MODELLING AND ASSESSMENT OF DEBRIS FLOW EROSION AND DEPOSITION USING GEOINFORMATION TECHNOLOGIES

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ABSTRACT. Debris flows are one of the most destructive geological-geomorphological hazards in mountain areas. Although the frequency of their occurrence is low, their sudden character increase the risk and requires preventative measures as well as increased preparedness for action in case of the event propagation. Studying the dynamic of debris flows can contribute to better understanding the process and to mitigate the risk. The aim of the current research is to analyse the geomorphic change due to debris flow occurrence and to assess erosion and deposition. The study is carried out on a gully induced debris flow located in a low mountain area of the Eastern Rhodopes (Bulgaria). The methodology of the research includes making of digital elevation models (DEMs) generated of two point clouds acquired in two terrestrial laser scanning (TLS) field campaign and deriving of surfaces of slope and curvature. The spatio-temporal changes in erosion and deposition are assessed in GIS environment by analyses of the changes in slope and topographic curvature of the debris fan and low part of the transport channel for the period October 2019 – June 2020. The results show that although increasing the convex areas at the debris fan, the volume of the deposits is decreased with 0.58 m^3, which can be explained by mass movement to the lower erosion basis. The results of the GIS analysis are interpreted having regard the grain-size analysis of sediments from the channel and debris fan, and confirm the activity of the process in the studied period.

Keywords: debris flow, erosion, modelling, DEM, TLS

МОДЕЛИРАНЕ И ОЦЕНКА НА ЕРОЗИЯ И АКУМУЛАЦИЯ ОТ КАЛНО-КАМЕНЕН ПОРОЙ С ИЗПОЛЗВАНЕ НА ГЕОИНФОРМАЦИОННИ ТЕХНОЛОГИИ

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РЕЗЮМЕ. Кално-каменните порои са едни от най-разрушителните геолого-геоморфоложки процеси в планинските територии. Въпреки ниската честота на проява, внезапният им характер увеличава риска и изисква превантивни мерки, както и повишаване на подготвеността в случай на проява на тези явления. Изучаването на динамиката на кално-каменните порои ще допринесе за по-добро разбиране на процеса и намаляване на риска. Целта на настоящото изследване е да се анализира промяната на топографската повърхнина, предизвикана от проява на кално-каменен порой и да се направи оценка на ерозията и акумулацията. Изследвана е промяната от кално-каменнен порой, проявен в овраг, в нископланинския релеф на Източните Родопи (България). Методологията на проучването включва съставяне на цифрови модели на релефа (ЦМР) от два облака от точки, получени при две наземни лазерни сканирания (НЛС) и генериране на повърхнини на наклоните и на топографската кривина. Пространствено-времевите промени в ерозията и акумулацията са оценени в ГИС среда чрез анализ на промените в наклоните и кривината при наносния конус и долната част на ерозионния канал за периода октомври 2019–юни 2020 г. Резултатите показват, че въпреки увеличаване на изпъкналите площи в наносния конус, обемът на наслагите е намалял с 0,58 m^3, което може да се обясни с движението на материала към по-ниския ерозионен базис. Резултатите от ГИС анализа са интерпретирани във връзка с резултатите от гранулометричния анализ на седименти от ерозионния канал и наносния конус на кално-каменния порой и потвърждават активността на процеса в изследвания период.

Ключови думи: кално-каменен порой, ерозия, моделиране, цифров модел на релефа, наземно лазерно сканиране

