories at European level, made in the Copernicus program developed by the European Union and the European Space Agency. The classification of land categories is based on 44 classes organized on 3 levels. Satellite images from different platforms/satellites were used to create the data sets (https://land.copernicus.eu/pan-european/corine-land-cover).

Geospatial data of the main roads and constructions in the area were vectorized using Google Earth Pro satellite images downloaded and georeferenced.

Euclidean distance provides in each cell of the raster the value of the distance from the nearest source (in this case represented by the main roads and constructions) and was calculated using the ArcGIS software [19].

3. RESULTS

The development of the risk map involved a series of activities such as: i) flight campaign for field data collection, processing and post-processing of LiDAR data to obtain the digital elevation model; ii) extraction of some characteristics of the terrestrial surface: terrain slope (degrees), slope orientation, hillshade; iii) identification of the land cover categories and of the main roads and buildings in the analyzed area; iv) development of an automated geoprocessing data model using the Model Builder component of ArcGIS.

3.1 Digital Terrain Model for the Râmeț area

To obtain the digital elevation model, raw data recorded by the LiDAR system went through a series of processing steps: trajectory processing and strip adjustment, point cloud classification and terrain filtering (separation of ground points from above ground) and point interpolation sampled to obtain the digital terrain model (Fig. 3).

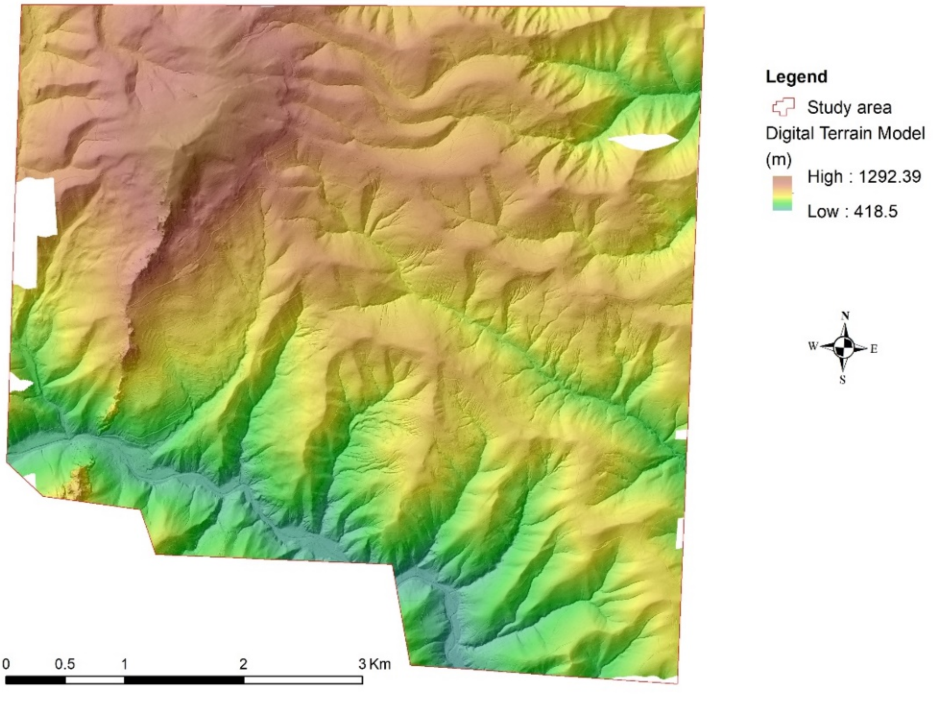

Fig. 3 The Digital Terrain Model obtained from LiDAR data, for the Râmeț area

The error obtained after processing the trajectory and positioning the scanned bands was 0.55 m.

This error was reduced to 0.36 m after calibrating and adjusting the bands. After classifying the point cloud and separating the points so that only the points representing the ground were obtained, the set of points thus filtered was interpolated using the Nearest Neighbour algorithm from ArcGIS, which provides the smallest interpolation errors (RMSE: 0.2 - 0.4 m).

The resulting raster, representing the digital terrain model, has a spatial resolution of 0.5 m and is shown in Figure 4.

