ASSESSMENT OF DEBRIS FLOWS-PRONE WATERSHEDS IN SOUTHERN SLOPES OF STARA PLANINA MOUNTAIN BY COMBINED RASTER AND MORPHOMETRIC ANALYSIS

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ABSTRACT. The southern slopes of Stara Planina Mountain are one of the well-defined areas in Bulgaria in terms of debris flows hazard. For the present study, we choose five watersheds located north and northwest of the village of Anton (Zlatitsa region) to make a preliminary hazard assessment for debris flows. Used methods include field observations, GIS and morphometric analysis of the relief, raster analysis and modeling of certain parameters. We determine and characterize the source, transition and deposition zones, and areas prone to erosion in river channels, thus giving an idea where in the studied watersheds could be formed areas with an accumulation of material with the potential to be mobilized and involved in debris flows during extreme meteorological events. To the obtained data we take into account the influence of lithology and tectonic conditions in the area, which affect the distribution of material on the slopes. Obtained results could be used for regional hazard estimations and mapping, and assess if the used approach is applicable for other areas in the country.

Keywords: natural hazard, debris flows, erosion, GIS, morphometry

ОЦЕНКА НА ВОДОСБОРИ С ПРОЯВА НА КАЛНО-КАМЕННИ ПОТОЦИ В ЮЖНИТЕ СКЛОНОВЕ НА СТАРА ПЛАНИНА, ЧРЕЗ КОМБИНИРАН РАСТЕРЕН И МОРФОМЕТРИЧЕН АНАЛИЗ

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РЕЗЮМЕ. Южните склонове на Стара планина се очертават като една от добре изразените области в България по отношение на опасността от кално-каменни потоци. За настоящето изследване избрахме пет водосбора, разположени северно и североизточно от с.Антон (Златишко) за да бъде направена предварителна оценка на опасността от възникване на кално-каменни потоци. Използваните методи включват теренни наблюдения, ГИС и морфометричен анализ на релефа, растерен анализ и моделиране на определени параметри. Определени и характеризирани бяха зоните на подхранване, транспорт и отлагане, както и районите, склонни към ерозия в речните канали, които биха ни дали представа къде в изследваните водосбори могат да се формират зони с натрупване на материал с възможност да бъде мобилизиран и въвлечен в кално-каменни потоци при екстремни метеороложки явления. Към получените данни отчитаме и влиянието на литологията и тектонската обстановка в района, които оказват влияние при разпределението на материал по склоновете. Получените резултати биха могли да бъдат използвани при регионална оценка на опасността от кално-каменни потоци и тяхното картиране, а също и да се прецени дали използваният подход е приложим за други области на страната.

Ключови думи: природна опасност, кално-каменни потоци, ерозия, ГИС, морфометрия

Introduction

Debris flows are often seen event in mountain areas and cause significant damage to infrastructure, property, and citizens because of the high mobility and energy, which also have an impact and cause changes in river channels and slope morphology. Debris flows are described as "turbulent flowing mixtures of sediment and liquid in nearly equal proportions" (Iverson, 1997), quickly formed and fast-moving mass that flows on slopes with high angles (Hungr, 2005). The assessment of debris flows hazard is important in mountain areas worldwide because of their high-damage possibilities. Debris flows are triggered by factors like erosion, geological characteristics, slope, climate conditions and their intensive activity in recent years could be explained in some cases with climate changes (Chen, 2016; Uzielli et al., 2018; Nikolova et al., 2018; etc.).

In Bulgaria, debris flows are still not so well-studied as impact and distribution, but instead of these last few years, different research groups work on hazard evaluation of their regional occurrence in Bulgaria. Most of the studies are based on geomorphological analysis for the assessment of catchments suspected for debris flows. Few well-described examples for debris-flow activity are from Stara Planina Mountain (Gerdjikov et al., 2012; Kenderova, Baltakova, 2013; Dotseva et al., 2014; 2019a), Pirin and Rila Mountains (Baltakova et al., 2018; Dotseva et al., 2019b), Kresna Gorge and Struma River valley (Dobrev, Georgieva, 2010; Kenderova et al., 2013a,b; 2014; Nikolova et al., 2018), etc. Some of these areas were mapped by Iliev (1994) in Map of Geological Hazard in Bulgaria and noted in works of Kamenov, Iliev (1963) and Iliev, Bruchev (1994).