Introduction

Erosion and deposition are the processes that provide information about the spatio-temporal dynamic of debris flows. These processes are closely related to intensive rainfall and occurrence of torrential flows but in many cases debris flows occur in ungauged basins and then modelling of debris flow susceptibility based on geomorphological parameters is of great importance for planning of mitigation measures. The review of publication about modelling of debris flow geomorphic changes shows two main approaches. The first one is direct use of digital elevation models (DEMs) and calculation the elevation difference between old and new surfaces (Lane et al., 2003; Wheaton et al., 2010; Schürch et al., 2011, Theule et al., 2012; Cavalli et al., 2017). The second approach is based on spatial analyses of DEMs derivatives like as slope, topographic curvature, roughness and other morphometric parameters (Cavalli et al., 2017; Grelle et al., 2019). Terrain variables slope gradient and curvature are used for determining terrain based erosion reference units for erosion modelling and deriving potential erosion areas (Flügel and Märker, 2001; Tcherkezova and Sarafov, 2015). Cavalli et al. (2017) analyse the relation between geomorphometry and geomorphic changes and conclude that erosion prevails on positive values of planform curvature, which correspond to concave features, while the majority deposition areas occur on convex features. Many researchers analyse morphometric parameters of debris flows areas and different indices calculated on the basis of catchment morphometry (Melton index, topographic wetness index, stream power index) to determine debris flows source, erosion channel and deposition areas and to evaluate the dynamic of the processes (Wilford et al., 2004; Rowbotham et al., 2005; Chen and Yu, 2011; Zhou et al.,, 2016). For this purpose high resolution DEMs of debris flows areas are used which shows the growing application of geoinformation technologies in debris flows research. Monitoring of debris flows through multi-temporal LiDAR data is becoming a common practice (Loye et al., 2016; Cavalli et al., 2017; Morino et al., 2018). Although the growing use of remote sensing in debris flow research it is still a challenge to determine the most effective DEM resolution for the particular area of research and to generate the model of the terrain when it is covered by forest and shrubs vegetation.

Considering the recent trends in studying debris flow erosion and deposition, the aim of the current study is to analyse the geomorphic change of a debris flow by using terrestrial laser scanning (TLS) and GIS analyses. This is a part of wider research of debris flow in the Eastern Rhodopes which is the first one in this area applying geoinformation technologies and particularly TLS data. It will contribute meaningfully to the organizing the monitoring of debris flows and mitigating the negative impacts of this hazardous event.

Study area

The current study is done on the example of a gully located in the Eastern Rhodopes, Bulgaria (Fig. 1). The area is characterized by often occurrence of debris flows due to the intensive rainfall, deforested slopes and rocks highly susceptible to weathering and erosion. The sampling area is the lower part of a gully incised in a steep slope, located near to the village of Golyama Bara.

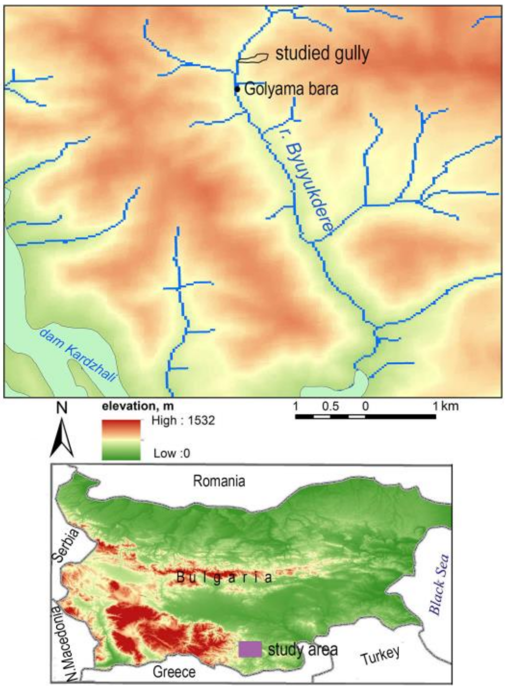

Fig. 1. Study area

The catchment of the gully reaches an altitude of about 600 m and is covered by low deciduous vegetation and shrubs. The transport channel is very steep with a width from 0.40–0.60 m in its narrowest sections, to 2–3 m in the widest. It ends with a well-defined debris fan, built of boulders and pebbles (Fig. 2). The gully is a left tributary of the river Byuyukdere that flows in the dam Kardzhali. In the lower course, the river valley is conditioned by a fault, which explains the high slope gradients of the left tributaries in this section.