This digital terrain model is needed to analyse the influence of topographic factors on avalanche risk. The terrain elevation influences the meteorological conditions, the vegetation and the snow depth.

In general, heavy snowfall and wind speed increase with altitude. Avalanche activities are generally minimal in low elevation areas because the air is warmer and most of the time the snow melts when it touches the ground.

Analysing the map representing the digital model of the terrain for the Râmeț area, it is observed that the altitude of the area is approximately in the range of 418 -1292 m, falling within the altitude limits from which avalanches were observed (500 m).

Also, the presence of large differences in altitude over a relatively small area, favours sudden changes in meteorological parameters, the latter being other important factors in triggering avalanches.

3.2 Characteristics of the earth's surface: surface slope, slope orientation, hillshade

The slope of the earth's surface represents its inclination to the horizontal plane. Basically, it is given by the angle between the earth's surface plane and the horizontal plane. The calculation of the slope is made in the right triangle determined by the plane of the earth's surface (hypotenuse), the plane of the vertical and the plane of the horizontal (cathetus), using the tangent trigonometric function.

The slope is one of the most used geomorphometric parameters, it being related to the intensity of geomorphological processes (surface erosion, landslides). The slope can be expressed in degrees or percentages.

An angle of 30 degrees is usually required to trigger avalanches. However, there are different scales and ways to measure the angle of the slope that affect the critical trigger angle and prevent the comparison of data from different sources.

The European Avalanche Risk Scale classifies slopes as: moderately steep terrain: slopes shallower than about 30 degrees; steep slopes: slopes steeper than about 30 degrees; very steep, extreme terrain: particularly adverse terrain related to slope angle (more than about 40 degrees), depending on the land configuration, the porosity of the soil and areas near the ridges.

Taking into account this type of classification, the slopes calculated (in degrees) for the Râmeț area and represented in Figure 4 have been reclassified, each class being assigned a degree of risk from 1 to 5, where 1 is low risk, 2-moderate, 3-significant, 4-high and 5-very high risk. In the analyzed area, the slopes of more than 30 degrees predominate.

The steepest slopes, with values over 40 degrees being located in the west and southwest of the area.

The Aspect is derived from each cell of the raster that contains the digital elevation model of the terrain and represents the geographical orientation (exposure) of each slope. The orientation of the slopes influences the amount of radiation that the land receives, which significantly contributes to the stability of the snow layer.

As the sunny slopes stabilize faster, shaded slopes remain unstable for a long time. It is observed that in the analyzed area the exposure of the slopes is predominantly oriented to west and south-west direction (Fig. 5).