The determination of the source, transition, and deposition zones is one of the main steps for hazard assessment of watersheds prone to debris flows. For this purpose are used different methods like analysis of remote sensing data, spatial GIS analysis, dynamic and physical-based models, etc. In the present study, we characterise the main zones related to debris flow hazard in five watersheds from the southern slopes of Stara Planina Mountain, near Anton Village. The research area is chosen generally because of field observations and data about torrential events in the past (Mishev et al., 1962; Kerenski et al., 1977), confirmed also by recent field and tectonic-geomorphological data (Gerdjikov et al., 2012; Glabadanidu et al., 2012).

Debris flow potential of the watersheds will be assessed by analysis and evaluation of geometrical and slope conditions in the watersheds and morphometric parameters, sensitive to flow type and erodible potential – Form Factor, Elevation Relief Ratio, Drainage Density, and Melton Ruggedness Number. Also, we apply simple GIS procedures as raster analysis and binary masks as proposed by Grelle et al. (2019), which were used for identification of areas in channels that are erosion-prone and could act like debris flows source areas. This type of approach has some limits - it does not consider specific debris flow factors like rainfall rates, flow velocity, energy, rheological characteristics, volume and thickness of sediment material in the channels, etc. Instead of this, it is a very useful step for hazard pre-assessment and easy for application in contrast with more complex physical-based models for debris flow development and evolution.

Along with GIS analysis field work was carried out for evaluation of the influence of lithology and tectonic conditions in the area, which affect the distribution of material on the slopes and its involvement in the flows.

Geological and Geomorphological Setting

The study area is located to the north and northeast of the village of Anton, on the southern slope of Stara Planina Mountain, where the topography is characterized by steep slopes and deeply incised river channels (Fig. 1).

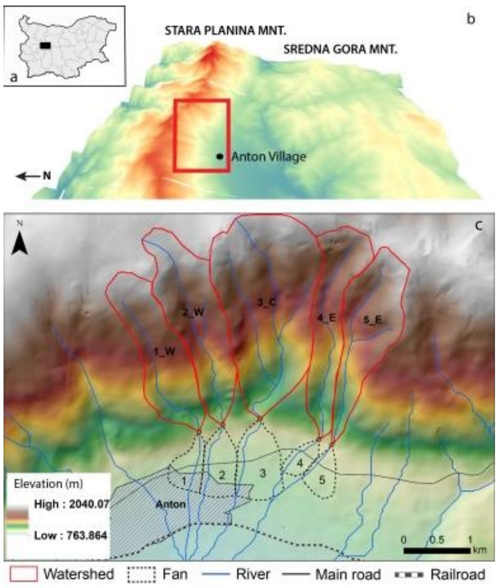

Fig. 1. a,b- Location of the studied area; c- Hillshaded DEM with delineated watersheds and associated fans

The area above 1500-1600 m is covered by grass and shrub vegetation, exposed to intensive erosion and weathering, and with a high chance to form slope-induced processes. Lower parts of the watersheds were occupied by forests. The climate is characterized by mean annual temperatures of 9.3°C and mean precipitation ratio of 615 mm/y (up to 700 mm/y in upper parts of the Mountain). Extremely high rates of precipitation and snowmelt in the spring often leads to water drain over steep slopes, thus forming floods.

Rock types play a key role in the formation and accumulation of sediment cover which could be eroded and involved in debris flows. The geology of the area is represented by granodiorites of Vezhen Pluton, metasediments of a low-grade metamorphic complex with lenses of metabasitic rocks, and gneisses of the high-grade metamorphic complex (Antonov et al., 2010) (Fig. 2). All rocks are with Paleozoic age. Zlatitsa basin fill is represented by Quaternary alluvial, colluvial, and deluvial sediments, which formed coalescing fans at the slope base. Quaternary loose accumulations were distributed like screes on slopes in upper parts of the watersheds, in riverbanks, and on riverbeds, but due to their small size, they are not shown on the map.