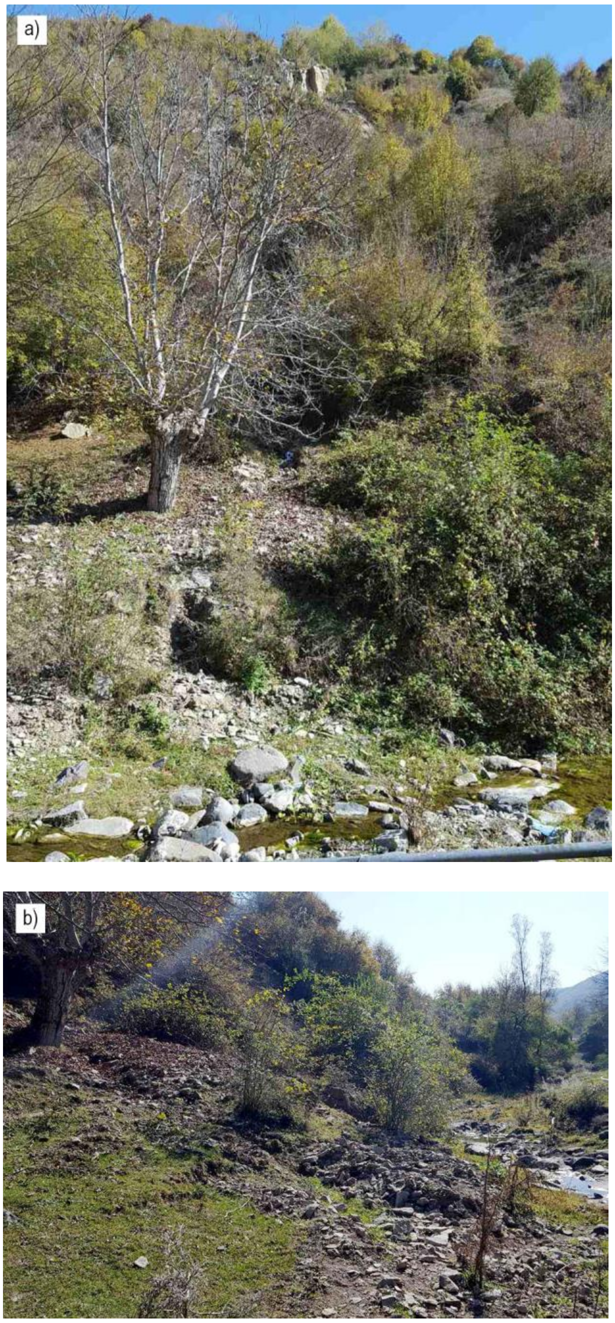

Fig. 2. Debris flow area: a) the watershed with debris source area in the upper part of the photo; b) debris fan.

The rocks in which the gully is cut are of Paleogene age (Jordanov et al., 2008). They are represented by medium acid volcanics – latites to andesites, tuffs, tuffites and epiclastites. These rocks build the contemporary debris fan. The large size of the clasts can be explained by the rocks susceptibility to weathering and erosion as well as by the high slope gradient and are an indicator of high kinetic energy of the slope processes during intense rainfall.

The often occurrence of debris flows in this part of the Eastern Rhodopes impacts on the sediment regime in the rivers and retention capacity of the dam Kardzhali. This increase the flood risk and requires consistent monitoring of the debris flows and mitigation measures.

Data and methods

The analyses of erosion and debris deposition are done on the basis of field surveying and high resolution DEMs. Two consecutive terrestrial laser scanning (TLS) campaigns were performed in order to derive DEMs of the low part of debris flow area and to analyse geomorphic change. The first campaign was organized in October 2019, and the second one – in June 2020. During the first campaign 2 scans were carried out, from which a set of 2 point clouds were obtained. The second campaign was performed with more terrain details via 4 scans. The TLS data was derived using Stonex X300 laser scanner – a mid-range (1.6–300 m) device with two cameras and Wi-Fi web interface. All scans were performed in 360° panoramic mode. Standard resolution was deemed appropriate for the required terrain details. All the data was processed via the Stonex 3D Reconstructor software. The following workflow was followed during the data processing stage:

1. Data pre-processing – during this step noise and outliers were removed from the point clouds via median and range-reflectance filter;
2. Computation of normals of the point cloud;
3. Confidence coefficient was computed, based on the incident angle between the laser beam and the tangent plane of the target, the distance to the target and the material of the object;
4. Registration of the point clouds via identical points and features;
5. Vegetation removal via manual selection and cropping. It has to be noted that the first campaign required much less vegetation cleaning than the second, due to seasonal vegetation changes.
6. Georeferencing of the point clouds.

An example of point cloud before and after vegetation removal is given in Fig. 3.

