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DEBRIS FLOWS IN KRESNA GORGE (BULGARIA)—GEOMORPHOLOGICAL CHARACTERISTICS AND WEATHER CONDITIONS

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Abstract: Over the last decades, numerous extreme climate events such as extreme temperatures, droughts, heavy precipitation, and storms associated with climate change have been recorded in many countries, including Bulgaria. As a result, geomorphological hazards such as landslides, debris flows, mudflows, high-speed soil erosion, etc. often occur on the territory of the country. The debris flow is one of the most common hazardous processes in small catchments of the main river basins in Bulgaria. The Kresna Gorge located in the middle part of Struma River valley is a typical area with such processes which often cause the damages to the E79 international highway. The purpose of the present study is to characterize debris flows in Kresna Gorge (southwestern part of Bulgaria) by comparative analysis between the two events (occurred on May 24, 2009 and July 28, 2019). In order to achieve the aim of the study the geomorphological features and flow type of 2019 event were identified and the results were compared with the previous publications which investigated the event on May 24, 2009. In the present paper, the sediments and the type of transportation of the investigated event (July 2019) were determined by grain-size and clast-shape analysis. The impact of weather conditions on debris flow occurrence was shown by the analysis of the synoptic conditions on the day before the event. The results of the study bring to clarifying the geological-geomorphological and meteorological factors for the occurrence of debris flow and are important for geomorphological hazard management.

Keywords: debris flows; geomorphological features; synoptic situations; rainfall

Introduction

Debris flows are compound hazardous events which are caused by three main groups of factors: (1) geological-geomorphological (lithology, unconsolidated deposits, slope gradient, altitude), (2) meteorological (extreme rainfall, storms, alternation of dry and rainy periods, extreme temperatures), and (3) land cover and land use. One of the main triggering factors for a debris flow are weather conditions, and nowadays many publications are focused on the impact of climate change on debris flow occurrence (Jomelli, Brunstein, Déqué, Vrac, & Grancher, 2009; Jomelli, Pavlova, Giacona, Zgheib, & Eckert, 2019; Pavlova et al., 2014; Rebetez, Lugon, &

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Baeriswyl, 1997; Savi et al., 2016; Turkington, Remaître, Ettema, Hussin, & Westen, 2016; Winter et al., 2010). Kononova and Malneva (2012) analysed the formation of debris flows in connection with atmospheric circulation and showed good correlation between debris flows occurrence and cyclone frequency.

The first exploration of debris flows in Bulgaria started at the beginning of the 20th century when in 1905 the Bureau of Strengthening of the Slopes and afforestation was opened in the town of Kazanlak (Central Bulgaria) (Popsavov, 2005). Most of the existing publications on debris flows in Bulgaria analyze mainly the geological and geomorphological features of these phenomena (Brouchev, Frangov, Varbanov, & Ivanov, 2001; Dobrev & Georgieva, 2010; Gerdjikov, Vangelov, & Glabadanidu, 2012; Kenderova & Baltakova, 2013; Kenderova, Baltakova, & Ratchev, 2013; Kenderova, Ratchev, & Baltakova, 2013; Nikolova, Kamburov, & Rizova, 2020; Nikolova, Zlateva, Berov, Kamburov, & Velev, 2020). According to Nikolova, Rachev, and Kenderova (2018), debris flows are compound event and this requires the analysis of various factors and prerequisites for their occurrence and manifestation. Despite the numerous publications in the foreign literature which indicate the impact of climate change and extreme weather events on the occurrence of debris flows, in Bulgaria this problem has not yet been sufficiently studied. The relation climate–weather conditions–debris flows in Bulgaria has been analyzed in only a few papers (Kenderova, Baltakova, & Ratchev, 2013; Kenderova, Rachev, & Baltakova, 2014; Nikolova et al., 2018; Vasilev & Kenderova, 2002).

The debris flows are among the most frequently occurring natural hazardous processes in the middle part of Struma River Valley (Bulgaria). These phenomena can cause significant damage by affecting settlements, agricultural land, and infrastructure. On May 24, 2009, in the northern part of Kresna Gorge, a debris flow from the stream blocked the main road E79 for 24 hours and caused damages of the infrastructure. Ten years later, on July 28, 2019 another debris flow from the same site blocked the road again. Between these events (2009–2019) debris flows with a much smaller mass and intensity occurred several times without blocking and causing any damages of the main road.

