DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).
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Possible impact of climate and weather condition on debris flows occurrence (on the example of Kresna gorge, Bulgaria)

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Climate change and extreme weather events are important topics in the scientific publication due to their impact on environment and various aspects of human activity. Tendencies in air temperature and precipitation variability and occurrence of heavy rain or warm and dry periods are among the main factors for debris flows initiation and development. The purpose of the present paper is to analyse the relationship climate – weather – debris flows occurrence. The study area is the region of Kresna gorge, situated in the south-west part of Bulgaria where the debris flows are characteristic phenomenon. The research work is done on the basis of monthly and extreme data for air temperature and the information about synoptic situations during the days with debris flows. In order to achieve the aim of the study the extreme air temperature and precipitation indices, such as number of extreme hot and extreme cold months, number of extreme dry and extreme wet months and number of days in relation to air temperature and precipitation thresholds are analysed, and synoptic situations are examined. The results of the research are important for better understanding the causes of occurrence of debris flows and in particular the role of climate and extreme weather events is clarified. The knowledge on factors triggering debris flows will help for effectively tackling environmental problems.

debris flows, synoptic situations, extreme precipitation, Kresna gorge, Bulgaria

Возможное воздействие климатических и погодных условий на формирование селевых потоков (на примере ущелья Кресна, Болгария)

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Изменение климата и экстремальные погодные явления являются важными темами научных исследований из-за их воздействия на окружающую среду и различные аспекты человеческой деятельности. Тенденции изменения температуры воздуха и осадков и возникновение сильного дождя или теплых и сухих периодов являются одними из основных факторов инициирования и развития селевых потоков. Целью настоящей статьи является анализ взаимосвязи климата - погодных явлений. Область исследования – район ущелья Кресна, расположенного в юго-западной части Болгарии, где характерны селевые явления. Исследование проводится на основе ежемесячных и экстремальных данных по температуре воздуха и информации о синоптических ситуациях в течение дней с селевыми потоками. Для достижения цели исследования, анализируются экстремальные показатели температуры воздуха и осадков, такие как количество экстремально жарких и экстремально холодных месяцев, количество экстремально сухих и экстремально влажных месяцев, количество дней по отношению к температурам воздуха и порогам осадков, а также синоптические ситуации. Результаты исследования важны

для лучшего понимания причин возникновения селевых потоков и, в частности, роли климата и экстремальных погодных явлений. Знания о факторах, вызывающих селевые потоки, помогут эффективно решать экологические проблемы.

селевые потоки, синоптические ситуации, экстремальные осадки, ущелье Кресна, Болгария

Introduction

Debris flows are one of most destructive and events with negative environmental, social and economic impact because of their rapid occurrence without warning which make their investigation and prediction quite difficult. Climate and weather together with the geological and geomorphologic and hydrological characteristics are the main factors for debris flows occurrence and development. The scientific literature shows many publications which state the impact of climate change and extreme weather events on debris flows [*Rebetez et al., 1997; Winter et. al, 2010; Turkington et al., 2016; Chiarle et al., 2011 etc*].

Debris flows are one of the characteristic phenomenons in the middle part of Struma river valley and in Kresna gorge in particular. For the first time *Glovnya* [1958] point out the catastrophic character of these events in the region of Struma valley. Recently the interest to investigation of causes and consequences of debris flows in Bulgaria has been increased. The previous studies are related mainly to geological and geomorphological features of the events [*Bruchev et al., 2001, Dobrev and Georgieva, 2010; Gerdjikov et al., 2012, Kenderova et al., 2013a, 2013b*]. The relation climate – synoptic situations – debris flows has been analysed in [*Kenderova and Vasilev*, 1997, 2002; *Kenderova et al., 2013b, 2014*].

The aim of the present paper is to investigate the role of climate and weather for debris flows occurrence on the background of the peculiarities of physical geographical conditions and climate in the region of Kresna gorge. In order to achieve this aim monthly and daily precipitation values and cumulative precipitation totals are analysed as well as the synoptic situations in the case of most characteristic events are described.

Study area, data and methods

Kresna gorge is a part of the middle Struma River Valley and is situated in Southwest part of Bulgaria between Pirin Mountain on the east and Malashevska Mountain on the west (Fig. 1.) The gorge is long about 16 km and has average altitude 475 m a.s.l.