The cleaned data was subsequently exported in ASCII point cloud format (X, Y, Z) was further processed in GIS environment. As a result DEMs with a horizontal resolution 0.1 m are derived. Taking into account the characteristics of the studied area and the size of the debris deposits, the models are smoothed in using ArcGIS Spatial Analyst Tools – Neighborhood – Focal Statistics with neighborhood type (moving window) 5 x 5 cells, statistics type "Mean". On the basis of the smoothed DEMs and analyses of the slope and topographic curvature the low part of the debris flow transport channel and deposition area are delineated. The changes in profile and planform curvature are considered as an indicators for erosion and deposition. For this purpose curvature rasters are calculated on the DEMs, derived of the data of October 2019 and June 2020. Profile curvature is the curvature parallel to the maximum slope. Positive values of the profile curvature indicate that the surface is concave which can be related to mass wasting and erosion, and negative values indicate convex surface and can be related to accumulation of the deposits. Planform curvature is perpendicular to the direction of the maximum slope and allows to determine ridges and valleys. When the planform curvature is positive the surface is convex and flow lines divergent, while the negative values of the planform curvature indicate that the surface is concave and flow lines convergent.

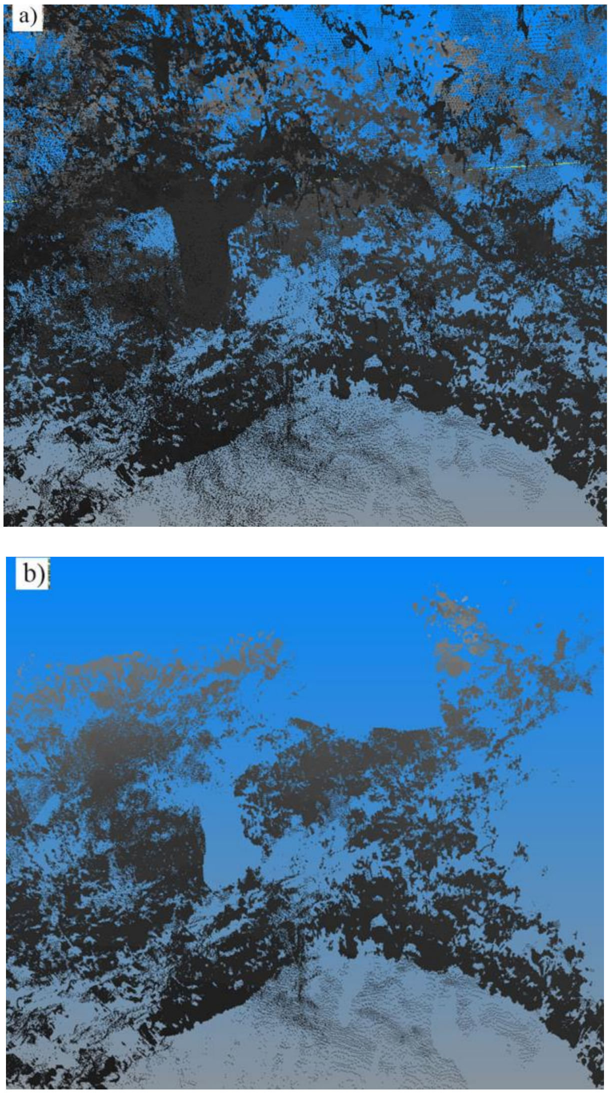

Fig. 3. Point clouds: a) before vegetation removal; b) cleaned data.

The volume of the contemporary deposits on the debris fan is calculated using Cut Fill tool of ArcGIS 3D Analyst Tools, which calculates the volume between two surfaces: the surface of the debris fan (unsmoothed DEM) and a straight surface, modeled between the base of the fan and the fan apex (Fig. 4).

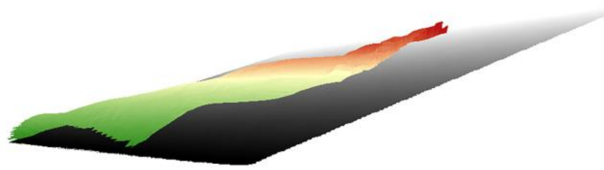

Fig. 4. Debris deposits above the flat surface

The observed geomorphic changes estimated by morphometric analysis are considered in relation of the results of morphoscopic and grain-size analyses of the debris deposits. The form of the boulders and pebbles is determined by coefficient of elongation (C_e) and coefficient of flattening (C_f), Serebryanniy (1980), calculated as a ratio between the axis "a", "b" and "c" of the measured clasts as follow: $C_e = b/a$, and $C_f = c/b$. Conclusions about the conditions of the transport and deposition are done on the basis of the degree of sorting (standard deviation) calculated on the grain size cumulative curves (Folk and Ward, 1957) as:

$\sigma_1 = (\varphi_{84} - \varphi_{16})/4 + (\varphi_{95} - \varphi_5)/6.6$, where φ is grain size diameter in a logarithmic scale.

