Geomorphological and Sedimentological Indicators of Contemporary Erosion Processes: An Example of the Eastern Rhodopes Mountains (Bulgaria)

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Abstract: - Erosion processes, triggered by water, occur and propagate on sloping surfaces and have a significant negative impact on the soil quality and vegetation, as well as cause a change of the topographic surface. In the long term, they can lead to an increase in sediment transport, siltation of dams, and higher flood hazard. The development of water erosion reflects on the slope profile and the specific landforms like rills and gullies. In this regard, the geomorphological features of the areas can be considered indicators of the spatial distribution of erosion and accumulation. The sediment properties give information about the conditions of the transport and the intensity of the hydrogeomorphic processes. The current study aims to analyse the short-term changes in erosion and deposition by application of morphometry and grain size analysis. Topographic wetness index (TWI) and cross-section profiles of two small gullies were analysed based on high-resolution digital terrain models (DTMs), generated from unmanned aerial system (UAS) data. Remote sensing was combined with field geomorphological research and sediment sampling. The results of the research show about average 2 cm change in erosion and deposition for the period October 2021 – November 2022. Despite TWI and cross-section profiles depending on the DTMs resolution, they are reliable indicators for erosion and deposition. The grain size analysis supports the morphometric analysis. Coarse to very fine sands are predominant in most cases of sediment sampling. The sorting coefficient shows very poorly to moderately sorted deposits which indicates transport in a more dynamic environment and temporary flow.

Key-Words: - erosion, morphometric analysis, grain size analysis, gully, digital terrain models

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1 Introduction

Erosion and deposition of disintegrated slope materials are determined by a complex of factors including slope runoff, rainfall, slope gradient, rate of weathering of the lithological base, vegetation, etc. They are closely related to the form of the topographic surface but on the other side, they model the landforms and, in this relation, geomorphological properties of the area can be considered as indicators for the development of contemporary erosion processes and accumulation. The analysis of the publication about the evaluation of erosion and deposition shows an increasing number of studies based on the application of geoinformation technologies and particularly, using high-resolution digital terrain models (DTMs). The relation between erosion and topographic factors as well as using derivatives of the DTMs like slope gradients, curvature, stream power index, topographic wetness index, and Melton ratio for determining the spatial distribution of erosion and deposition is the subject of many publications, [1], [2], [3], [4]. Special attention is given to the topographic features and the cell size of DTMs in erosion susceptibility assessment and particularly in delineating rill and gully erosion, [5], [6], [7], [8]. In, [5], the authors recommend a grid size equal to, or finer than 1 cm for monitoring sediment delivery of rill/interrill erosions but also state that 5 cm of grid size gives good results. Analysing the topographic factors on the base of 5 m, 12.5 m, 20 m, and 30 m digital elevation models. In, [7], the authors state that elevation, slope aspect, slope degree, catchment area, plan curvature, profile curvature, stream power index, and topographic wetness index are reliable indicators for gully erosion susceptibility modelling. High resolution of the models is needed for calculating the volumes of eroded and accumulated materials, [8]. Regarding the previous studies, the resolution of the DTMs has to be determined taking into account the purpose of the research as well as the size of the erosional landforms. Combining the geoinformation technologies and classical geomorphology (morphometry and sedimentological analyses) provides better results in studying contemporary geomorphological processes and can increase the efficiency of the study, particularly in studying slow surface processes like soil erosion.

The current research aims to analyse the morphometric properties of the topographic surface of the erosional slope, and grain size statistical parameters of the sediments as indicators of short-term change in erosion and deposition. The emphasis is on the topographic wetness index (TWI), cross-section elevation profiles through different parts of gullies, and grains' mean size and sorting. Knowledge about the relation between the geomorphological and sedimentological features of the area and erosion processes is of importance for land use and conservation practice.

2 Study Area

The area of interest is a highly eroded slope in the catchment area of the river Byuyukdere, Eastern Rhodopes (Bulgaria), Figure 1. The research was carried out on two gullies, located in the northern and southern parts of the area. The sampling points are marked as follows: 601-1 and 601-2 - at the northern gully, and 602-1 and 602-2 – at the southern gully (Figure 1). The total area of the studied site is around 3.6 ha and the length of the gullies is approximately 95 m for the northern gully and 120 m for the southern one. The area is built with volcanic and sedimentary rocks from the Paleogene age, [9]. The volcanic rocks are highly weathered and presented by andesitic lava-breccia, tuff, tuffites, and epiclastic rocks. They are highly weathered and are characteristics of the northern gully which explain the greater depth of this gully in comparison to the southern one. Breccia-conglomerate sandstone formation builds the southern part of the study area, as well as a small the most northern part. The sedimentary formation is presented by coarse sandstones and locally separated breccia conglomerate clasts. The variation in the grain size makes the area more susceptible to weathering and erosion.