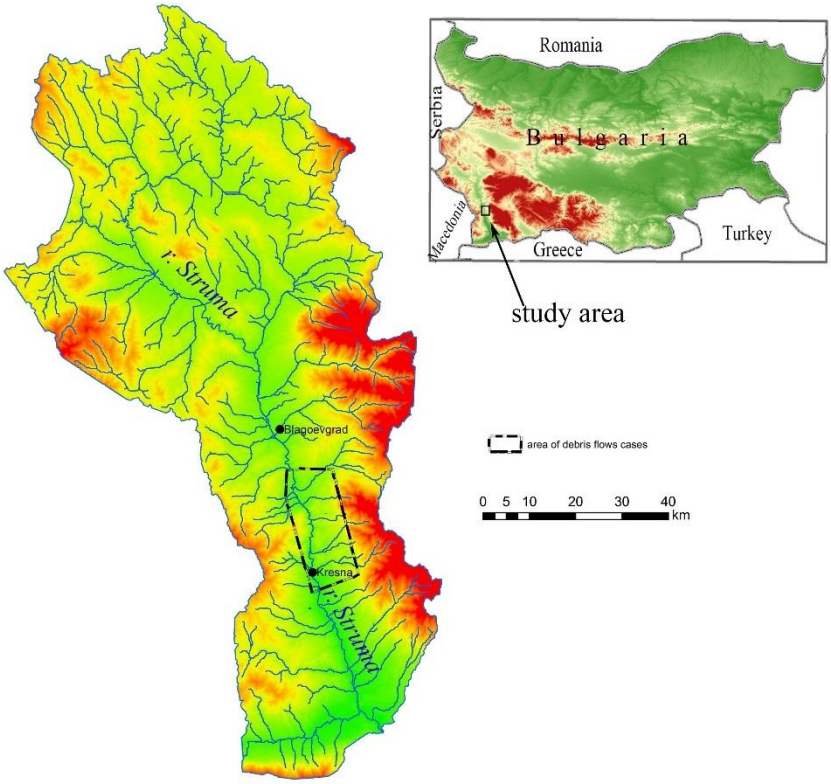


Fig. 1. The investigated region (Struma River valley and Kresna gorge)

Steep and stepped slopes of the Kresna gorge are split from deep-cut river valleys, where there are conditions for a strong denudation [*Dobrev and Georgieva, 2010*]. The modern river valley is imposed on older structures. The rivers, which begin from a lower altitude, flow into Neogene and Paleogene sediments, and those that come from higher altitude are developed in gneisses and migmatites. The region of middle Struma River and Kresna gorge in particular is characterized by actively flowing debris flows of disconnected type that transport a large amount of bulk material [*Kenderova et al., 2013a*]. Some consequences from debris flows are shown on Fig. 2.

Fig. 2. The consequences from debris flow at the region of Middle Struma Valley happened on 4 December 2010 (on the left) and 24 May, 2009 (on the right).

Due to debris flows the international highway E79 was closed for several times but the catastrophic event had a negative impact on the settlements and agricultural areas also.

There is not a meteorological station either a rain-gauge station in the investigated region and because of this in the present research we use the data from station Blagoevgrad which is situated in the Struma river valley on a distance about 20 km north from the place where the debris flows were registered. The daily data are taken from the information of automatic weather station which is published on the specialized web site https://stringmeteo.com/, and the monthly values are from meteorological yearbooks and bulletins.

The present study answers the question to what extend recent climate trends may affect debris flows. The peculiarities of climate in the investigated region are shown by the investigation of the occurrence of extreme precipitation and air temperature months. The extremely dry and wet months are determined. As extremely dry months we consider the months with monthly precipitation totals less than or equal to 10-th percentile of the distribution of initial values, and the extremely wet months are those one with the precipitation more than or equal to 90-th percentile. This method has been applied also to monthly air temperature for determination of extremely cold months [according to 10-th percentile threshold] and extremely warm months [according to 90-th percentile]. The long-term analysis is made on the basis of the data for the period 1961-2015.