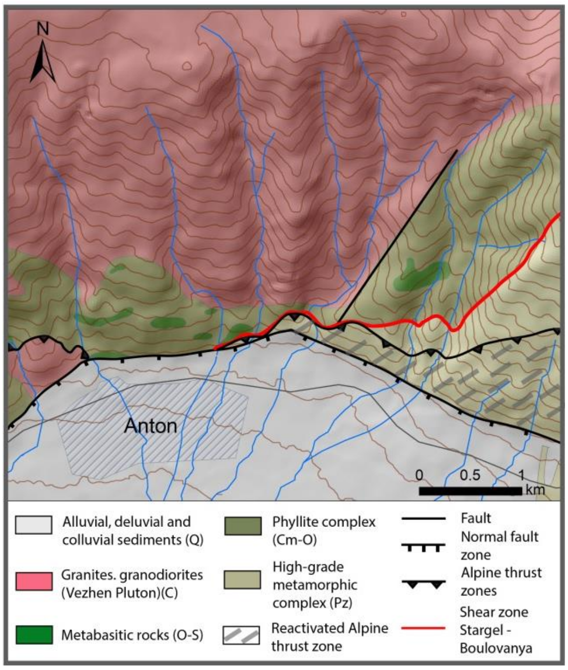

Fig. 2. Geological map of the studied area (modified after Antonov et al., 2010)

According to the classification proposed by Attewell and Farmer (1976) for rock hardness, rocks in watersheds fall into a range of very high strength (> 60 Mpa) for granodiorites and gneisses to medium to weak (< 5 to 5 – 30 Mpa) for low-grade metamorphic rocks (phyllites) in middle and lower parts of the watersheds.

One of the main tectonic features in the study area is the Quaternary normal fault zone traced along the southern slopes of the Stara Planina Mountain. Gerdjikov et al. (2017) described it as a “long-living tectonic zone with reactivation of older Alpine compressional structures”. The zone.has well-pronounced geomorphological expression, strong impact on watersheds shape, size, channel length, incision, erosion and deposition (Gerdjikov et al., 2012; Glabadanidu et al., 2012).

Another tectonic zone that influences the area is the shear zone Sturgel-Bolouvanya which is the boundary between high- and low-grade metamorphic rocks (Gerdjikov et al., 2007). The zone is with Variscan age, at which the lower parts of the earth's crust (high-grade metamorphic rocks) are exhumed. As a result of the Variscan orogeny, in both complexes was formed a foliation parallel to the zone and dipping to the SW with an angle of 30-50^{o}. Polyphase Variscan and Alpine tectonics having a strong effect on the rock strength, so in the vicinities of the fault zones, the rocks are often rather weak.

Materials and Methods

For the analysis purposes, EU-DEM v.1.1. (25 m) was interpolated by the bilinear interpolation method to grid resolution of 10 m. According to previous studies 10 m cell size is an appropriate resolution for the determination of slope gradient and debris flow areas (Tarolli and Tarboton, 2006; Carrara et al. 2008; etc.). Generated DEM was hydrologically adjusted, and the extracted river network was further corrected. Based on the topographic map of the scale of 1:50 000, remote sensing data, and DEM watershed areas, adjacent fans and watersheds closing sections were mapped. The pre-processed DEM was used for the extraction of Slope and Curvature maps, basin geometry, and morphometric parameters.