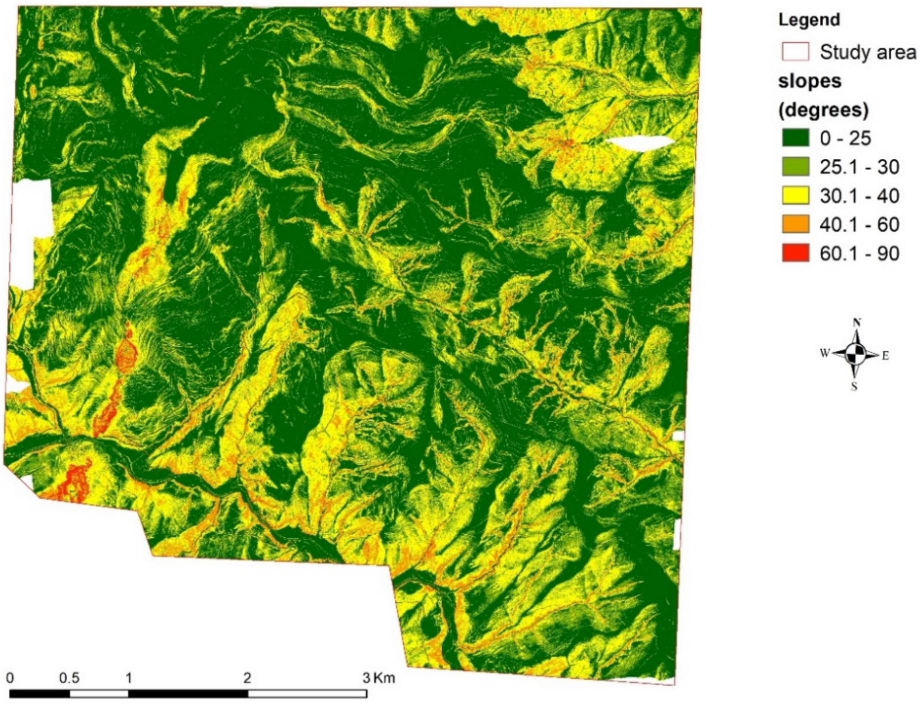

Fig. 4 Slope map for Râmeț area

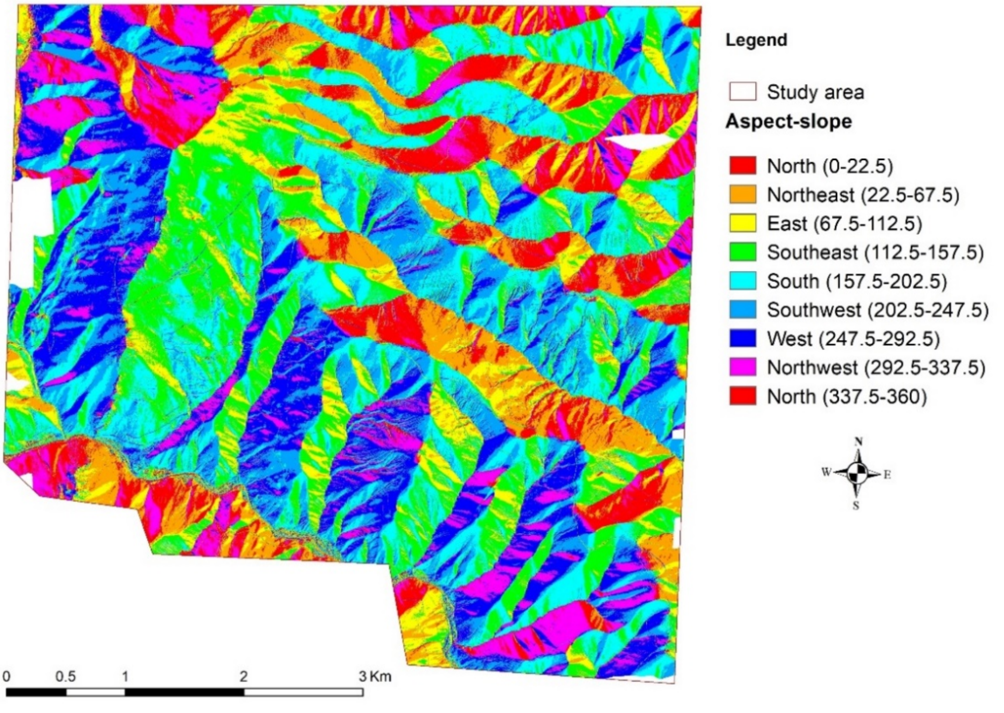

Fig. 5 Aspect map for Râmeț area

The raster containing the hillshade has integer values from 0 to 255 and is obtained considering that the surface is illuminated by a source positioned at infinity. This raster is used to improve the visualization of an area for analysis or graphical display, especially when using transparency. This raster was used to make the Figure 1 and Figure 4.

3.3 Land cover categories according to Corine Land Cover

The Corine Land Cover (CLC) data offered by the Copernicus platform are vector and raster data type. In the present project, the vector data were used due to the more accurate representation of reality compared to the raster data, which represent the same areas but with a more pixelated appearance.

The categories of land use identified in the study area are: Broad-leaved forest 55%, Natural grassland 24%, Agricultural areas 18%, Mixed forest 2%, Bare rock 1% (Fig. 6).