The geomorphologic characteristics of debris flow that occurred in May 2009 and the synoptic situation leading to intense rainfall, as well as the precipitation amounts in the area for a 30-day period prior to the event were analyzed by Kenderova, Baltakova, and Ratchev (2013), Kenderova et al. (2014), and Nikolova et al. (2018). The purpose of the present study is to make a comparative analysis between the two debris flows (occurred in Kresna Gorge on May 24, 2009 and July 28, 2019) in terms of geological-geomorphological and meteorological factors for the occurrence of such phenomena. In order to achieve the aim of the study, the geomorphological features and flow type of 2019 were determined, and the synoptic conditions on the day before the event, as well as the daily rainfall in the area were analyzed.

Materials and methods

Study area

The study catchment is located on the eastern slope of the Maleshevska mountains, at the beginning (northern part) of the Kresna Gorge, southwestern Bulgaria (Figure 1). The catchment has an area of 0.38 km^2. The source of the stream is at the height of 776 m a.s.l. and inflows from the right side into the Struma river at 276 m a.s.l.

The stream is of the second order and has the length of the long profile of 1.54 km (Table 1). Drainage pattern is formed of first-order streams with high drainage density (8.73 km/km²). Based on the collected field data, digital spatial data and some calculated morphometric parameters in GIS environment (slope inclination, local elevation range, and drainage density) allowed us to define three different zones in the catchment—upper, middle, and low zone (Figure 1).

The upper part of the catchment is between 770 and 500 m a.s.l. The slopes at this height are gentler and vary between 10° to 25° and the stream bed inclination is around 10°–15°. The vegetation cover is very rare at this part of the catchment and slope wash processes and semi-active fluvial channels predominate. At about 680 m a.s.l. two first-order flows form the second-order stream.

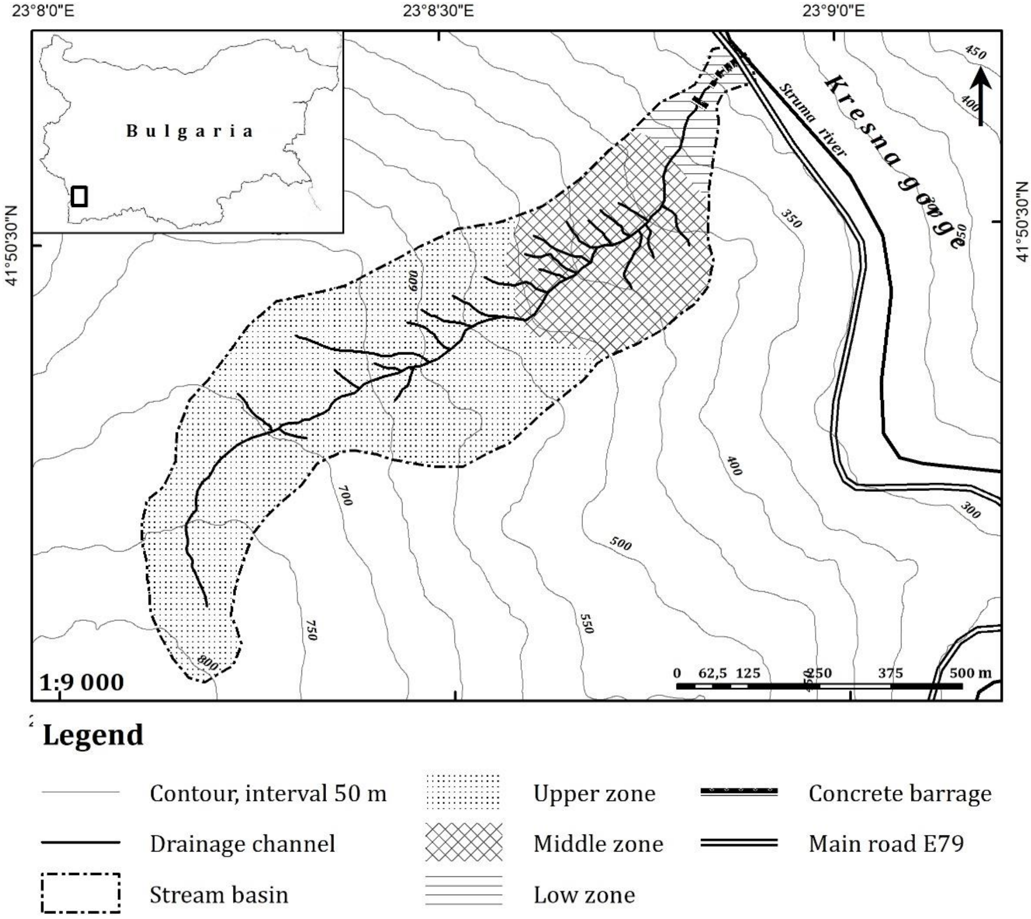

Figure 1. Study area.