Morphometric analysis is based on calculations of four indices – Form Factor, Elevation Relief Ratio, Drainage Density, and Melton Ruggedness Number (MRN). Form Factor (HSF) (Horton, 1932) represents the shape of the watershed and influences the run-off distance, time, and peak discharge, where the higher the value of Form Factor more circular is the shape. Elevation Relief Ratio (ERR) (Pike et al., 1971) is related to the erosional evolution of the watershed and indicates the stages of youth, mature or old. Low values of the Elevation Relief Ratio indicate hard rocks and a small degree of the slope. Melton Ruggedness Number (Melton, 1965) is a slope index used for recognition of a type of the sediment transport – waterflood/bedload, mixed/debris flood, or debris flow and represents the relief ruggedness within the watersheds. Drainage Density (DD - 1 km/km^2) (Horton, 1932) reflect the erosion activity and the permeability of the soils and rocks in watersheds.

For the definition of the erosion-prone areas in the main channels was used the spatial distribution of three parameters - Slope Ratio (SR) and Area of the watershed in square kilometers (A), obtained by DEM, and Trigger Ratio (TR) calculated in the Raster Calculator as a ratio between SR and ST (Slope Threshold) (Grelle et al., 2019). ST is equal to:

$$ST = k.A \qquad (1)$$

where A is the watershed area in km^2; and coefficient k - express the erosion proneness, related to soil properties, water saturation, vegetation, etc.

Different values of k and ST respectively were used to model the possible trigger conditions in the watersheds. For a visual representation of TR and delineation of erodible zones in river channels were used binary mask values (1 = yes; 0 = no).

Field data and observations were used for confirmation of the obtained results, characterization of source, transitional and depositional zones, and geological conditions in watersheds.

Results

DEM analysis, field observations and historical data

The average altitude in studied watersheds is from 1450 to 1570 m. The slope angle is one of the main triggering factors for debris flows and range between 21.10 and 24.96 degrees. These values correspond to the initiation slope ratio for debris flows (Hungr, 2005) (Fig. 3). The slope exceeds 40 degrees in some places in the upper parts of the watersheds.

The source areas are located at an altitude above 1600 m, in the upstream area of watersheds. The channels characterized by V-shape and steep slopes with sparse vegetation on both sides, and also seasonally covered by snow (which leads to frost weathering). Gully and rill erosion is observed at the channels heads. Intense erosional processes form screes and loose material accumulations consisted of eroded Vezhen Pluton granitoid. The area is thus a potential source of initiation of debris flows in conditions of appropriate hydrodynamic conditions and inducing material in debris flows down to the slope.

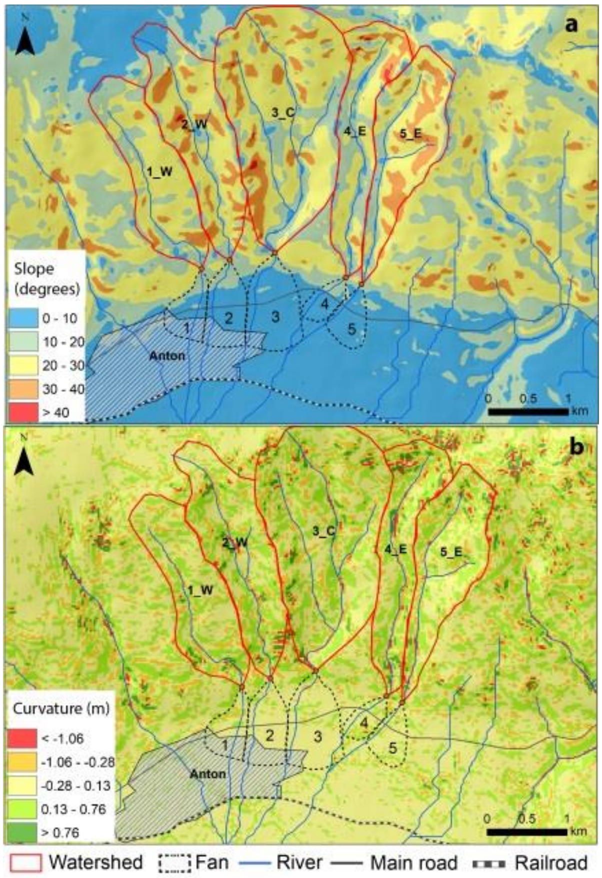

Fig. 3. a- Slope computed as a gradient of the DEM surface; b- Curvature, computed as a gradient of the slope surface

