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RECOGNIZING DEBRIS FLOW HAZARD IN HEAVILY FORESTED WATERSHEDS: AN EXAMPLE FROM ETROPOLE AREA, CENTRAL BULGARIA

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ABSTRACT. The mountainous Etropole area is well known with frequent river floods that occur during the summer period. On 1st of August, 2014 extreme rainfall event initiated not only river floods, but also debris flows in steeper riches of the smaller valleys. One of the affected areas is situated at the margin of Etropole Basin, on the slope to the south of Etropolska Ribaritsa village. Related to debris flows and floods, erosional and depositional geomorphic forms were documented in two watersheds three months after the event. The debris flow deposits have comparatively small volume (tens of m^3) and consist exclusively of the Kostina Formation quartzites. Field studies also demonstrated that the occurrences of the Quaternary deposits are not only limited to the bottom of Etropole Basin, but they cover almost completely the slopes south of Etropolska Ribaritsa village. The matrix of these deposits often contains a lot of clay and they play an important role for supply of clasts material for debris flows. Field data, eyewitness reports as well as morphometric data indicate debris flows as a significant hazard for the local communities. These findings support the need for taking mitigation measures and also the necessity for more extensive hazard assessment of debris flows in the Etropole area.

Keywords: debris flow, floods, natural hazard, GIS analysis, Quaternary deposits

РАЗПОЗНАВАНЕ НА ОПАСНОСТТА ОТ ДЕБРИТНИ ПОТОЦИ В ЗАЛЕСЕНИ ВОДОСБОРИ: ПРИМЕР ОТ РАЙОНА НА ЕТРОПОЛЕ, ЦЕНТРАЛНА БЪЛГАРИЯ

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РЕЗЮМЕ. Планинският район около гр. Етрополе е известен с честите речни прииждания, които се случват през летният период. На 1 август 2014 г. екстремни валежи инициират не само речни прииждания, но и кално-каменни потоци в по-стръмните части на по-малките долини. Един от засегнатите райони е разположен в края на Етрополският басейн, на склона южно от с. Етрополска Рибарица. Свързаните с кално-каменните потоци и наводненията ерозионни и акумулационни геоморфни форми са описани в два водосбора три месеца след събитието. Отложенията от кално-каменни потоци имат сравнително малък обем (десетки m^3) и се състоят изключително от кварцитите на Костинската свита. Теренните проучвания показват, че наличието на кватернерни отложения не е ограничено само до дъното на Етрополският басейн, но те покриват почти изцяло склоновете южно от с. Етрополска Рибарица. Матрикса на тези отложения често съдържа много глина и те играят важна роля за подхранването на кално-каменните потоци с кластичен материал. Теренните данни, докладите от очевидци, както и морфометричните данни показват, че кално-каменните потоци представляват значителна опасност за местните общности. Тези констатации потвърждават необходимостта от предприемане на мерки за превенция, както и необходимостта от по-разширено оценяване на риска от възникване на кално-каменни потоци в района на гр.Етрополе.

Ключови думи: кално-каменни потоци, наводнения, природна опасност, ГИС анализ, Кватернерни отложения

Introduction

Heavy or excessive rainfalls are common during the period May-July in Bulgaria and they often lead to flash floods. In mountainous terrains these rainfalls sometimes lead to the formation of mass movement processes known as debris flows. Debris flows are common events in mountainous areas causing losses of infrastructure and property damages. They are defined as very rapid to extremely rapid surging flow of saturated debris in steep channels (Hungr, 2005).

Debris flows events are not so prominent on the territory of Bulgaria, but they are starting to occur more often in last years and this is a result mainly of the climate. There is some data about the southern slopes of Stara Planina Mountain like Kazanlak area (Kenderova, Baltakova, 2013), near Tzurkvishte and Anton villages (Kamenov, Iliev, 1963; Iliev-Bruchev et al., 1994; Gerdjikov et al., 2012). Similar events have been described near Lozen village (Sofia region), Pirin Mountains (Baltakova et al., 2018), Rhodopes (Bruchev et al., 2001), Yamna village (Etropole area) (Dotseva et al., 2014), Asparuhovo (Varna town), and a lot similar events at the Kresna Gorge (Dobrev, Georgieva, 2010; Nikolova et al., 2018) and Struma valley (Glovnya, 1958; Kenderova, Vassilev, 1997, 2002; Kenderova et al., 2013a, b; 2014).