In order to study the potential impact of precipitation on debris flows occurrence the daily precipitation and synoptic situations are analysed. The links between debris flows and intense rainfall is analysed by [*Kenderova and Vasilev, 1997*] and [*Kenderova et al., 2014*]. From other side, the occurrence of debris flows depends not only of the intensity and duration of precipitation in a single day but also of the long-term precipitation prior to storm events [*Winter et al., 2010*]. In this paper, the impact of previous rainfall on the occurrence of debris flows is investigated by the calculation of cumulative precipitation for 30 days period prior to the events. The analysis of the relation daily rainfall – cumulative precipitation – debris flow could give important information for the determination of the precipitation threshold for debris flow occurrence. The present paper is a first step of our work towards such activity.

Climate features in the study area

The main initial conditions for debris flows are geological factors, topography, land use and vegetation. Additionally, to these factors, climate trends and climatic and weather extremes are important for debris lows occurrence [*Turnerand and Schuster, 1996; Kenderova et al., 2013*]. Climate impact studies may be disadvantaged by the insufficient meteorological data for the area under consideration, non-linear dependencies and the fact that geomorphological processes may be delayed or non-linear over time [*Viles and Goudie, 2003*]. In order to characterize the climate in the study area we have used monthly air temperature and precipitation for the closest meteorological station – station Blagoevgrad.

The climate in the investigated region is transitional between moderate continental and Mediterranean. The positive trend in annual and seasonal air temperature for the period 1961-2015 has been established. The values of trend are highest for the summer [0.5 °C/10 years] and they are statistically significant. The trend is also statistically significant for annual temperatures. On the background of positive trend for air temperatures the changes of precipitations are different for various seasons – positive sign for autumn and winter and negative for spring and summer but the trend is not statistically significant.

The annual cycle of precipitation is characteristic with two maxima – in May - June and in November - December. The main minimum is in August. The investigation of extreme dry and extreme wet months shows decrease of extreme dry months and increase of extreme wet months (Fig. 3).

The annual cycle of precipitation and increase of extreme wet months are among the factors for initiation of debris flows. The hot summers and prolonged droughts lead to complete drying of the weathering products from the surface layer, which facilitates their rapid disintegration and disconnected their easy handling by the temporary waters and the faster penetration of the weathering agents in deep layers [*Dobrev and Georgieva, 2010*].

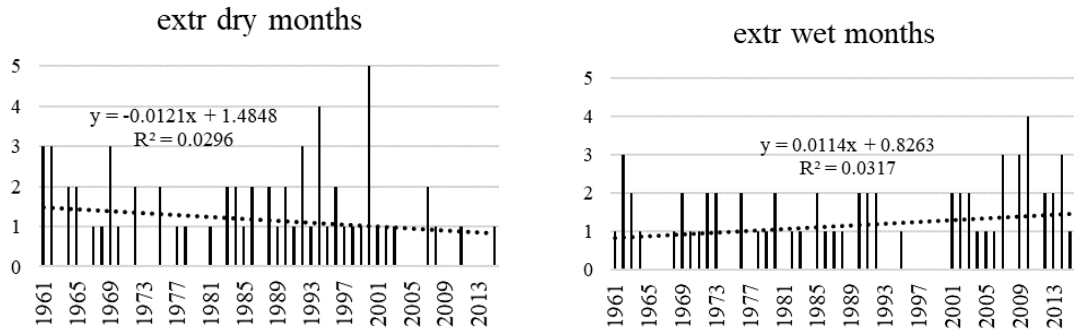


Fig. 3. Distribution of extreme dry and extreme wet months in station Blagoevgrad for the period 1961-2015

Results and discussions

The climate of the region of Kresna gorge is transitional between moderate continental and Mediterranean. The Mediterranean cyclones are typical feature of the climate in that part of Bulgaria and they often cause intensive rainfall during the cold part of the year which could initialize debris flows. The event is observed mainly in November – March, the period with intensive rainfall or fast snow melting.

The intense rainfall has important role for debris flows initiation. For the days in which the analysed debris flows occurred, the daily precipitation has quite different values and varies between 10.7 and 40.7 mm (Table 1). In most of cases daily precipitation amounts are about 30% of monthly precipitation for the particular month in which the event has occurred and above 50 % of average for the investigated period 1961-2015.