The middle zone covers the area between 500 and 380 m a.s.l. of the catchment. Here, a narrow channel with a depth of 8–12 m is formed and in some places the inclination of the stream bed reaches 45°. The slopes are very steep and exceed 35°–40°. In this zone, where the slope angle suddenly increases at about 500 m a.s.l., is the starting point of debris flow.

The lowest zone of the catchment reaches to the foothill of the mountains where the stream inflow into the Struma river (276 m a.s.l.). The stream bed here is much wider and varies between 10 to 30 m, and has an inclination from 20° to 35°. In this part, six concrete barrages and one tunnel under the main road were built in order to reduce the power of the flow and the damages. The highest barrage (320 m a.s.l.) crosses the widest part (30 m) of the stream channel, the second one (285 m a.s.l.) is 10 m long, and the other four barrages are stepped in the lowest part, near the road. After the tunnel, where the stream flows into the Struma river, an alluvial fan is formed.

Table 1
Morphometric properties of the stream catchment

Morphometric properties	Stream
Catchment area (km^2)	0.38
Source of the stream (m a.s.l.)	776
Stream outflow (m a.s.l.)	276
Mean altitude of the catchment (m)	535
Mean local elevation range of the catchment (m/km^2)	362
Mean slope inclination of catchment	22°
Length of the catchment (km)	1.38
Maximum width of the catchment (km)	0.36
Length of the river long profile (km)	1.54
Types of drainage pattern	Dendritic, Parallel
Drainage network length (km)	3.32
1st order (km)	2.19
2nd order (km)	1.13
Total count of the streams	22
Count of first-order streams	21
Count of second-order streams	1
Mean length of the first-order tributaries (km)	0.1
Drainage density (km/km^2)	8.73
Stream frequency (count/km^2)	57.89

The study area is located on the border between the temperate continental and Mediterranean climatic influences, which determines the precipitation regime. The annual cycle of the precipitation is characterized by two maxima—in May and in November (Topliiski, 2006). The catchment is entirely underlain by biotite granites of the Krupnik pluton with an age of Lower Oligocene. The granites are coarse-grained porphyritic granite with large potassium feldspars, and parallel texture (Marinova & Zagorchev, 1990). The Krupnik pluton is also rich in pegmatites vein rocks, which leads to the formation of cracks and fractures of the granites. The catchment is crossed by a fault with the direction from NNW to SSE, a part of Struma fault zone (Marinova & Zagorchev, 1990). These geological features contribute to the formation of steep and stepped unstable slopes. In combination with rare vegetation cover (mostly grasses and shrubs), intensive rock weathering and mass movement processes prevail.

Data and methods

In order to characterize the debris flows in the catchment, a geomorphological research, field work, description and sampling of the selected sites were carried out. To define the sediments and the type of transportation, grain-size and clast-shape analysis (Pettijohn, Potter, & Siever, 1972, 1987; Serebrianniy, 1980) was done. To calculate and analyze the morphometric parameters of the catchment, the digital elevation model (DEM) SRTM 1 Arc-Second Global, with resolution 30 m (U.S. Geological Survey, Earth Resources Observation and Science Center, 2014), orthophoto images and topographic maps were used (Ministry of Regional Development and Public Works of Republic of Bulgaria, 2010). The drainage network was digitized from topographic maps at 1:50,000 and 1:25,000 scales. Then all the calculations were performed in GIS environment.

The impact of weather condition on debris flows occurrence was analyzed by daily precipitation data for the day before the event and related synoptic situations which lead to the intense rainfall. Daily precipitation data are taken from the records of the automatic weather station (AWS)[1] located in the study area. The weather conditions are characterized by daily mean sea level pressure in hPa and geopotential height in m at 500 hPa for 27 July 2019 based on NCEP/NCAR Reanalysis (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 1994-present). The ERA INTERIM data in % (ERA INTERIM Reanalysis data) (European Centre for Medium-Range Weather Forecasts, 2011-present) was used to plot relative humidity in % at the level of 700 hPa. The analysis of rainfall characteristics during the event and antecedent conditions is a first step to the determination of precipitation threshold for debris flows occurrence.