This paper presents a description of debris flows that affected two watersheds in the area of Etropolska Ribaritsa village as well as it provides new data about the geology and geomorphology of the area and gives hints for the existence of debris flow hazard in heavily forested and generally supply-limited watersheds in the mountainous areas in Bulgaria. It is important to note, that the area of Etropolska Ribaritsa is not the typical place where the occurrences of debris flows can be expected: the slopes above the village are forested and there are no significant outcrops of geological units that can produce significant volume of debris.

Study area – geomorphological and geological setting

The village of Etropolska Ribaritsa is located 3 km east of the City of Etropole (Fig. 1). The area is situated on the northern slope of Stara Planina Mountain and the topography is characterised by comparatively steep hills, incised by dense network of gullies and valleys (slopes less than 43°). The village is situated in the easternmost extension of hills – enclosed flat piece of land, recently denoted as Etropole Quaternary Basin (Dotseva, 2018). In the local area, the plain is situated to the south of the prominent mountainous crest, here named Cherni Vrah Ridge. The Ridge is trending east-west and its elevation is gradually increasing eastwards from 1000 m (area of Cherni Vrah Peak) to 1350 m.

The climate in the region is moderate-continental with mean annual temperature of 10.7°C and mean annual precipitation values of 895 mm (Etropole station data). A dense forest and bushy cover are typical for the slopes, while flat areas are occupied by meadows.

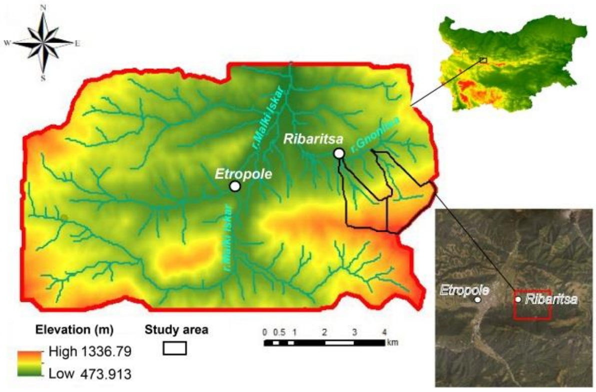

Fig. 1. Location of the studied area

The area is underlain only by Mesosoic sediments (Antonov et al., 2010), represented by Triassic limestones and dolostones, Lower Jurassic sandstones, conglomerates (Kostina Formation), Jurassic marls and sporadic limestones (Ozirovo Formation) (Fig. 2). It was recognized (Antonov, 1976) that the Triassic limestones built a prominent Alpine thrust (Etropole thrust), recently re-valuated by us (Vangelov et al., 2013). There are no data about the thickness and nature of the Quaternary slope and alluvial deposits. The crest and the upper parts of the northern slope of Cherni Vrah Ridge are built by resistant Triassic limestones and dolostones. To the north they are covered by 250 m wide in map view strip of the extremely well-lithified and strong coarse siliciclastic rocks of the Kostina Formation. The bedrock in the lower part of the northern slope is represented by dark shales, siltstones and rare claystones and limestones (Bachiishtenska Formation).

The research is focused on two watersheds situated to the south of the Etropolska Ribaritsa village. The watersheds drain into Gnoynitsa River – a right tributary of the Malki Iskar River.

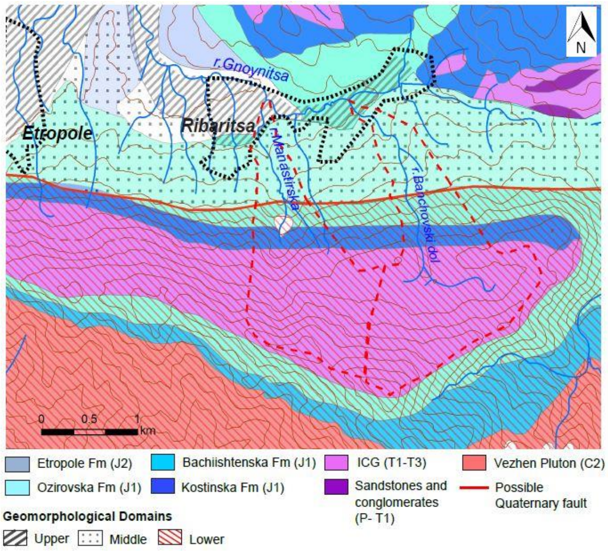

Fig. 2. Geological and geomorphological map of the studied area (after Antonov et al., 2010; modified)