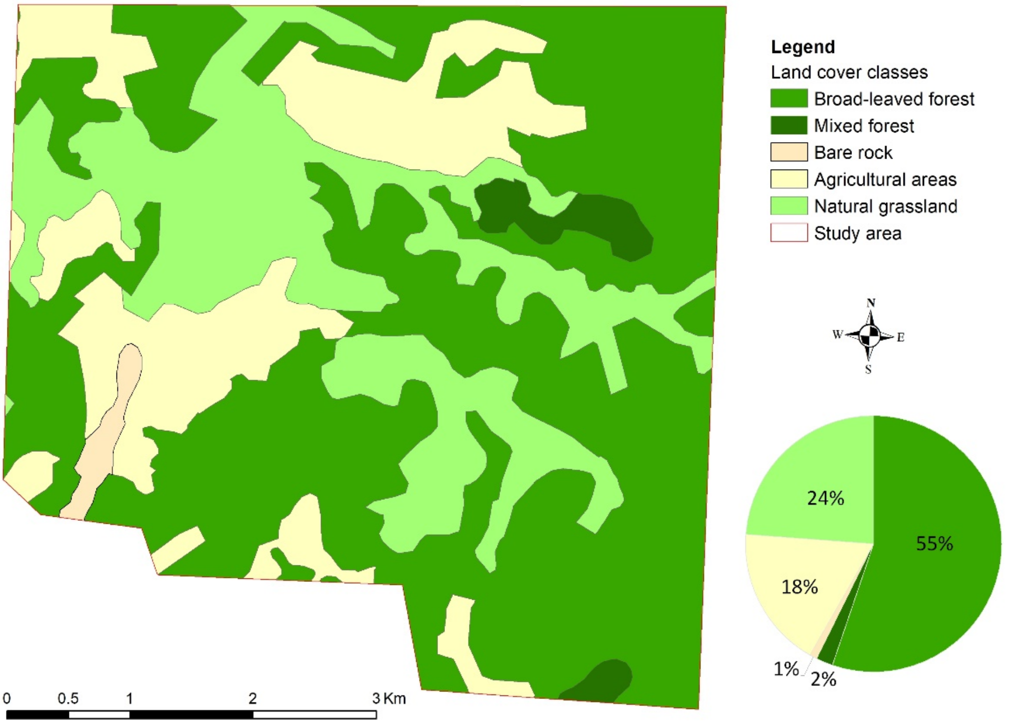

Fig. 6 Spatial distribution of land cover classes for Râmeț area

Land use is a data classification that is taken into account for the study of avalanches, because the surface roughness prevents the formation of continuous snow layers. A minimum layer of 0.3-1 m of snow is required to smooth the roughness of the ground. The highly variable roughness of the terrain can influence the internal evolution of thin layers of snow. Rocky outcrops or mossy rocks can promote instability by the appearance of ice crystals on them when the snow cover is thin. Forests reduce the probability of avalanches, because, especially in dense forests, the snow cover is too irregular to produce avalanches. In the analyzed area, the forests cover 57% of the surface, while the bare rocks and natural grasslands cover 25% of the surface.

The Euclidean distance raster contains the distance measured from each cell to the nearest source wich is represented by the main roads and constructions in the analyzed area (Fig. 7).