Table 1. Daily and cumulative precipitation at station Blagoevgrad for the days with debris flow occurrence

Date of occurrence	**Daily precipitation, mm**	**% of monthly precipitation**	**% of average for 1961-2015**
17 November 2007	13.5 (16 Dec)	20	22
24 May 2009	31.9	39	52
27 December 2009	40.7	31	81
3–5 December 2010	26.5 (4 Dec)	30	53
27 March 2018	10.7 (26 Mar)	13	27

With monthly precipitation total of 130 mm December 2009 is one of the wettest months for the investigated period. Precipitation anomaly for this month is 260 % of the average precipitation for the period 1961-1990. The highest daily precipitation for December 2009 was 41 mm and was registered on December, 27-th. This amount represents 30 % of monthly values for December 2009 and 81% of the average for 1961-1990. The combination of geological, geomorphological and meteorological conditions has caused debris flow in the region of Kresna gorge on 24 December due to which the highway E79 was partly closed and the road traffic was difficult.

The analysis of daily precipitation during 30 days prior to the event shows that debris flow was occurred after fast increase of daily precipitation due to heavy rainfall. Similar daily precipitation value (35 mm) was registered on December, 9-th, but the difference is that this precipitation is after dry period (cumulative precipitation for the period 11 November – 8 December is 1.6 mm only) and probably the most part of precipitation has infiltrated into the soil. The results of the analysis and Fig. 4 show that the debris floe on December 27-th was occurred not only because of heavy rainfall (41mm) but also due to the precipitation during the

previous days (30-days cumulative precipitation amount is 68 mm) which make favourable condition for increase of surface runoff from the region.

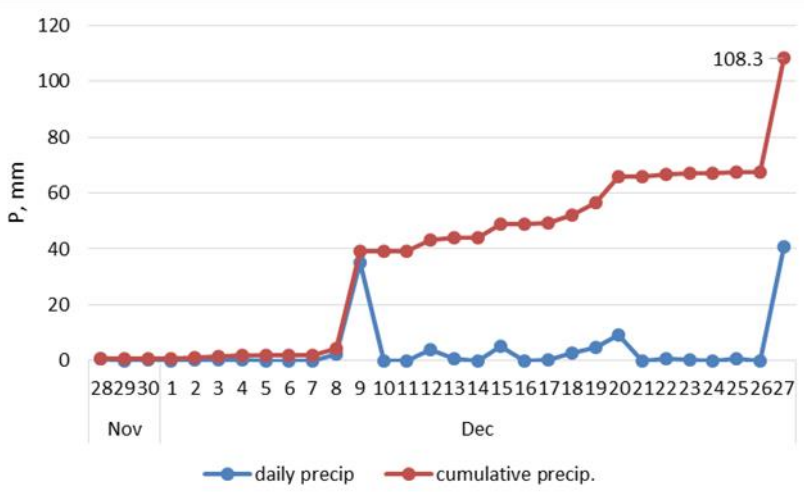
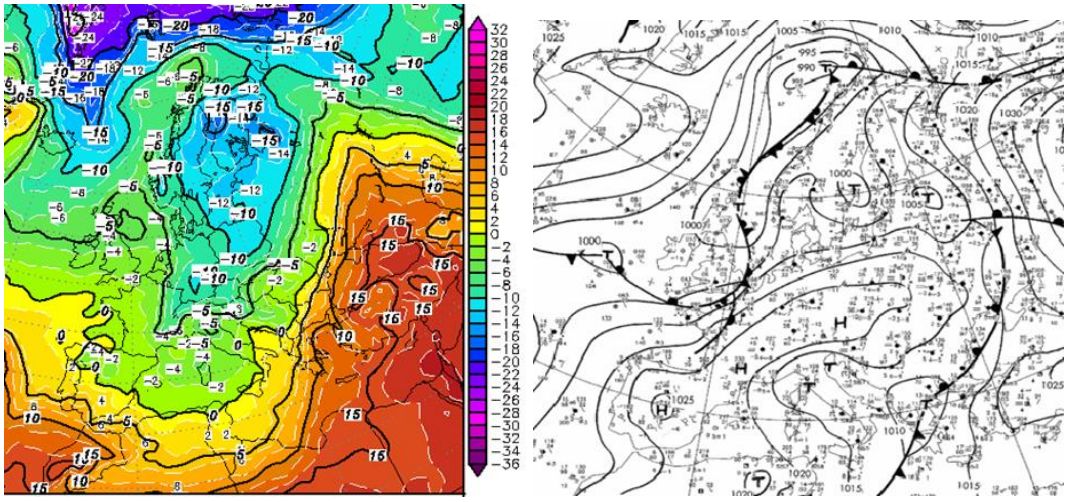


Fig. 4. Daily and cumulative precipitation at station Blagoevgrad 30 days prior to debris flow on 27 December 2009.