The Monastery river watershed (2.64 km^2) is located to the south of Etropolska Ribaritsa village. Debris and vegetation carried by the flood formed a temporary dam at the bridge over the river channel – the result is a change in its course and formation of a new channel incised within alluvial deposits and soils. The Banchovski Dol watershed (3.46 km^2) is situated in the eastern part of the Etropolska Ribaritsa village. Debris flow deposits form elongated, parallel to the channel levee, reaching a height of up to 2 m.

Event description

The area of the town of Etropole and Etropolska Ribaritsa village was affected by heavy rainfall on the night of 31st July, 2014. The rainfall started on 31st July in the afternoon, continued for 16 hours and at 6:00 am on 1st August a state of emergency was declared in the Etropole Municipality after the report from Civil Defence.

The data from the meteorological stations located in the Elatsite Mine (5 km southwest from Etropolska Ribaritsa village) are used to assess the precipitation rate. The amount of precipitation for 1st August from 0:00 to 07:20 am was 91.7 mm. Heavy rainfalls on 28th July (67 mm) and 29th July (46.7 mm) should also be taken into consideration as the total rainfall in these three days was extremely high and led to floods and mobilisation of the material which could be involved in debris flows.

The rainfall and associated debris flows and flash-flood caused substantial infrastructure damage – main roads were closed, almost all the roads in Etropolska Ribaritsa were damaged, up to 20 homes were flooded, most of the agricultural production was destroyed and water-supplies were cut-off. Eyewitnesses talk about the presence of big boulders, rocks and mud driven by Gnoynitsa River downstream and for several cars and a truck carried away by the river.

Reconnaissance field work was carried out three months after the event. Our field data shows that the river channels produced a sediment load, estimated to tens of cubic meter volume. Much of the sediments transferred from the channels were deposited in the area before the river channels inflow into the Gnoynitsa River, forming distinct cones and levees. The debris flow deposits consist of very poorly sorted clastic material with boulder size up to 1 m (Fig. 3).

Fig. 3. Monastery River (24.03532 E, 42.83062 N) debris flow poorly sorted deposits; looking upstream

Methodology

For the identification of the spatial distribution of debris flow hazards a number of methods are applied, such as GIS analysis and remote sensing, quantitative morphometric analysis and field studies.

Two watersheds affected by the event on 1st August, 2014 were selected for a more detailed study: Banchovksi Dol River and Monastery River (location shown on Fig. 1). For the extent and magnitude of 1st August, 2014 flash flood and the associated debris flows event data from eyewitnesses, reports, news publications and archives of Etropole Municipality were collected and analysed.

Field work included mapping of depositional and erosional features associated with debris flows as well as an attempt to delineate and characterise the origin of the Quaternary deposits that mantle the northern slope of Cherni Vrah Ridge.

A desktop study, based on a GIS, was realized, including analysis of a Digital Elevation Model (SRTM-ASTER), satellite and aerial imagery. SRTM-ASTER combined a digital elevation model with 25 m cell size and NDNR Hydrology tool in ArcGIS software were used for the extraction of the basin's boundary, flow direction, flow accumulation and drainage network and for the generation of thematic maps for Slope, Aspect and Hillshaded relief. GIS software was used also for processing and analysing the morphometric parameters of the watersheds. Some of the parameters were evaluated by mathematical equations.

Basin geometry was extracted in GIS environment. Parameters like Basin area (A) and Perimeter (P) are important factors for any watershed and influence on the hydrological conditions, run-off distance of the flows and sediment load. Basin Length (Lb) is measured by the longest path of the watershed, parallel to the mainstream (GIS derived) and was used for calculation of Form Factor and Relief Ratio. The Form Factor (Rf) (Horton, 1932) varies from 0 to the unity and represents the shape of the watershed – the higher the value of Form Factor, the more circular the shape is. The watershed shape influences the run-off distance, time and peak discharge.