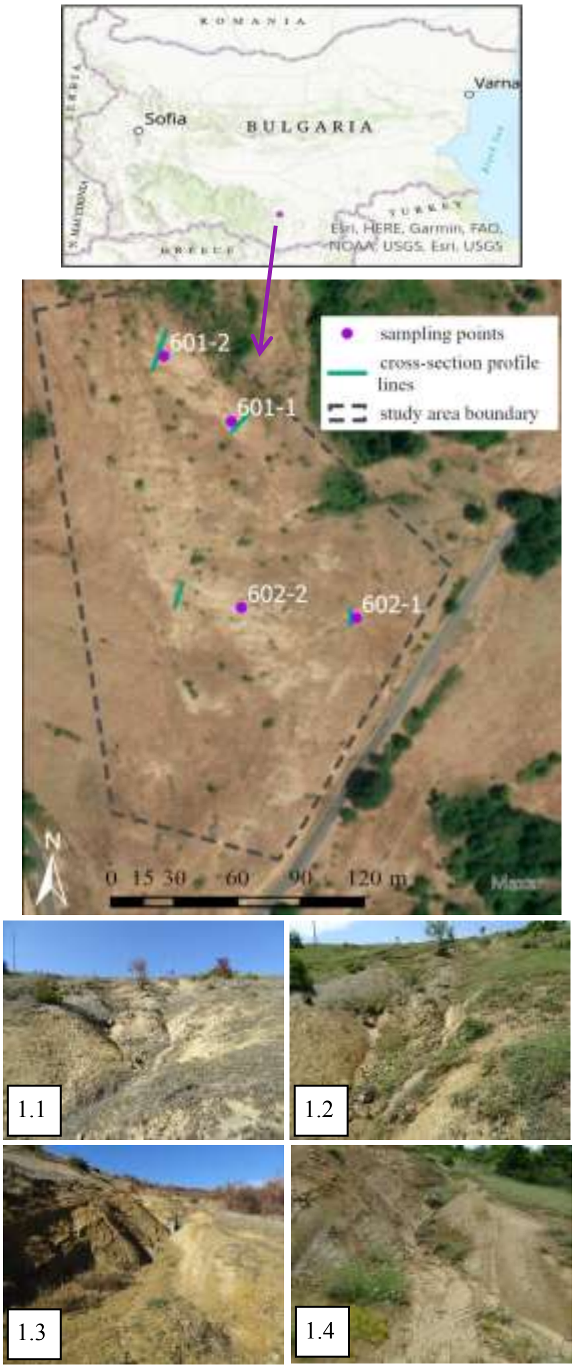

Fig. 1: Study area with location of sampling points and profile lines. Views of the sampled gullies (southern gully: 1.1 – October 2021, 1.2

– June 2022; northern gully: 1.3 – November 2022, 1.4 – June 2022)

Other factors that facilitate water erosion are relatively high slope gradients (15-30°) and the absence of vegetation, only single shrubs can be seen as very rare. The climate of the area is continental- Mediterranean. The maximum precipitation is in May-June and November-December. The alternation of dry and wet periods favors the disintegration of the materials and removal of the sediment particles by intensive rain and small temporary flows.

The intensive erosion increases the sediment load of the small river Byuyukdere that flows into the Kardzhali dam. This impact on the retention capacity of the dam and could increase the flood risk which requires consistent monitoring of erosion processes and sediment transport.

3 Material and Methods

The current study is based on terrain data, morphometric, and grain size analyses. High-resolution terrain data was acquired during two field campaigns - October 2021 and November 2022.

The photogrammetric imaging was performed with a Phantom 4 RTK unmanned aerial system equipped with a 20-megapixel digital camera. The onboard integrated RTK module provided real-time, centimeter-level positioning data for improved absolute accuracy on image metadata. The same flight parameters were applied to both flight campaigns: oblique-viewing trajectory with gimbal pitch angle at 60 degrees - 3D mode, an altitude of 60 m with 80% along-track and across-track overlap. Of each one of the flights 368 images in *jpg format were obtained.

For model georeferencing purposes 20 GCPs (ground control points) were placed, distributed evenly across the object. 6 of them were used as control points and the other 14 - as checkpoints. The points were stabilized with wooden pegs and signaled with black and white square-shaped marks. They were measured with a multi-frequency GNSS receiver CHC i50 in RTK mode in the ETRS89 coordinate system, UTM 35N projection.

The photogrammetric processing was performed in Agisoft Metashape Professional 1.6.0 (Agisoft LLC, 2020) applying the “structure for motion” algorithm. This algorithm allows individual images or characteristic points of them to be linked without the need for the images to be of the same scale, i.e., they can be of different resolutions.

Dense point clouds were generated and were further processed to remove vegetation and filter ground points. High-resolution digital terrain models (DTMs) were created from the ground points in ArcGIS Pro 3.1.0 (ESRI, 2023) environment using the Natural Neighbor interpolation method, interpolation type – Triangulation. Taking into account the erosional relief of the studied area and the size of the gullies, DTMs with a cell size of 1 m and smoothed by Focal statistics (Neighborhood 5x5 cells; Statistics type Mean) were used for morphometric analysis. Slope gradients and topographic wetness index (TWI) were calculated as indicators of slope processes. The slope surface is the first derivative of the elevation. It influences surface runoff and mass movement. TWI is a relative indicator of the ability of the topographic surface to collect water and is therefore considered an indicator of erosion processes, [10], [11]. It was computed in a GIS environment using Map Algebra and the application of natural logarithm of the ratio of the contributing area to the tangent of the slope gradient, [3]. For determining the contributing area, the flow accumulation raster, generated by ArcGIS Pro Hydrology Tools, was used. The higher TWI the greater the incision of the gully.