The debris flow which occurred in the investigated area in the beginning of December 2010 is connected to the typical synoptic situation for the studied area in this time of the year. The rainfall during the period 3-4 December 2010 is related to the well-developed Mediterranean cyclone which has passed through the territory of Bulgaria and has determined the powerful cumulonimbus clouds (Fig. 5a) On December 4-th the Mediterranean cyclone is blocked above the territory of Bulgaria for about 12 – 18 hours from the local areas with a high air pressure situated on the west and east of the cyclonic center and this brings additionally to the increasing of convective clouds and intensity of rainfall. The temperature distribution of the AT 850 hPa shows the presence of two air streams - hot air from south-southeast and colder from west-northwest (Fig. 5b). Thermal contrast creates conditions for convective clouds and high intensity of rainfall. The local orographic features favour conditions for the development of convective cells and powerful cumulonimbus clouds.

During this period the heavy precipitation has been observed in the area of northern tributaries of the Struma River with the daily amount between 30 and 50 mm on different places. The registered daily precipitation at closest to the investigated site meteorological station, Blagoevgrad is 26.5 mm for December, 4-th. This amount is 30 % of monthly precipitation for December, 2010 and 50% of the monthly average for the period 1961-1990. The analysis of cumulative precipitation shows that the amount for the 30-days period reach 156.1 mm (Fig.6a) and for the 12-days period prior to the event the cumulative precipitation amount is 86.4 mm which is about 173% of the 30-years (1961-1990) monthly precipitation for December (Fig. 6b). We have to notice also a fast increase of the precipitation between 3-th and 4th of December which have initiated the debris flows.



a) b)

Source: www.wetter3.de

Fig. 5. Distribution of air pressure and temperature on 4 December 2014: a) Land synoptic situation; b) 850 hPa temperature ºC.

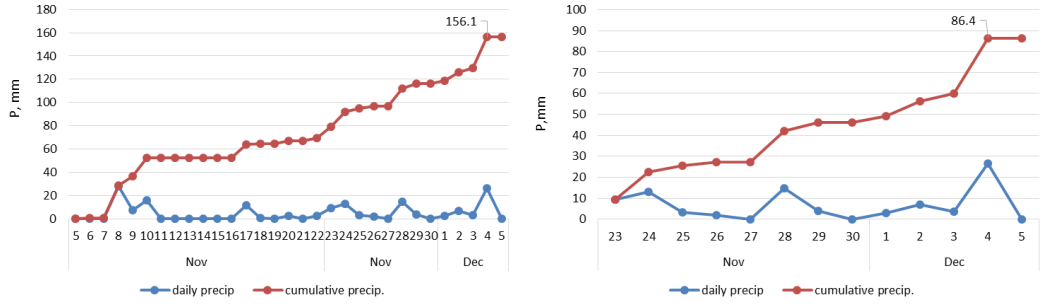


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Fig. 6. Daily and cumulative precipitation at station Blagoevgrad: a) 30 days prior to debris flow on 4 December 2010; b) 12 days prior to debris flow on 4 December 2010

The consequences of debris flows on 3-4 December 2010 are observed in the valley of one of the tributaries of the Struma River, the River Potoka where a large alluvial fan exists with various features (oxbow, sand bars, levees etc.). According to the analysis made by [*Kenderova et al., 2013*], the levees were mostly transverse to the flow direction and were left by incoherent flows carrying coarse debris.

According to the information from Road Infrastructure Agency, Bulgaria, the traffic on the highway E79 in the region of Kresna gorge was difficult on 5 March 2015 and 27 March 2018 due to sliding of earth materials and stones on the road. Monthly precipitation for March 2018 is about 190 % of the average for the period 1961-1990. The data from automatic weather station in Blagoevgrad do not show high daily precipitation amount for the days of the landslide. From other side the events happened after quite long rainfall period during which the cumulative precipitation has reached high values (Fig. 7).