Results

As a result of the TLS, detailed DEMs of the contemporary debris fan and the low part of the transport channel have been compiled as it written above. Two main morphometric parameters – curvature of the topographic surface and slope, derived of DEMs are analysed as indicators of the geomorphic change. The outputs of the analysis are given in Table 1.

Table 1. *Morphometric parameters*

	debris fan			
	October 2019		June 2020	
	concave, %	convex, %	concave, %	convex, %
profile curvature	48.07	51.93	45.16	54.84
planform curvature	46.83	53.14	43.38	56.58
average	47.45	52.54	44.27	55.71
	transport channel			
	October 2019		June 2020	
	concave, %	convex, %	concave, %	convex, %
profile curvature	55.74	44.26	51.55	48.45
planform curvature	52.54	47.46	51.16	48.84
average	52.54	47.46	51.36	48.64
mean slope, degrees	debris fan			
	October 2019		June 2020	
	15.28		19.36	
	transport channel			
	October 2019		June 2020	
	30.12		42.31	

The values of the curvature show that the area of convex parts of the debris fan is larger than the area of concave ones. This confirm the model of accumulation of the deposits. The comparison between October 2019 and June 2020 indicates increasing the convex areas in the debris fan which is related to changes in the spatial distribution of the deposits, where the accumulated mass in the upper and middle part of the debris fan were moved to the lower part (Fig. 5).

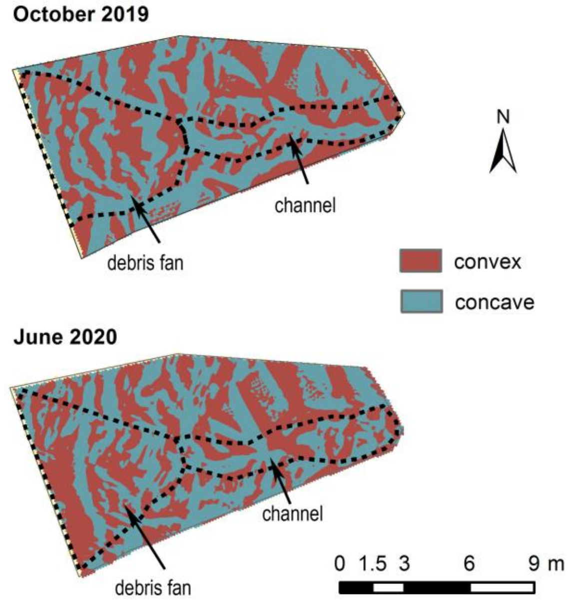

Fig. 5. Profile curvature

Planform curvature shows the changes in the convergence and divergence of the flows lines and in this regard allow to determinate the debris transport channel and deposition area (Fig. 6).

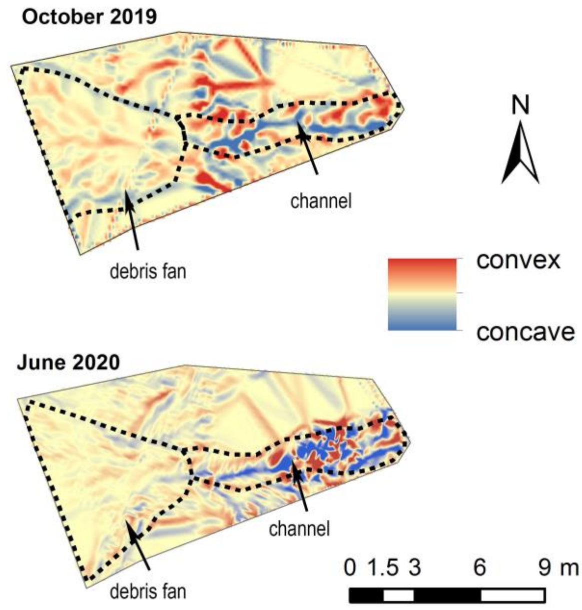

Fig. 6. Planform curvature

The changes in the curvature of the surface at the transport channel in the observed period are less expressed (Table 1). Although the concave parts are predominant the analysis show sight decrease of their areas and increasing of the convex parts. This can be explained by erosion and movement of debris deposits from the source area to the upper and middle part of the channel, and temporary stationing of the deposits due to lower flow energy or retaining role of vegetation. Increasing of the slope also indicate mass wasting to the local erosion basis from October 2019 to June 2020 (Fig. 7). The images in Fig. 7 are of the low part of the transport channel and correspond well to the models of profile curvature (Fig. 5), where convex parts are visible at the low part of the channel in October 2019, and are replaced by concave ones at the model of June 2020.