Cross-section elevation profiles at the lower and the upper part of the studied gullies were generated on the base of 5 cm horizontal resolution DTMs from both remote sensing campaigns. The changes in erosion and accumulation were evaluated as a result.

Remote sensing methods (UAS data acquisition) were combined with classical geomorphological field studies – terrain observations and sampling of four key sites in the selected gullies. Samples for grain size analysis of the superficial deposits were taken from the gullies bed at the lower and the upper part of the gullies (Figure 1). The following grain size statistical parameters were computed: Mz (mean size), σ (standard deviation), Sk (skewness) and K (kurtosis) by, [12], method. For this purpose, Gradistat, Version 9.1 were used, [13], [14].

The graphic mean size (Mz) parameter is the average grain size value and can be calculated, using the equitation (1):

$$\mathrm{Mz} = \frac{\varphi_{16}+\varphi_{50}+\varphi_{84}}{3} \quad (1)$$

where φ_{16}, φ_{50}, and φ_{84} are the particle diameters in φ at the respective percent, determined on the cumulative curve of the grain size distribution.

Standard deviation is considered as grain-size sorting, [12], [13], [14]. It is calculated by the formula (2):

$$\sigma = \frac{\Phi_{84}-\Phi_{16}}{4} + \frac{\Phi_{95}-\Phi_{5}}{6{,}6} \quad (2)$$

the meaning of φ is as above.

The higher the value of σ the worse the sorting and indicates more dynamic transport conditions.

Skewness is related to sorting and is a measurement of the degree of symmetry of grain size distribution, [12], [13]. It is calculated using the equation (3):

$$\mathrm{Sk} = \frac{(\Phi_{84}+\Phi_{16}-2\Phi_{50})}{2(\Phi_{84}-\Phi_{16})} + \frac{\Phi_{95}+\Phi_{5}-2\Phi_{50}}{2(\Phi_{95}+\Phi_{5})} \quad (3)$$

the meaning of φ is as in the above equations.

Kurtosis is a measure of the sharpness or peakedness of the grain size frequency curve, [12]. It is calculated by the formula (4):

$$\mathrm{K} = \frac{(\Phi_{95}-\Phi_{5})}{2{,}44(\Phi_{75}-\Phi_{25})} \quad (4)$$

The sediment sampling was carried out at the same time as the UAS campaigns, and also in June 2021, taking into account the seasonality of precipitation. Particle size determination was performed in the Laboratory of Geochemistry at the University of Mining and Geology “St. Ivan Rilski”, by sieve/aerometric method and according to the Bulgarian State Standard BDS EN ISO 17892-4:2017.

The grain size statistics were calculated in φ units. The conversion of grain diameter (d) from millimeters to φ is according to the following equation (5):

$$\varphi = -log \quad (5)$$

The grain size statistical parameters were used to reveal the character of the sediment transport and the depositional processes.

An advantage of the methodology applied in the present study is the integrated application of geoinformation technologies, classical morphometry, and grain size analysis which allows a more complete to reveal the features of erosion and deposition.

4 Results

4.1 Morphometric Indicators

The analysis of the surface parameters slope and TWI shows very similar patterns for both DTMs, based on the data of October 2021 and November 2022. A predominant part of the studied area (57%) has slope gradients between 15° and 30° (Figure 2). The differences between the slope surfaces from the first and second UAS campaigns are negligible. Bit higher gradients are observed on the model based on the data of November 2022. The maximum value of the slope is 61°, while the model of October 2021 shows a maximum slope gradient of 59° (calculated on 5 cm DTM, smoothed 20x20 cells). This could be related to erosion and gully incision in the middle and upper part of the slope.