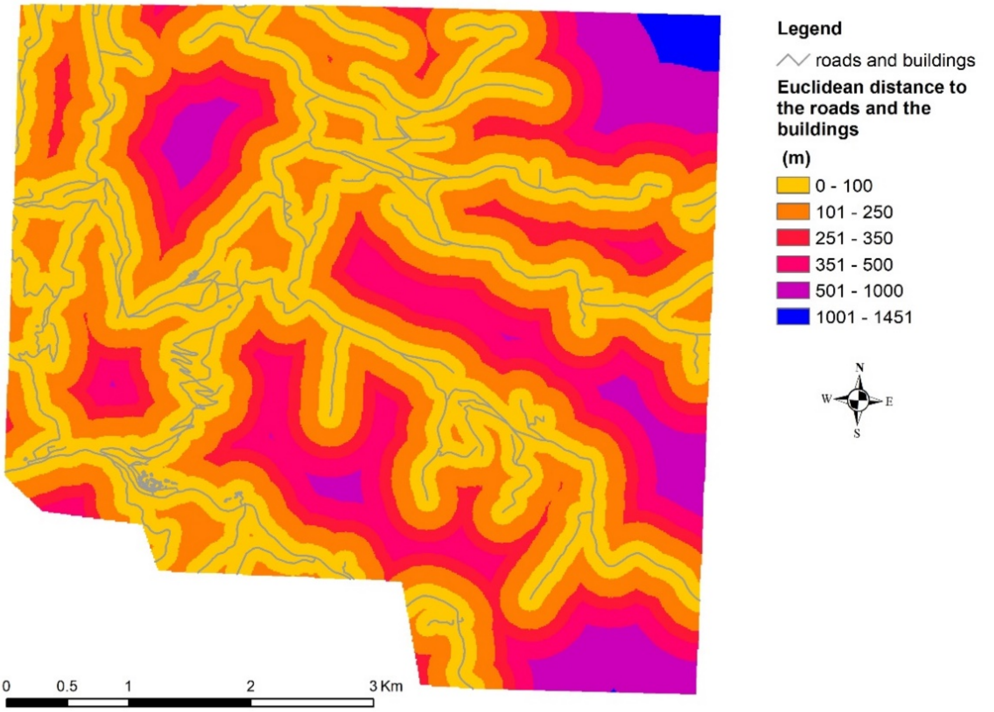

Fig. 7 Euclidean distance from roads and buildings for Râmeț area

3.4 Avalanche risk map

Avalanches pose a major natural hazard, endangering human life and infrastructure in mountain areas around the world.

Quantitative assessment of avalanche phenomena is hampered by the dangers that may occur when accessing the study areas, in order to collect data from the field. Also, most field measurements involve destructive methods, thus compromising data and the study of evolution over time.

Avalanches are not reproducible events, therefore qualitative estimation based on different statistical or numerical methods remains essential for their study, but these methods depend, as shown, on a series of data that are difficult to obtain.

The complex interaction between the characteristics of the terrain, the meteorological and hydrological conditions lead to the formation of the avalanche.

A single avalanche event cannot be predicted in time and space, especially due to the very large variability of the triggers.

Avalanche risk mapping is very important for short-term forecasting and emergency management.

The statistical approach is a method of mapping avalanche risk and this involves weighting several factors that contribute to its formation process.

The flow of operations necessary to make the risk map has been automated by creating a geoprocessing model that performs spatial analysis on GIS data, through computing tools which he appeals. The program was made in ArcGIS 10.8.1 software, its scheme being shown in the Figure.8.