The transition zones are located in altitude between 1600 and 950 m in the middle and downstream reaches of watersheds and represents the main transport part of the channels. The slopes are steep and the movement of the formed flow can acquire high speed. Field observations show that both sides of the channels are vegetated with forests but there are unstable areas that could generate loose material. The almost entire transition zone in Watersheds 4_E and 5_E was occupied by weak and easy erodible low-grade metamorphic rocks, likely to produce sediment material that could be included in the flows. The main processes in this zone are downward erosion and incising of the river valleys.

Torrential depositions in the study area are represented by very poorly to poorly sorted material, with a pebble to boulder size of the angular to sub-rounded clasts. There are indications for modern accumulations but with small intensity and inability to form large fans. Depositions form lateral levees and on areas with low-slope gradient in river valleys, near the confluence of river tributaries and on the margins of the active river channels (Fig. 4). The presence of well-preserved depositions related to debris flow activity observed on the river banks in Fans 4 and 5 (Fig. 4 d) could confirmed the occurrence of at least one event in the last 100 years. This could be verified by historical data found in Kerenski et al. (1977) which speak for high-intensity torrent events in watersheds near Anton village in 1927, leading to widespread sediment depositions covering the area with size more than 20000 m^2. According to Mishev et al. (1962) which characterized in detail the fans in Zlatitsa graben, torrential depositions are typical for the area east of Anton Village as a result of torrential events at the end of XIX Century and beginning of XX Century.

Fig. 4. a,b,c – Debris flow deposits and morphology of the active channel in lower parts of Watershed 3_C (a – 42.74726 N, 24.28382 E; b- 42.74756 N, 24.28412 E; c - 42.75018 N, 24.28660 E); d – Debris flow deposits accumulated on eastern river bank of Fan 4 (42.73907 N, 24.29021 E). The deposits have been cleared, but they can still be distinguished on field

Morphometric and raster analysis

Studied watersheds have typical area size and shape for debris flow prone watersheds. They occupy area from 1.52 to 3.76 km^2 and elongated shape according to Form Factor values between 0.14 and 0.37.

The values of the Drainage Density index are between 1.57 and 2.12 km/km^2, indicating moderate permeability and moderate soil erosion.

Elevation Relief Ratio ranging from 0.37 to 0.46 and shows that watersheds are subject of medium to high erosion processes, which collaborates well with features as steep slopes, but also with the presence of erodible metamorphic rocks in lower parts of the watersheds. The relief can be classified as youthful. The results for Melton Ruggedness Number (0.54 – 0.73), Elevation Relief Ratio and watersheds geometry indicate active and intensive erosional processes and high susceptibility to debris flows.

For identification of potential erosion areas in the main channels were used different values of coefficient k and Slope Threshold (ST). They control the TR which, in turn, affects the distribution of erosion. After the applied sensitive analysis for coefficient k and ST, and according to field observations, values of k between 0.26 and 0.30 were considered as appropriate for modeling the erosion probability (Fig. 5). The spatial distribution of triggering values (TR) is a result of binary masks obtained by TR ≥ 1 (1 (yes) to cells with slope angles greater than or equal to the slope threshold ST and 0 (no) to cells that have an ST less than one - Grelle et al., 2019).

Results delineate zones in channels from the watersheds upstream area and transition zone that are prone to erosion and able to produce sediment bedload involved in the flows.