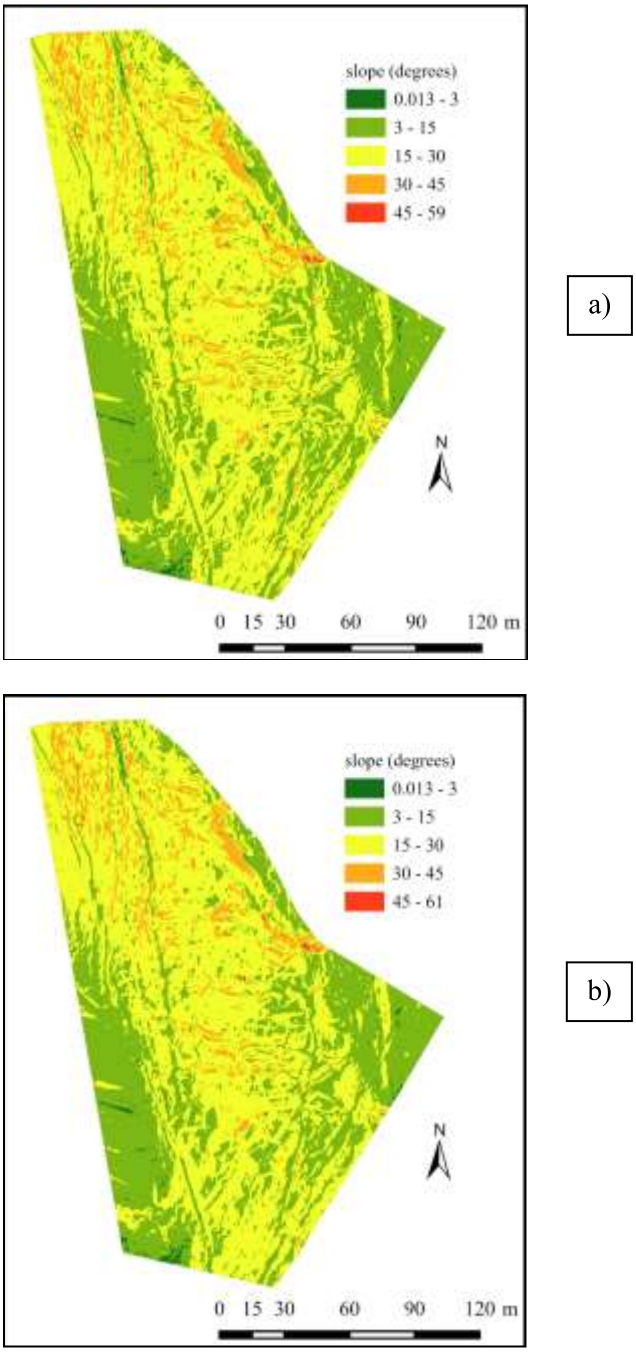

Fig. 2: Spatial distribution of slopes: a) October 2021; b) November 2022

There is also no visible change in the visualization of the spatial distribution of the TWI.

The calculated values, based on 1 m DTM and smoothed by Focal statistics 5x5 cells, show a higher value for October 2021 (12.3747) compared to November 2022 (10.9288), Figure 3. This indicates a slight reduction in surface roughness from 2021 to 2022 which could be explained by the movement and accumulation of slope materials. However, the differences between the TWI of October 2021 and November 2022 show different spatial distributions of the slope processes. The cases where the TWI is higher for November 2022 compared to October 2021 are considered as erosion and those where the values for 2022 are lower - as accumulation (Figure 3). The analysis of the results about both studied gullies shows more active erosion in the bed of the northern gully as well as in the upper part of the southern one, while accumulation or very slight to no change of the surface is more often observed in the southern gully.

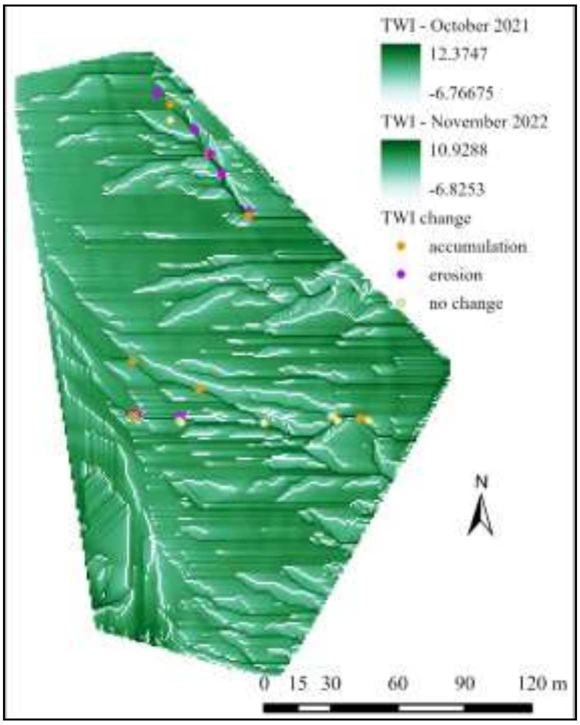

Fig. 3: Topographic wetness index. Points show the change in the TWI between October 2021 and November 2022 and related changes in the topographic surface

A clear indicator of contemporary erosion and accumulation processes is the change of the cross-section topographic profiles through the gullies. Two profile lines for each gully, one at the lower and one at the upper part, were analysed. The location of the profile lines is shown in Figure 1. The comparison of the elevation profiles at the lower part of the northern gully shows a 2 cm accumulation in the gully bed for one year. Regarding the highest point of the profile, the elevation decreased from 615.38 cm to 615.19 cm (Figure 4). The difference between 20 cm denudation at the highest part and 2 cm accumulation at the lower one indicates that some of the materials are deposited on the slope and did not reach the gully bed, and also some of the materials in the bed were moved down the gully. The changes in the elevation of the left slope of the gully are smaller - about 4 cm in the higher part of the slope and 2 cm near the gully bed. Cross-section profiles of the upper part of the northern gully show a 3 cm decrease in the maximum elevation from October 2021 to November 2022. The gully bed was cut about 2 cm (Figure 5). Lateral erosion and accumulation have resulted in slight displacement and widening of the gully bed.