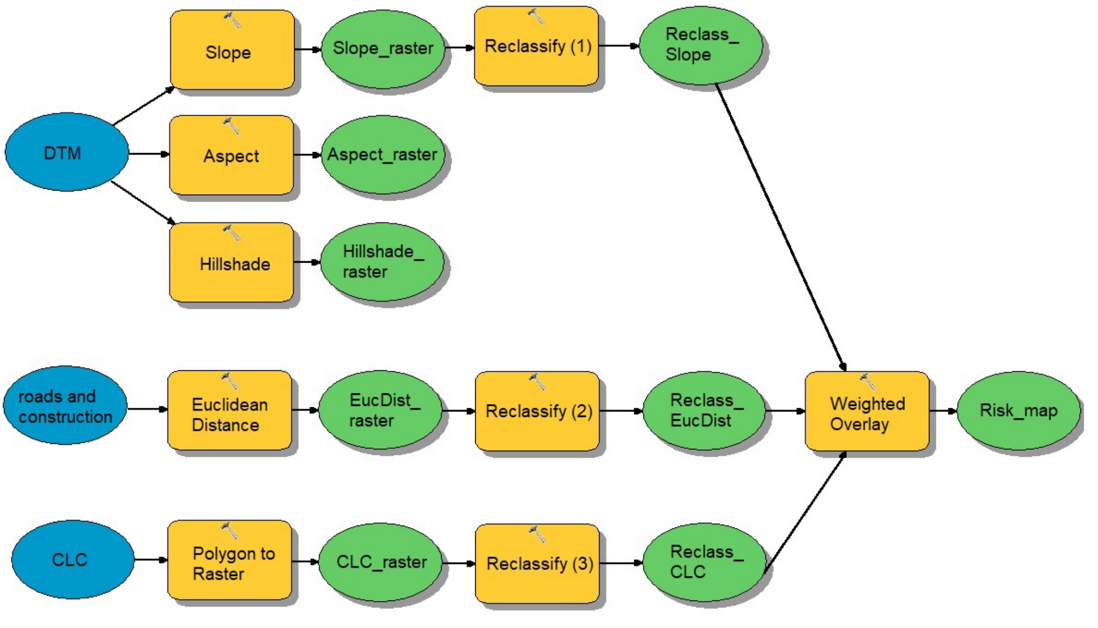

Fig. 8 Graphic scheme of the geoprocessing model developed for generating the risk map

The weighted overlap technique used to produce the avalanche risk map for this study is is one method of modeling suitability.

The final results of the application of this method were divided into five risk categories: low, moderate, significant, large, very large, as shown in Figure 9.

High resolution digital terrain model (0.5 m) made it possible to identify areas with variations of the slope angle, specific to micro-topography (convex curvature of the descending slope, such as an unevenness), which causes stress concertation that favour the formation of avalanches.

Analyzing the map from Figure 9, it is observed that areas with significant avalanche risk, have slope angles over 30 degrees and land with no vegetation or forest.

The high and very high-risk categories were obtained in the southwestern part of the analyzed area, where the land is characterized by bare rocks, agricultural lands or grasslands, as well as slopes higher than 40 degrees, with aspect-slope north, northwest.

Areas with slopes below 30 degrees and covered with high vegetation (forest type) do not present a risk of avalanches or have a low or at most moderate risk.

The areas occupied by each category of avalanche risk expressed in both km^2 and percentages are shown in Figure 10.

It was obtained that 53.92% (15.28 km^2) of the analyzed area does not present any avalanche risk, 20.46% (5.80 km^2) has a risk significantly, 10.76% (3.05 km^2) has a high risk, 9.45% (2.68 km^2) has a low risk, 5.13% (1.45 km^2) has a moderate risk and 0.28% (0.08 km^2) has a very high risk of avalanches.

It has also been observed that there is a low risk of avalanches in built-up areas. These areas are located at a distance of at least 300-400 m from the areas where a high or very high risk of avalanche has been identified.