Fig. 7. Debris flow transport channel: a) October 2019; b) June 2020.

The volume of the contemporary debris deposits on the fan, calculated relative to the reference slope surface, is 5.99 m^3 in October 2019 and decreased to 5.41 m^3 in June 2020. This indicates that 0.58 m^3 rock and earth masses are removed to the direction of the erosion basis. Having regard the relatively small area of the gully and contemporary debris fan (nearly 25 m^2 of the fan) we can conclude that the area is subject to intensive erosion. The results of the geospatial modelling of the low part of the transport channel and the contemporary debris fan correspond well to the sampling of the deposits and to the results of the carried out morphoscopic and grain-size analyses.

The morphoscopic analysis of the clasts and calculated coefficients of elongation and flattening show that the disk-shaped and flat-drawn shape of the deposits predominates. This, on the one hand, suggests that they are moved along the slope by dragging, and on the other hand, it is related to the way the pyroclastic rocks weather. All fragments have a low degree of smoothness (0 and I), which indicates a short transport. The analyses of the size of the debris deposit at "a" and "b" axis show the largest size of the clasts at sampling in October 2019 (average "a"= 28 cm, average "b" = 17.7 cm) while in July 2019 the sampling shows average "a"= 21.7 cm and average "b" = 13.5 cm, and in June 2020 the average size of the sampled clasts is 22.9 cm along the axis "a" and 12.9 cm along the axis "b". This suggests that debris flow occurred between the first 2 sampling periods (July 2019 – October 2019), which was confirmed by local people who spoke about the event in the end of July. The decreasing of the size of the rock fragments at sampling in June 2020 can be explained by activation of the process and gravitational or water-gravitational movement of boulders and earth masses to the lower erosion basis of the gully – the river Byuyukdere, that reflect on the volume of the debris fan.

The grain size analysis of samples taken in October 2019 shows extremely poorly sorted materials. Sorting coefficient varies between 5.89 and 8.15 and increase from the transport channel to the basis of the debris fan, which is an indicator for turbulent nature of the flow, combined with gravitational movement of material and dynamic environment of deposition. Comparison of the values of sorting with the results of previous sampling in July 2019, when the sorting coefficient of the deposits in the flow channel is calculated at 3.73 show poorer sorted materials in October 2019 and indicate a process of torrential nature occurred between the two observation periods.

Conclusion

Erosion and deposition of gully induced debris flow are estimated in the current study on the basis of the detailed DEMs derived from TLS in two consecutive campaigns. The results show that the considered gully is a subject of intensive erosion and mass movement triggered by intensive rainfall causing torrential flows.

The analyses of the terrain and derived models of slope and curvature show that although increasing the area of convex parts of the contemporary debris fan in comparison with their extent eight months before, the volume of the deposits decreases. This indicates that the models of curvature of the topographic surface and particularly profile curvature give reliable information about the character of the geomorphological processes and the spatial distribution of the erosion, mass wasting and deposition, but give only relative quantitative information about the processes. Although the relative character of the models of curvature the information of them can meaningfully contribute to the erosion susceptibility assessment.

Detailed information about the intensity of erosion and deposition can be received of high resolution DEMs. Beside the DEM resolution and the chosen methodology, the results depend also on the way of data processing. In cases when the slopes of the gully are covered with trees and shrubs, as in the current study, and in applying manual removal of vegetation from the point cloud it is a challenge to achieve maximum accuracy of the result due to differences in vegetation removal. The season of data acquisition and vegetation state also impact on the quality of the results.

Though some uncertainties in the models the interpretation of the results according to the results of field sampling and grain size analysis shows the reliability of the applied methodology for debris flow investigation and for assessment of the geomorphic change.

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