Higher values of accumulation are observed in the bed of the lower part of the southern gully – around 7 cm, from October 2021 to November 2022, at the lateral parts of the gully bed, near the slope, and nearly 11 cm in the middle of the gully bed (Figure 6). The feeding is from the slopes of the gully as well as from the upper part of the gully bed, and because of the small slope gradients at the end of the gully, the removing of sediments from this part is slow. The distribution of erosion and deposition of the materials results in the widening of the gully bed and a decrease in the maximum elevation of the analysed section of the study area. The width of the riverbed increased from 1.38 to 1.87 cm, and the height of the slopes decreased by about 2 cm in one year. Despite the cross-section profiles through the upper part of the southern gully showing that the maximum elevation of the line for November 2022 is 1 cm higher than in October 2022, the slope height above the gully bed decreases by around 1 cm for the period of the study, where the elevation is changed from 625.53 m to 625.52 m (Figure 7). The slope wash and transport of the material in the gully bed from the area above the bed result in nearly 4 cm higher gully bed in November 2022 compared to October 2021.

Regarding the topographic data we could conclude that the average rate of erosion and deposition in the studied area is around 2 cm for the period October 2021 – November 2022.

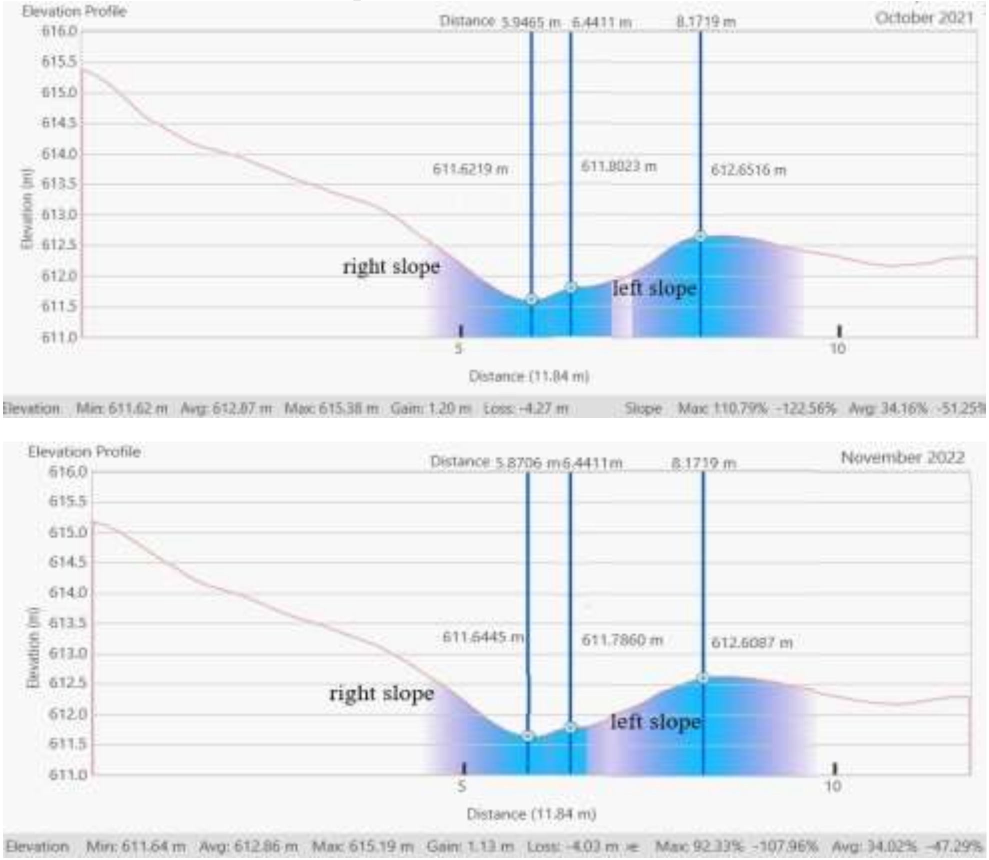

Fig. 4: Cross-section topographic profiles – the lower part of the northern gully