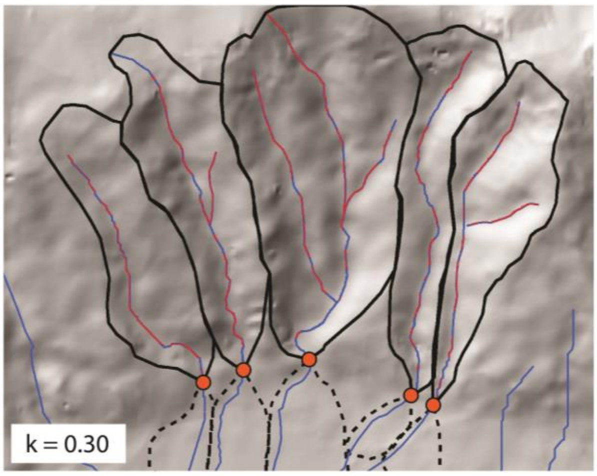

Fig. 5. Erosion-prone areas in river channels, modeled with coefficient k = 0.30 (red lines)

Specific features of Watershed 3_C

Watershed 3_C have more specific characteristics than the other four studied watersheds. Typical are low slope angles in downward parts of the watershed where we observe a large volume of eroded material, and gully erosion at the same time (Fig. 4 a, b, c). Also, Form Factor (0.37) shows that this watershed has a more circular shape and occupies a bigger area in contrast with the other four watersheds.

The main clast source and respectively accumulated material in the almost entire watershed is represented by the granite rocks of Vezhen Pluton. Erosion and denudation in the source zone are effective enough to disintegrate rocks, which are transported in gullies and rills or form unconsolidated colluvial cover on the steep slopes. This scenario also applies in source zones to the other watersheds but here is well field observed (drone footage and remote sensing data).

Erosive proneness in this watershed is supported by results from the morphometric analysis of ERR (0.46) and DD (2.12 km/km^2). The widest erosion could be connected to the weak rocks from the low-grade metamorphic complex and tectonic features in addition to geomorphological conditions of the watershed.

In lower parts of this watershed were formed areas with a low slope angle that could prevent debris flows to reach the alluvial fan. These areas, covered by alluvial and colluvial-alluvial sediments could also act as temporal accumulation zones. In some places active channels or parallel to them gulleys cut deep into the sediments, fulfilled with the accumulated material. One of this places could be seen on the modeled erosion-prone areas in channels where the main river makes a turn (Fig. 5).

The value of MRN (0.54) corresponds to low ruggedness areas located on the valley floor and according to an obtained result, the watershed falls in the category of mixed/debris flood, but close to values for debris flows (> 0.60) (Wilford et al., 2004). In this watershed are more likely to occur debris flow events accompanied by debris flood phases downstream were the channels slope is more gentle.

Conclusions

It is well-known that the southern slopes of Stara Planina Mountain are one of the debris-prone areas in Bulgaria as a result of specific geomorphological, geological, and climate conditions, sparse vegetation, etc. Depositions from past debris flow events were observed in most of the fans located in the Mountain Range slope base where the Quaternary normal fault zone has a major impact on the watersheds evolution, debris flow activity, and sedimentation. Field and historical data, as well as certain characteristics of the area, made us investigate in detail five watersheds which can be defined as debris-prone in the area of Anton Village.

The estimation of zones prone to erosion in main channels as one of the key parameters to consider when analyzing the dynamic process of debris flows was performed by the simple GIS-based proposed by Grelle et al. (2019) approach. Delineated erosion zones that could be a source for debris flows in the channels are located not only in the upstream area of the watersheds but also in their lower parts.

The results of morphometric analysis predict debris flow activity for five studied watersheds with possible debris flood transition downstream in Watershed 3_C, medium to high erosion activity, and youthful stage of watersheds evolution. From characteristics of the source and transition zones, as well as the geological specifications and recent debris deposits over the fans and river banks, studied watersheds could be described as susceptible to debris flow initiation and transportation.

The obtained data could be used for regional hazard pre-assessment and susceptibility mapping. Further analysis of volume and grain-size distribution of the recent sediments need to be carried out for evaluation of deposition zones and their possible extent as well as a more detailed analysis of Watershed 3_C which have slightly unusual characteristics in contrast with other four watersheds. Obtained results could be supported by analysis of hydrological and meteorological conditions, faults influence over the erosional processes as well as evaluation of physical properties of the flows for completed debris flow hazard and risk assessment of the area.

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