Basin Relief (Melton, 1957) and Relief Ratio (Schumm, 1956; Strachler, 1958) were used for evaluation of the erosional properties and steepness of the basins. Low values of Relief Ratio indicate hard rocks and low degree of the slope, but Rh increases with the decreasing of the drainage area and the size of watersheds (Gottschalk, 1964). Elevation Relief Ratio is related with the morphometric erosional evolution of the watershed and indicates youth, mature or old stage. Melton Ruggedness Number (Melton, 1965) is a very appropriate slope index for debris flow recognition and represents the relief ruggedness within the watersheds (Melton, 1965). Drainage Intensity index reflects the erosion activity and the permeability of the soils in watersheds (Horton, 1932).

Lithology complements the overall picture, and may also be a factor for susceptibility of watersheds and debris flow forming. The bedrocks in the triggering zone were rated by their mechanical properties and their susceptibility to erosion and mobility.

Results

Analysis of DEM and its derivatives and remote sensing observations

The analysis of all available datasets (topographic maps in scale 1:5000, DEM and its derivatives as slope and various imagery data) indicates presence of three geological and geomorphological domains in the studied area (Fig. 2). They differ significantly in terms of slope dips, terrain ruggedness, small-water channels density and geometry and also in geological substrate.

The first domain (here referred as Upper domain) occupies the highest elevation in the area and is characterised by intermittent rock outcrops. Kostina quartzitic sandstones are the often forming cliffs with height up to several meters. More complicated is the landscape and the active processes at places where the Triassic carbonate rocks crop out: they can form devoid of vegetation ridges, can be completely covered by rubbles and soil and often are affected by karst processes (e.g. the area of Etropole monastery and to E-SE they are affected by large-scale karst phenomena). The lower boundary of the Upper domain is generally marked by a distinct, sharp break in slope (Fig. 2). This domain is strongly affected by erosional processes and is the main source of sediment supply for the Quaternary deposits.

The second domain (here referred to as Middle domain) occupies an intermediate position and here the slopes have dips less than 15°. Despite the general lower slope dips, the valleys and streams are comparatively deeply incised.

The third domain (here referred as Lower domain) is defined as the flat bottom of the Etropole Basin, delineated on the map on the basis of a calculated slope with dip less than 6°. Alluvial Quaternary sediments cover this flat area and river channels are unconfined (terminology of Bisson et al., 2005). Most of this area is strongly affected by anthropogenic modifications. The main active processes here are sporadic deposition along and next to the river channels (at times of extreme rainfalls) as well as fluvial reworking of older deposits.

Morphometric characteristics of the watersheds

The Monastery River and Banchovski Dol River watersheds were located at average altitude from 913 m to 961

m. Slopes between 20° and 45° are necessary to promote the initiation of debris-flows (Hungr, 2005). The mean slope in the studied watersheds is between 14.11 and 17.97 degrees.

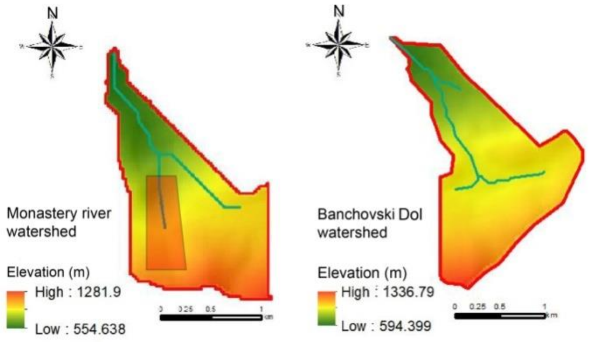

Fig. 4. Watersheds DEMs: Monastery watershed with inactive part of the stream shaded in red (left) and Banchovski Dol watershed (right)

While the Banchovski Dol Valley has a normal hydrological system, the Monastery River is strongly affected by karst processes. The upper part of the valley is completely dry and the active stream is initiated at the spring Ayazmoto, situated just next to the Monastery. Morphometric parameters of the studied watersheds were calculated and the results are presented in Table 1.