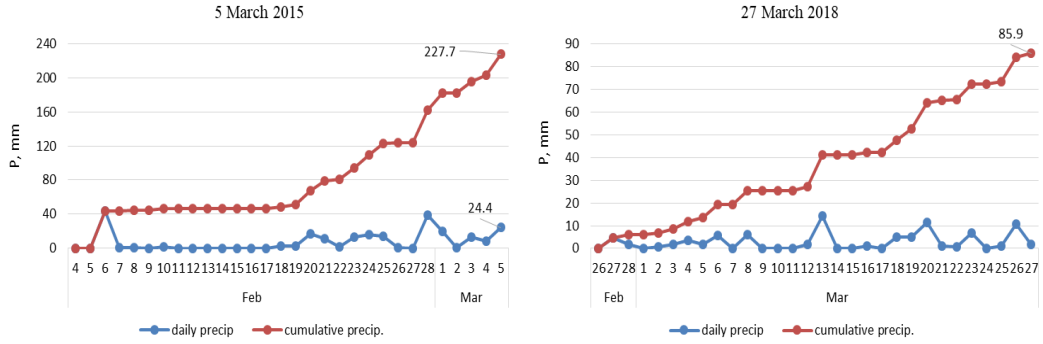

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Fig. 7. Daily and cumulative precipitation at station Blagoevgrad 30 days prior to debris flow on: a) 5 March, 2015 and b) 27 March, 2018

The weather situation on March 27, 2018 is characterized by a well-formed Mediterranean cyclone with a centre over Bulgaria and with the development of convective clouds and precipitation on the front in the cyclone. The temperature distribution on 850 hPa shows thermal contrast which brings additionally for formation of powerful cumulonimbus clouds. The similar synoptic situation was observed in November 2007 when the debris flow and landslides were registered also in the region of Kresna gorge (Fig. 8).

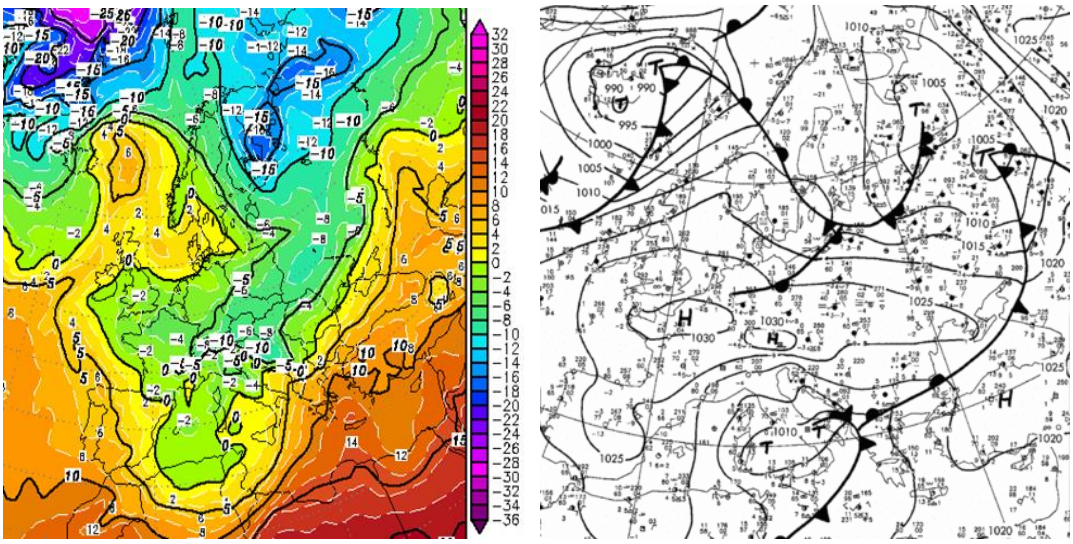

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Fig. 8. Distribution of air pressure and temperature on 17 November 2007 a) Land synoptic situation; b) 850 hPa temperature ºC

The debris flows in Kresna region are characteristic not only for cold part of the year but such events were observed also in September, 2008, April 2007 [*Dobrev and Georgieva, 2010*] and May 2009 [*Dobrev and Georgieva, 2010; Kenderova et al., 2013*].

A catastrophic debris flow was observed in north part of Kresna gorge on 24 May 2009 when the international highway was closed for more than 24 hours by stones and sediments with a volume about 6000 – 7000 m^3 [*Dobrev and Georgieva, 2010*]. Generally, May 2009 was very wet month which monthly precipitation reaches 134% of the average for the period 1961-1990. From other side the debris flow happened after a relatively dry period followed by heavy precipitation. According to the data from meteorological station Blagoevgrad the precipitation amount for 30 days period prior the event was 30 mm while daily precipitation on 24 May was approximately the same value (32 mm), Fig. 9.