Results and discussion

Field descriptions, sampling, and analysis

After the confluence of the two flows from the first order at 680 m, the channel of the stream is formed (up to 2 m wide) and a cut that does not exceed 0.5–1 m, as well as asymmetric slopes (sloping left and steep right). The material from the surface erosion, screes, and landslides accumulates in the stream bed and along its banks, which leads to meandering and, in some cases, disappearance of water in the deposits. In this part, there are also temporary flood sections on the left bank with a length of up to 10 m, which rise above the meandering bed at 10–20 cm. It seems that they often change their location.

The muddy character of the stream starts at 510 m a.s.l., where there is a rock threshold with a height of 8–12 m. In this place, the stream forms a waterfall, which in its lower part reaches the bottom of a small (with a diameter of 3.5 m) extension, filled with slope sediments and weathered rocks from the nearby outcrops. The depositions at the base of the rock threshold are not rounded and they are characterized by a predominance of coarse sediments (pebbles and boulders) (Table 2).

The pebbles exceed 80%, and the maximum dimensions of the boulders along the "a" axis reach 80 cm, typical for weathered rocks and screes. The petrographic composition and color of the fine sediments confirm the presence of the granite province.

[1]The AWS near the village Krupnik was installed in April 2019 by the team of prof. N. Dobrev, Geological Institute, Bulgarian Academy of Science within the framework of the National Science Program "Environmental Protection and Reduction of Risks of Adverse Events and Natural Disasters".

Table 2
Clast-shape analysis of the sediments in the investigated site No. 858 (upper), 860 (middle), and 861 (lower) part of the stream

Clast-shape analysis	858 upper	860 middle	861 lower
Count	30	30	30
Average (cm)			
“a“axis	25.5	24.8	21.8
“b“axis	18.4	17	14
“c“axis	11.8	10.8	8.6
Maximum (cm)			
“a“axis	78	48	48
“b“axis	42	34	27
“c“axis	40	19	18
Minimum (cm)			
“a“axis	12	13	10
“b“axis	8.5	8	6
“c“axis	3	5	4
Standard deviation			
“a“axis	13.1	8.8	9.3
“b“axis	7.9	6	5.7
“c“axis	7.2	3.8	3.6
Mean roundness	0	0.3	1.1
Form (count)			
Discoid	12	12	11
Equant	10	10	5
Bladed	3	3	10
Prolate	5	5	4

The most common landforms on the left slope in the middle part of the stream basin are screes and rock falls. They “start” from the rock escarpment, with the size up to 10–15 m^2, and at the footslope, they form well—shaped cones and screes. In the mid-slope area, between the rocky slopes and the cones, there are small temporary channels (Figure 2). There are also inactive (or older) cones that do not reach the stream bed and form small block fields with an irregular shape.

Figure 2. Left (a) and right (b) slopes in the middle zone of the basin.

On the right slope of this part of the stream basin, the creep processes predominate. In places where the slope is around 30°, the upper part of the soil is disturbed and forms terracettes with a height up to 20 cm. The channel in this part of the basin is cascade and step-pool and there are 5 more rock thresholds with heights between 2 and 4 m. On the relatively flat area between them, near the channel bed, the bars with a height of 2 m can be seen (Figure 3).

Figure 3. Bars near to the stream bed, marked with red line.

Downhill at this zone, the width of the channel gradually increases, from 7–8 to 22–24 m. In places, the stream bed is braided, separated by bars of accumulated sediment, where, in places, it reaches 1 m in height. They are composed of intermixed deposits in which the cobbles, boulders, and pebbles predominate (Table 3). The fine fractions are represented by sand and gravel, the amount of which is the highest in the middle part of the bars. Fractions larger than 4 mm along the entire length of bars make up over 60%, and those smaller than 0.02 mm slightly exceed 5% at the overbank.