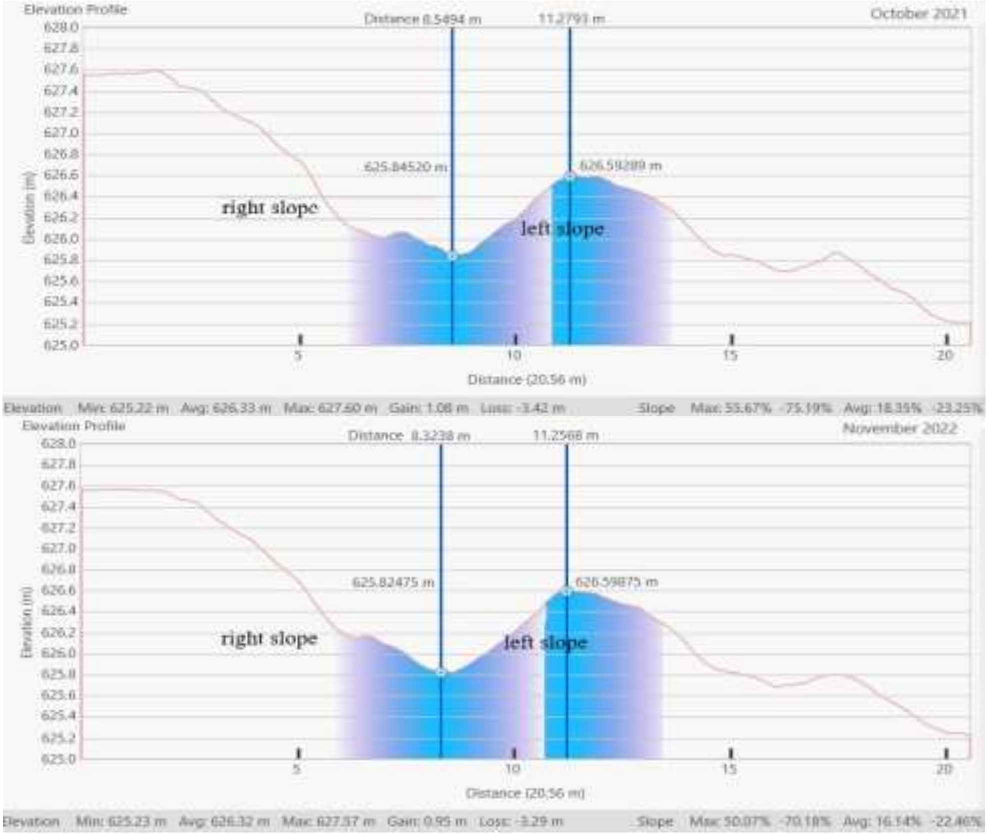

Fig. 5: Cross-section topographic profiles – the upper part of the northern gully

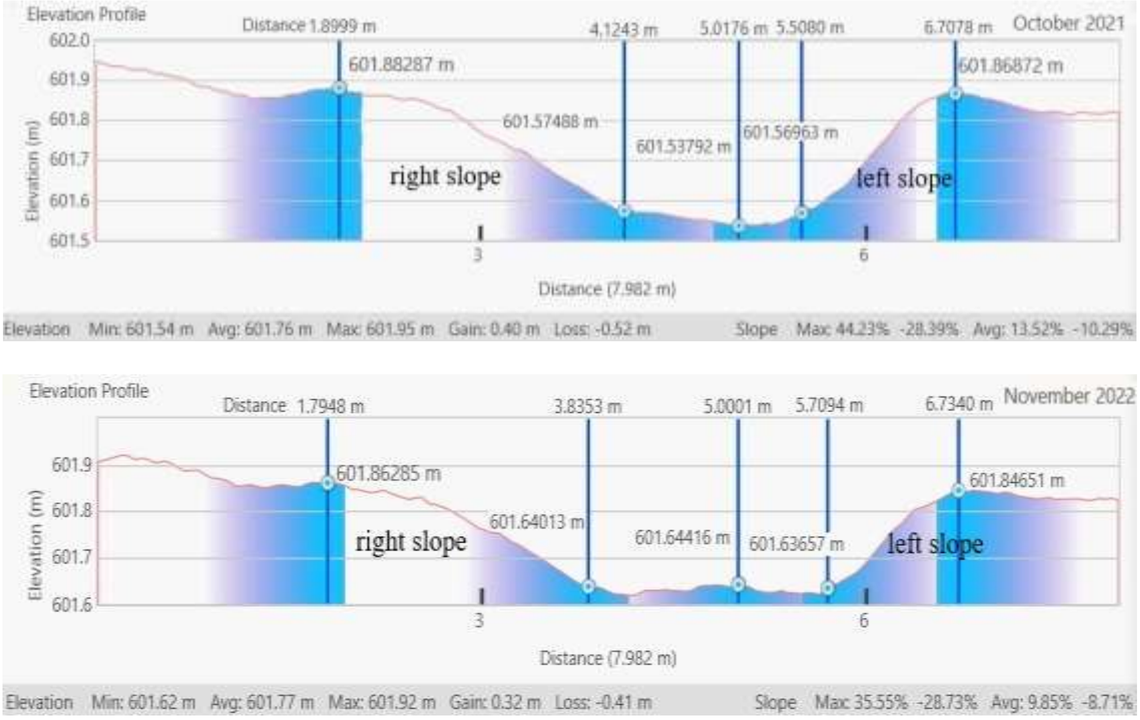

Fig. 6: Cross-section topographic profiles – the lower part of the southern gully