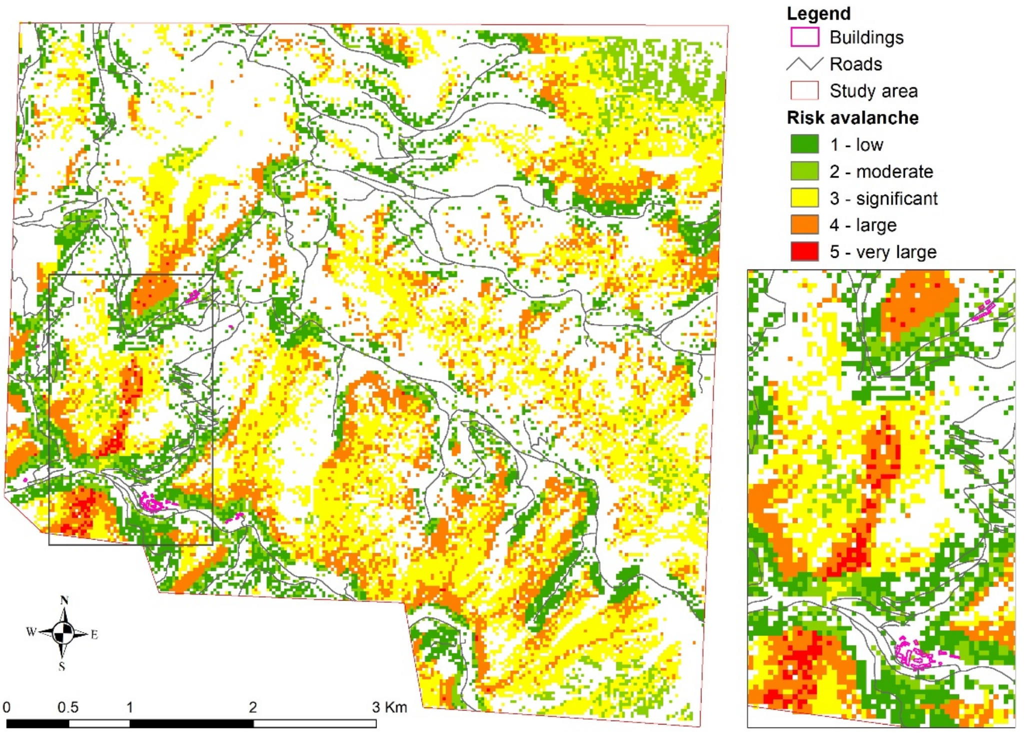

Fig. 9 Risk of avalanche for Râmeț area

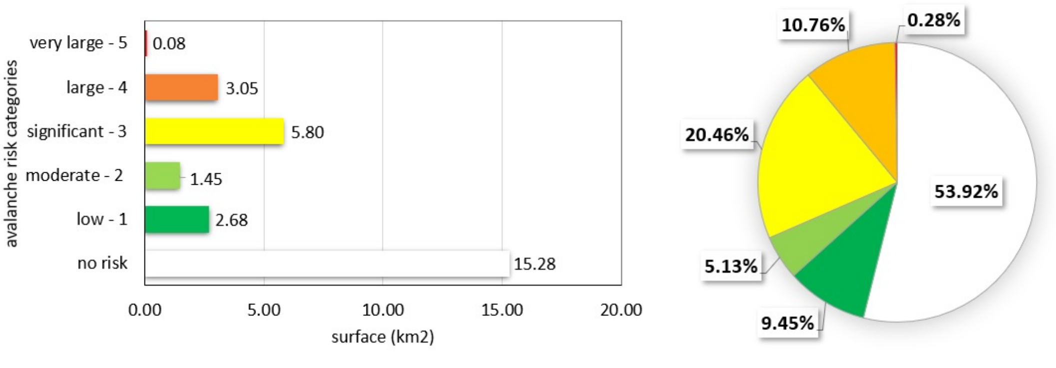

Fig. 10 Areas covered by avalanche risk categories, expressed in km^2 (left) and in percentages (right)

4. CONCLUSIONS

Assessing and managing extreme risk situations could be a way to improve and even streamline interventions in the event of serious hazards, and in this process, an important step is to develop risk maps. In this paper, the avalanche phenomenon was analyzed as a risk generating for emergency situations and based on some contributing factors, the avalanche risk map of the analyzed area was obtained.

The appearance of avalanches is influenced by topographic, meteorological and hydrological factors. More specifically, the most important factors that influence the appearance of avalanches are: altitude, slope, slope aspect, meteorological factors, distance from the nearest road or construction.

Avalanches occur at high altitudes on steep slopes. In order to be able to manage possible emergencies caused by avalanches, a first step is to identify the areas most prone to this phenomenon.

There is a vital need for prediction especially in places that are most vulnerable to avalanches - residential areas, communications network infrastructure and vital facilities - places that can cause serious problems beyond the damage caused by avalanche exposure. This study combines information from topographic scanning with LiDAR system (conducted by INCAS), with statistical methods, to assess the distribution of vulnerability to avalanches in the Râmeț mountain area in Alba County.

Data resulting from the LiDAR processing, data from the European Space Agency's Copernicus program, as well as data produced by authors based on satellite images were compiled and graphically represented using GIS techniques and software.

The results indicate a high risk of avalanches in areas where both the altitude and the slopes had high values, while the land is lacking of vegetation or has a low vegetation cover. These areas are located at a distance of approximately 300-400 m from the built-up areas, therefore the risk of damage to road infrastructure or buildings is low or moderate.

The results have a strong scientific basis and can provide meaningful information to prevent, mitigate and manage avalanches. Therefore, the methods presented in this study should be tested for application in other localities, as they may improve snow avalanche susceptibility assessments in other avalanche prone regions.

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