Table 1. *Morphometric parameters computed for the studied watersheds*

Basin geometry	Formula	Monastery River	Banchovski Dol
Area (A) (km^2)	GIS derived	2.64	3.46
Basin length (Lb) (km)	GIS derived	3.44	3.55
Form factor (Rf)	Rf=A / Lb^2 A - Watershed area; Lb - Basin length	0.22	0.27
Maximum altitude (Z) (m)	GIS derived	1281	1336
Minimum altitude (z) (m)	GIS derived	554	594
Mean altitude (Zmean) (m)	GIS derived	913	961
Maximum slope (Degrees)	GIS derived	33.12	28.96
Minimum slope (Degrees)	GIS derived	0.46	0.45
Mean slope (Degrees)	GIS derived	17.97	14.11
Basin relief (Bh) (km)	Bh=Z-z Z - max. altitude; z - min. altitude	0.72	0.74
Relief ratio (Rh) (km)	Rh=Bh / Lb Bh - Basin relief; Lb - Basin length	0.21	0.20
Elevation relief ratio (ERR)	ERR=Zmean-z /Z-z; Zmean - mean altitude; Z - max. altitude; z - min. altitude	0.49	0.49
Melton rugged-ness no (MRn)	MRn=Bh-z/A$^{0.5}$ Bh - Basin relief; z - min. altitude; A - Watershed area	0.44	0.39
Drainage intensity (DI) (1/km^2)	(DI = LD / A) LD - Total stream length; A - Watershed area	1.09	0.97

Basin geometry analysis shows that the Monastery River and the Banchovski Dol watersheds have small size, which is usual for debris flow occurrence – 2.64 km^2 and 3.46 km^2. The Form Factor for the two studied watersheds is 0.22 and 0.27, respectively, and shows that they have an elongated form. In terms of hydrological response, the elongated forms of the basins will provide not so fast discharge like those with circular form. According to the results for Basin Relief, Relief Ratio and Melton Ruggedness Number, the two watersheds show high susceptibility to debris flows and active erosional processes. This is also proved by the values of the Drainage Intensity index. The calculated ERR for the analysed watersheds is 0.49 which shows that they are subject to medium to high erosion processes and the relief can be classified as youthful to mature. The studied watersheds are underlain by Mesozoic quartzitic sandstones, limestones and dolostones, and Quaternary deposits, which have moderate to high susceptibility rates because of their unstable state under certain conditions (like heavy rainfall), high mobility rates and susceptibility to erosional processes.

Field studies

Field studies were conducted in the areas of the two selected watersheds. Most of the length of the lower reaches of the stream channels was investigated, as well as parts of the hill slopes. An important discovery is the presence of comparatively thick Quaternary cover, that not only occupies the bottom of the Etropole Basin, but also blankets the ridges and valley hill slopes. The bedrock is very locally represented, typically as two dimensional outcrops at the channels beds and rather sporadically on the slopes.

Four types of Quaternary deposits can be distinguished: alluvial, colluvial, mixed colluvial-alluvial and rock fall deposits. What is typical for all of these deposits is that they are built almost exclusively by clasts from the Kostina Formation. Limestone clasts are extremely rare. The lower domain is characterised by alluvial deposits where the active deposition is limited to the unconfined stream channels and occurs only in cases of heavy rainfalls. The ridges are covered by unconsolidated colluvium, with typical angular clasts reaching a size of up to 1 m. Colluvium is also typical for the upper reaches of the streams. The thickness is difficult to be estimated, most probably varies between 0 and 1–3 m. Mixed in origin colluvial-alluvial deposits are common in unconfined, first-order channels. They are represented by angular and variously rounded clasts that reach a size of up to 2–3 m. In some cases active channels or parallel to them rills cut 1–2 m deep into the sediments. The thickness is probably up to 5 m. Rock fall deposits are spatially limited to the foot of the travertine wall situated below the Etropole monastery.

The alluvial deposits, localised within the valleys in the middle domain are of special interest. All of them have typical features of debris flow deposits – presence of very large boulders, lobate surface morphology, position just next to the active river channel, formation of lateral levees. Older alluvial deposits (debris flow deposits 1 – DFD1) are everywhere incised by the active river channels. (Fig. 5).They are represented by weakly consolidated, most commonly matrix-supported breccia-conglomerates. The matrix is sandy with high clay content. Clasts are angular to sub-rounded and reach a meter in size. Morphologically DFD1 form decameter-scale lateral levees, sometimes reaching several meters in height. The largest DFD1 is represented by an alluvial cone in the Monastery River Valley.