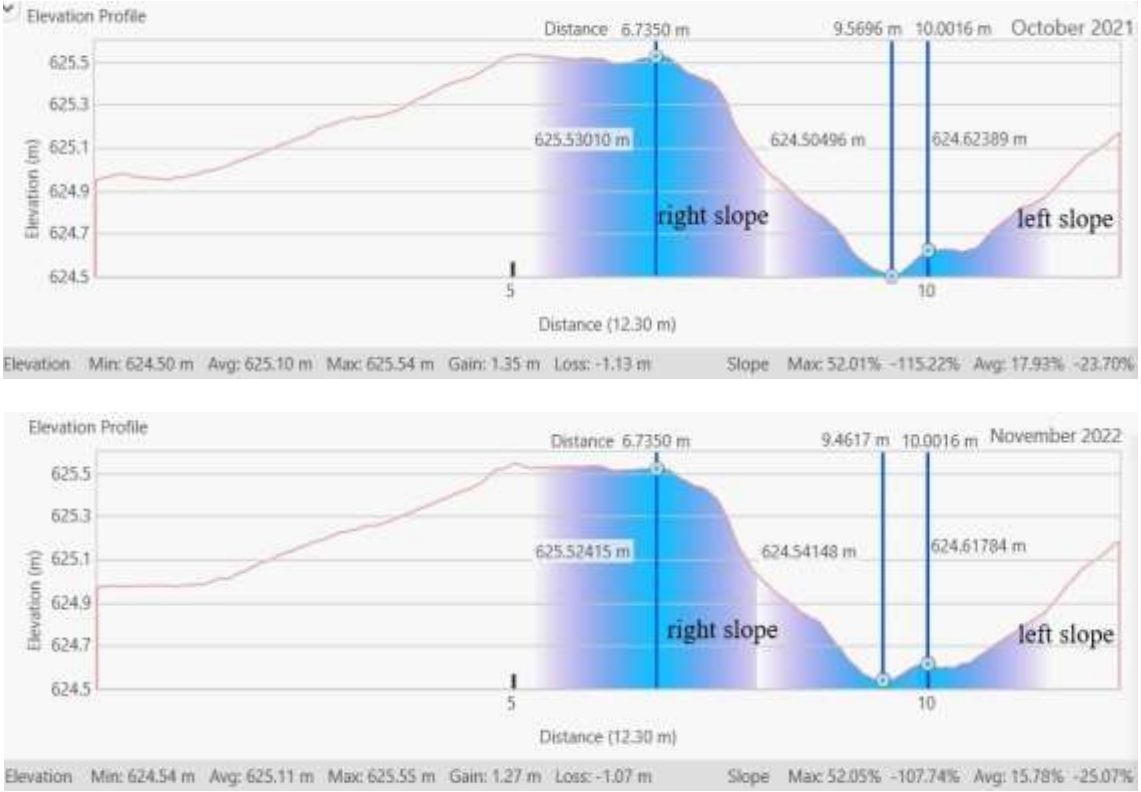

Fig. 7: Cross-section topographic profiles – the upper part of the southern gully

4.2 Sedimentological Features

The variability of precipitation and changes in hydro-geomorphic conditions in the study area results in the characteristics of the deposits, particularly in the grain size distribution of the sediments. On the other side, particle size is a fundamental factor that controls erosion, transport, and deposition of sediments, [15], [16]. The erodability of soils increases in case of large sand fraction and low clay and silt contents, [17]. The calculated values of the main parameters of grain size statistics are determined by [12], and are shown in Table 1.

The graphic mean size values of the sample from the lower part of the northern gully (601-1) range from 2.19 to 3.02 φ. This means that fine sands are dominant in the samples from October 2021 and June 2022. Very fine sands are characteristic of the sample from November 2022. The size of the grains in the low part of the northern gully decreases from October 2021 to November 2022 which is an indicator of the development of weathering and erosion. Larger variations can be seen in samples taken in the upper part of the northern gully (sample 601-2), from -1.58 to 2.91 φ (Table 1). In the three samplings (October 2021, June 2022, and November 2022), the deposits ranged from medium sand to very fine gravel. The average size becomes coarser, excepting the last sampling when a significant decrease in the grain size to fine sand is observed. The grain size of the material in the upper part of the sampled northern gully in all samples is larger than that one in the lower part, i.e. as it moves down the slope, the finer particles accumulate at the bottom, while the coarser clasts are retained at the upper parts of the slope. This can be explained by the fact that when moving down the slope entrained by rainwater, finer materials move more easily and pass longer distances, while coarser materials require more energy. On the other side, the larger size of the grains indicates a higher power of the water or the development of gravitational processes. Inconsistent decrease of the grain size in the longitudinal profile of the gully could be related to the lateral feeding of sediments from the gully slopes, [18].

Similar to the northern gully is the distribution of the mean size of the grains in the southern gully (samples 602-1 and 602-2), Table 1. There are differences in the average size of the deposits in the upper and lower parts of the gully. The values of the graphic mean size vary from -0.22 to -0.65 φ in the lower part, and the materials become finer (very coarse sand to coarse sand). In the upper part of the gully, the values vary from -2.37 to 0.96 φ.

Table 1. Grain sizer statistical parameters (in φ)

Sample	**Mz**	**Description**	**σ**	**Description**	**Sk**	**Description**	**K**	**Description**
Northern gully								
601-1 Oct. 21	2.484	Fine Sand	0,953	Moderately Sortec	-0.115	Coarse Skewed	0.97	Mesokurtic
601-1 June 22	2.129	Fine Sand	1.098	Poorly Sorted	-0.078	Symmetrical	1.068	Mesokurtic
601-1 Nov. 22	3.02	Very Fine Sand	0.8	Moderately Sortec	-0.399	Very Corse Skewed	1.026	Mesokurtic
601-2 Oct. 21	1.629	Medium Sand	1.619	Poorly Sorted	-0.208	Coarse Skewed	0.996	Mesokurtic
601-2 June 22	-1.587	Very Fine Grave	3.265	Very Poorly Sorte	0.708	Very Fine Skewed	0.496	Very Platykurtic
601-2 Nov. 22	2.917	Fine Sand	0.756	Moderately Sortec	-0.171	Coarse Skewed	0.965	Mesokurtic
Southern gully								
602-1 Oct.21	-0.651	Very Coarse San	2.852	Very Poorly Sorte	-0.203	Coarse Skewed	0.779	Platykurtic
602-1 June 22	-0.223	Very Coarse San	2.961	Very Poorly Sorte	-0.373	Very Coarse Skewec	0.681	Platykurtic
602-1 Nov. 22	0.487	Coarse Sand	2.651	Very Poorly Sorte	-0.435	Very Coarse Skewec	0.873	Platykurtic
602-2 Oct. 21	-2.377	Fine Gravel	2.713	Very Poorly Sorte	0.682	Very Fine Skewed	0.777	Platykurtic
602-2 June 22	0.964	Coarse Sand	2.841	Very Poorly Sorte	-0.635	Very Coarse Skewec	1.322	Leptokurtic
602-2 Nov. 22	-0.532	Very Coarse San	3.107	Very Poorly Sorte	0.237	Fine Skewed	0.466	Very Platykurtic

This indicates a decrease in the materials from fine gravel to very coarse sand.