Table 3
Grain-size analysis of the sediments in the investigated site No. 858 (upper), 859 (middle), 860 (middle), and 861 (lower) part of the stream

Name of the investigated site	64–4 mm	4–2 mm	2–0.06 mm	0.06–0.02 mm	< 0.02 mm	Color by Munsel Munsell Color (Firm), 2010
858 upper	82.27	10.5	5.3	0.5	1.43	10YR 5/1 gray
859 middle	67.06	7.36	16.9	2.49	6.23	10YR 5/2 grayish brown
860 middle	61.11	11.22	25.1	0.79	1.82	10YR 5/3 brown
861 lower	80.1	7.2	11.9	0.46	0.35	10YR 6/2 light brownish gray

The sizes of the clasts decrease from the upper to the middle part of the stream, and their main roundness slightly increases, but does not reach 2 mm. The shape shows that the movement of gravels, pebbles and blocks was in equal proportions by dragging and rolling. The clast-shape analysis has shown that the sediments with dimensions over 20 cm (along the “b” axis) move by dragging. Most of the clasts with such dimension have a discoid and bladed form (Table 2). The gravel and pebbles fraction have mainly equant and prolate form, which is the evidence for transport by saltation.

The scars of previous debris flows can be seen on the bark of the only tree in the middle of the stream bed. In 2009 the highest marks on the bark were 1.8 m high. They are still visible, but the bark has partially recovered (Figure 4). In 2019, the highest fresh scars were 1.66 m in height.

The lower zone of the stream basin starts from an extension (380 m a.s.l.), where the largest concrete barrage is built, which covers almost the entire extension of the channel (33 m long). On it, a barrier was build (after 2009) which retains the largest fractions and leak water and fine sediments.

Figure 4. The scars on the tree in the stream bed in June 2009 (a) and August 2019 (b).

Below the barrage, the channel narrows sharply (up to 8–6 m) and incises the rocks. In this part the slope decreases from 35 to 20–15°. Rock thresholds with a height of up to 2 m and potholes (up to 1 m in diameter) are formed, which are partially filled. Here the large blocks and pebbles that have passed the barrages predominate. The lower four concrete barrages are stepped. The slope here increases sharply and reaches 30–35°. There are no large cobbles and boulders, but sand and clay predominate. As a consequences of the investigated events mostly mudflows with fine fractions are accumulated on the main road E79 and in the Struma River.

Analysis of climate data and weather conditions

The analysis of the data from the AWS shows that debris flows on May 24, 2009 and on July 28, 2019 occurred after a relatively dry period, followed by the intense rainfall. According to the information from the AWS in Blagoevgrad, the daily precipitation on May 24, 2009 was 32 mm (Nikolova et al., 2018), and on July 27, 2019 the AWS in the study area (near the village Krupnik) reported daily precipitation of 22 mm, which lasted for several hours only.

The precipitation triggers the subsequent hazard geomorphological events in the study area. In the previous similar studies (Kenderova, Baltakova, & Ratchev, 2013, 2014; Nikolova et al., 2018) it was found that precipitation totals with a values close to 30 mm per day are sufficient to initiate debris flows in the study area. The precipitation value of 22 mm recorded on July 27, 2019 by the AWS near the village of Krupnik and the analysis of synoptic conditions and orography allow us to conclude that larger precipitation amounts have fallen in the catchment, which contributed to the activation of the debris flow.

Based on the used reanalysis data we have analyzed the weather conditions over Europe and Bulgaria in particular for the day July 27, 2019 that led to the intense rainfall and related debris flows. On July 27, 2019 at the level of 500 hPa a wide ridge covering wide part of Europe, reaching north to

Scandinavia was observed (Figure 5a). At the same time, from the North Atlantic through Western Europe to the Mediterranean, a cyclonic throw is formed, that breaks the ridge, over the central parts of the continent and over the western half of the Balkans. A multicenter area of low pressure exists at the ground layer above Central Europe, while above Scandinavia, European Russia, and Ukraine there is a high pressure ridge, whose main center is far north in the Arctic (Figure 5b).