Younger alluvial deposits (debris flow deposits DFD2) are spatially restricted to the margins of the active river channels. Typically they are represented by lateral levees with length of about 3–10 m and height less than 1 m. It is important to note that the size of the largest boulders is gradually diminishing toward lower reaches of the valleys, thus toward the lower part of the middle domain the largest boulders are less than 1 m in diameter. Only in the valley of Monastery River our observations from 2014 event indicate presence of larger DFD2 (Fig. 6). The negative effects of the younger debris flows are marked by the road and bridge destruction – a feature observed during 2014 and 2019 field work.

Fig. 5. Banchovski Dol (24.04826 E, 42. 83359 N) with landscape representative for the Middle domain: comparatively steep valley slopes, active channel cutting bedrock as well as unconsolidated older DF deposits

Fig. 6. Debris flow deposits from the 2014 event, Monastery River (24.03532 E, 42.83062 N): conditions in July 2019 (left) and October 2014 (right)

Post-2014 debris flows/floods deposits can be distinguished on the basis of complete lack of vegetation. They have small volume (up to few cubic meters) and form meter-scale levees immediately next or even within the stream channels. Most commonly the debris are accumulated next to the channel curves, where the flooded river is attempting to make a cut-off chute (Fig. 7). Probably some of these deposits are related to the floods in the area of Etropole in 2018.

The small volume of the last years deposits as well as the presence of comparatively small clasts indicate low-magnitude events, due to the lack of stream transportation power in this low-gradient part of the valley. The presence of new depositions is indicative of the repeatability of phenomena under certain conditions and amounts of precipitation.

Within the middle domain the erosional features related to the debris flows activity are well-defined. Several forestry roads are cut by the active river channels and rather often they are incised 2–3 m deep into older alluvial deposits. The modified by debris flow erosion channels have a characteristic U-shape with flat bottom and vertical walls.

Fig. 7. Example of post-2014 deposits; meter-scale deposit situated next to the river curve, a place where during floods the river is attempting to make a cut-off chute (Eastern bank of Monastery River, 300 m above the confluence with Gnoynitsa River)

Discussion, conclusions and possible mitigation measures

Despite rather extreme climatic conditions, the 2014 event produced quite limited volume of the deposits reaching tens of cubic meters. Only in the Valley of Banchovski Dol River the flow had enough energy to bring large boulders very close to the bottom of the Etropole Basin. The magnitudes of the post-2014 events are even smaller: they are spatially limited to the stream channels or to their margins. The abundant unconsolidated older and modern alluvial deposits that mantle the valleys are the main source of debris for the modern debris flow events. It is clear that modern debris flow activity is mainly controlled by the occurrence of high-intensity rainfalls (probably exceeding 90 mm/24 h).

The area of Etropolska Ribaritsa can be regarded as a well-suited polygon for studying the processes that shaped the contemporary relief. Still, almost nothing is known about the precise age and sedimentology of the Quaternary deposits. Our study indicates that they are a very important factor with regard to providing supply for future debris flows.

An intriguing feature of the Quaternary sedimentary record is the presence of travertine rock falls. Their occurrence is spatially limited to the steep walls built by travertine and situated close to the main karst spring (Ayazmoto). The origin of these rock falls can be tentatively related to loosely dated XVIII century destructive Etropole earthquake. It can be speculated that the source of this earthquake is the well-defined lineament that follow the boundary between the defined here Upper and Middle geological-geomorphological domains. This supposition can be checked via geophysical and other studies.

In conclusion it is important to note that this contribution presents only initial report on occurrence of debris flows unknown to this moment. Further studies on the distribution of debris flows phenomena and mapping of Quaternary sediments in the area of Etropole are needed to have a better picture about the spatial distribution of the areas threatened by the debris flow phenomena. A future analysis of the rainfall data can probably help to create a warning system, based on the amounts of precipitation. As an important mitigation measurement for the populated area of Etropolska Ribaritsa can be proposed the construction of check dams along the studied valleys.

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