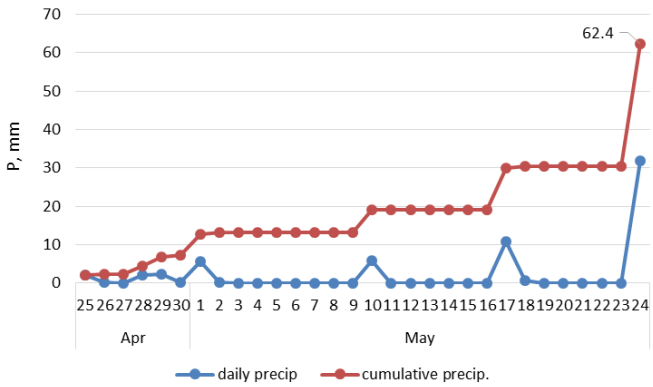

Fig. 9. Daily and cumulative precipitation at station Blagoevgrad 30 days prior to debris flow on 24 May 2009

The synoptic situation initializing heavy rainfall and debris flow was characterized by well-defined cold front which pass over the territory of Bulgaria from West - Northwest and developing of powerful cumulonimbus clouds (Fig. 10).

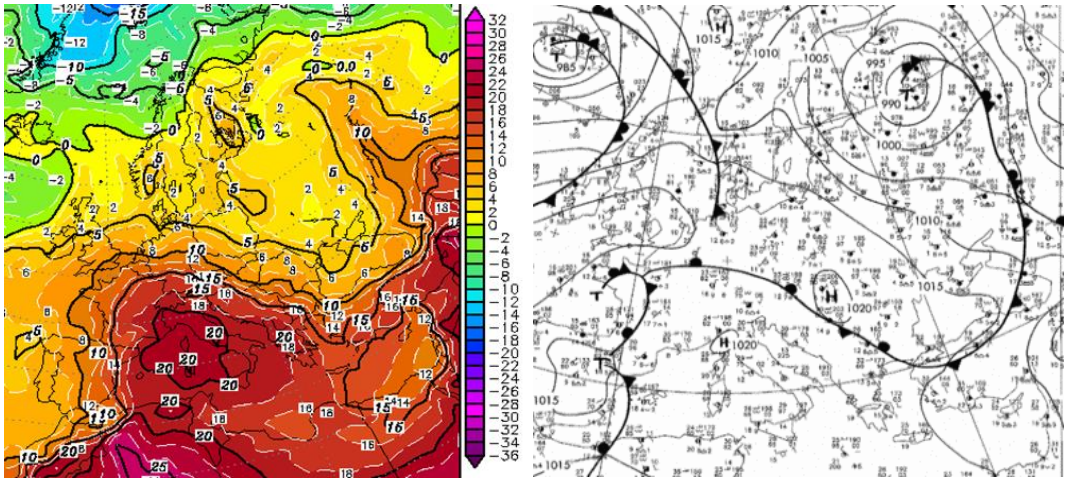

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Fig. 8. Distribution of air pressure and temperature on 24 May 2009 a) Land synoptic situation; b) 850 hPa temperature ºC

The favourable conditions for the formation of cumulonimbus cells, which bring to the intense rainfall, have been observed in some parts of cold front where the leading air flow and orography are combined with the warm and humid air from the southwest. The synoptic situations together with the orography and slope exposure are the main factors determining the territorial distribution of heavy precipitation affecting the volume of debris flow.

Conclusion

The analysis of the weather situations in all of the examined cases shows that the obligatory condition for the formation of precipitation that could leads to the formation of debris flows is the transfer of warm and humid air in combination with cyclonic activity and additionally created temperature contrast in height of active cold air. Undoubtedly, local orographic characteristics create conditions for the development of convective cells, powerful cumulonimbus clouds. The process is stochastic and entirely depends on the combination of several favourable factors that determine it because of which it is difficult to predict.

Most of the observed events are during the cold part of the year which determine the role of the Mediterranean cyclones for intense precipitation in the region/

The present work gives the information about the relation climate – weather - debris flows and points out the role of precipitation for the occurrence of catastrophic events. In the future the investigations will be related to the creation of data base for determination of precipitation threshold for debris flows occurrence as well as for development of measures to reduce and possibly eliminate the risk of debris flows occurrence.

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