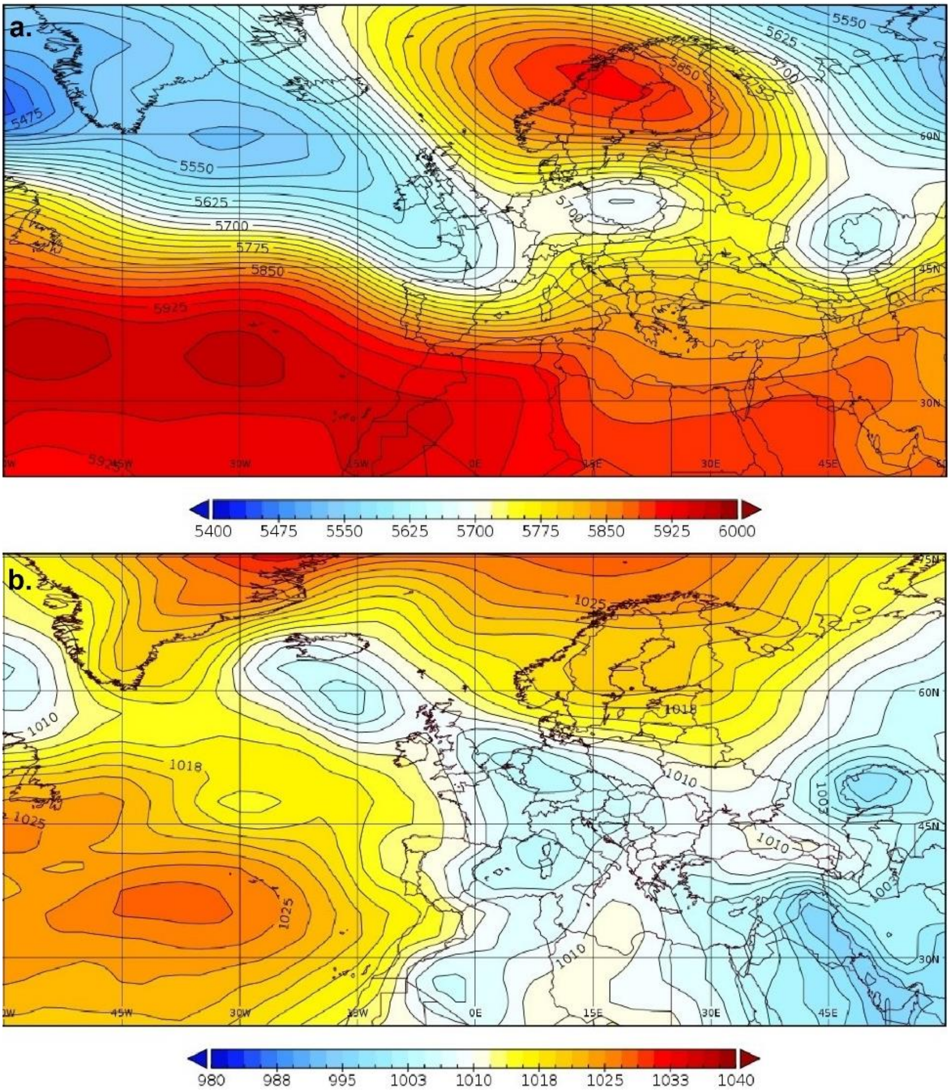

Figure 5. Distribution of daily mean geopotential height (m) at 500 hPa (a) and air pressure (hPa) at sea level (b) on July 27, 2019. From *NCEP/NCAR Global Reanalysis Products, 1948-continuing* [Data set], by National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 1994-present. (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html). In the public domain.

Over the Balkans, at the surface air layer, there is an area with a gradient-free baric field and relatively low pressure with values below 1010 hPa, equated to sea level. At an altitude of 500 hPa the air transport is weak and carries humid air from the southwest (Central Mediterranean) to the central parts of the Balkans. These conditions are suitable for the occurrence of convective thunderstorms accompanied by torrential rainfalls. A very unstable air mass is formed in the area and the intense precipitation and thunderstorms have been observed. The rainfall conditions are less favorable over Bulgaria. However, due to the cyclonic character of the air pressure field, the inflow of moist air in the upper layers, as well as due to the daily overheating in the ground layer, the air mass is relatively unstable and suitable for local thunderstorms. The best conditions for such phenomena are in the mountainous regions of western and especially southwestern Bulgaria.

The results from the present study coincide with Godev (1976) and show that the cyclonic baric field (Figure 5), air humidity between 50 and 90% (Figure 6) in the layer from 1500 to 5000 m, mountainous terrain, and overheating of the air are favorable conditions for the occurrence of powerful convective clouds with torrential rainfalls.