The differences in the grains' mean size in the deposits of the northern and southern gullies can be explained, to some extent, by the different lithological bases and also by the different rates of weathering of tuffs and sandstones.

The sorting coefficient in the lower part of the northern gully varies from 0.80 (October 2021) to 0.95 (November 2022). The deposits are determined as moderately sorted. The sampling in June 2022 shows poorly sorted materials (Table 1). This could be related to the intense rainfall a few days before the sampling. In the upper part of the gully, the sorting coefficient shows very poorly sorted materials (σ = 3.27) for June 2022, while the sampling in October 2021 indicates poorly sorted deposits (σ = 1.61), and in November 2022 – moderately sorted (σ = 0.75). No change in the sorting rate of the deposits in the longitudinal profile of the gully is observed in the samples of November 2022.

The sorting coefficient of the samples from the southern gully indicates very poor sorting in all sampling (Table 1). Regarding the small part of the study area, the difference in the sorting of the deposits in the northern and southern gullies is related more to the differences in the lithological composition (volcanic rocks and sandstones) than to the precipitation and slope runoff.

The skewness is considered a measure of the proportion of coarse and fine fractions, [19]. The negatively skewed distribution curve indicates turbulent energy conditions of the depositing environment, [20]. The values of the skewness of samples from the first and third sampling of the northern gully do not vary significantly, they indicate coarse and very coarse skewed graphics. Differences are observed in the samples of June - from -0.07 (symmetrical) for the lower part of the gully and 0.70 (very fine skewed) for the upper part.

The values of skewness of the distribution of the deposits from the lower part of the southern gully vary from -0.20 to -0.43 (coarse to very coarse skewed). Samples from the upper part of the gully indicate very fine to fine skewed graphics, while in the sample of June 2022, the curve of the grain distribution is very coarse skewed. The negative skewness confirms the variable conditions of the environment of deposition and can be considered as an indicator for transport by temporary flows or slope wash.

The values of kurtosis of the grain size frequency curve of the samples from the northern gully are 0.97 (October 2021) and 1.06 (November 2022). Sampling in June 2022 shows a very platykurtic curve (0.49). Considering that kurtosis is a second indicator of sorting, these values indicate poorly to very poorly sorted materials, [15].

About the southern gully, the kurtosis of the grain size curve is less than 1 at the sampling in autumn months (very platykurtic to platykurtic) and is higher at the sampling of the upper part of the gully in June (leptokurtic). According to [21], a mixture of two sediment fractions results in platykurtic distribution, respectively poor sorting, while a mixture of one predominant and one subordinate fraction gives a leptokurtic distribution. Excepting the leptokurtic curve, the other cases of the sampling confirm poorly sorted materials, which is an indicator of a temporary flow with variable energy.

5 Conclusion

The geomorphological and sedimentological features of the studied slope in the river Byuyukdere watershed (Eastern Rhodopes) indicate average erosion and deposition rates of around 2 cm from October 2021 to November 2022. The morphometric analysis was carried out on the base of high-resolution (5 cm cell size) DTMs that were created from the data acquired in two UAS field campaigns (2021 and 2022). The results of the current study highly depend on the resolution of the models and the filtering of the ground points. In this relation, future research should be directed at evaluating the impact of DTMs properties on morphometric analyses. TWI is a reliable indicator for the convergence of the flows and the ability of the surface to collect water. Better results are obtained using smoothed high-resolution DTMs.

Regarding the main statistical parameters of grain size distribution, the analyses show active erosion processes and sediment transport in a dynamic environment. The alternation of dry and wet periods impacts the disintegration of the slope materials that are entrained by slope runoff and additionally model the slope surface. More significant differences between the northern and the southern gullies are observed in the sorting coefficient of the deposits which is related to the lithological composition and the rate of weathering.

The current study gives insides of the topographic change in the part of the river Byuyukdere catchment area emphasizing the integrated application of the geoinformation technologies and classical geomorphology. The results of the morphometric analyses of the high-resolution DTMs as well as of the grain size analyses of the sediments can be used as initial information in erosion susceptibility assessment.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Valentina Nikolova elaborated the concept of the paper, contributed to the methodology and carried out the morphometric analyses of DTMs, and did a geomorphological interpretation of the results.

Radostina Risova calculated and analysed the grain size parameters, and contributed to the methodology and geomorphological interpretation of the results.

Veselina Gospodinova and Asparuh Kamburov acquired and processed UAS data, and contributed to the methodological part of the paper.

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Conflict of Interest

The authors have no conflict of interest to declare.