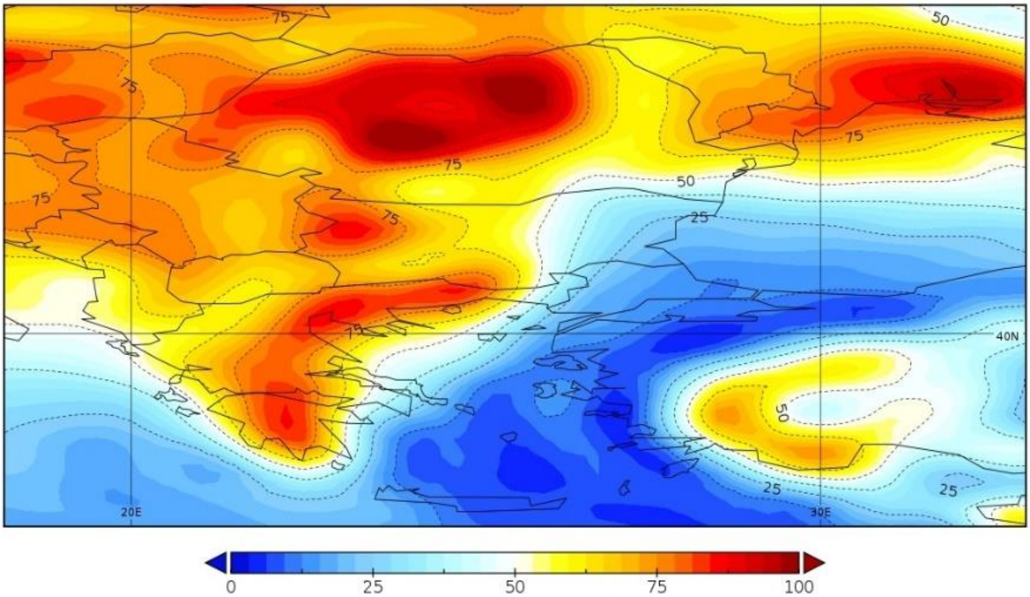

Figure 6. Relative humidity (%) for 27.7.2019 at 12:00 UTC at 700 hPa. From *The ERA-Interim archive* (Version 2.0) [Data set], by European Centre for Medium-Range Weather Forecasts, 2011-present. (https://www.ecmwf.int/node/8174). In the public domain.

The instability of the atmosphere is intensified by the high air temperatures measured at 2 m a.s.l., as in Southwestern Bulgaria the maximum temperatures for the investigated cases reach 30–34 ºC. As a result of the above described conditions, between late afternoon and midnight on July 27, 2019 a convective clouds with a local character was developed over western Bulgaria and a short-term, but in places intense rainfall occurred.

Conclusion

The researches in 2009 and 2019 show that both events started from the same place at a height 510 m a.s.l., which is related to the topographic settings, the colluvial deposits accumulated in the upper zone of the stream basin and tectonical settings. The "feeding" of the debris flow within the basin is mainly from the left slope, where old and currently active landslides and screes, as well as temporary erosion prevail. The different vegetation covers on the left and on the right slopes have led to the different exogenous processes. On the other hand, the lack of vegetation on the left will continue to feed the stream, which is associated with future debris and mud flows.

The predominated landforms formed after the two events are the braided channels, bars between them and near the banks, rock thresholds, and potholes. In many places, at the foot of the slope cones and screes were formed. Most of these landforms are temporary and after the rainfall they have changed their location and size. The grain-size analysis show that the type of the debris flow is predominated by large fractions, but most of the depositions are trapped by barrages. Only the fine sediments (gravel, sand, and clay) driven by water reach the main road (E79) and Struma River. This distribution of the fractions confirms that the infrastructure such as concrete barrages and the trunk under the road are not capable to hold and transport the debris and mud flow.

The comparative analysis of the synoptic situations that led to the extreme precipitation and debris flows on July 27, 2019 (daily precipitation 22 mm) and May 24, 2009 (daily precipitation 32 mm) shows different genesis of precipitation. The precipitation on May 24, 2009 was formed as a result of a well-defined cold front invading Bulgaria from west-northwest, while the precipitation on July 27, 2019 was caused by a gradient-free cyclonic field in an unstable humid atmosphere suitable for the occurrence of convective storms. In both situations, thunder cells of local nature are formed, affecting a relatively small area. The orography plays a decisive role in the occurrence of intense rainfall, which can provoke the emergence of debris flow. In order to determine the precipitation threshold, further observations at the region are needed.

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