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Analysis of debris flows by application of GIS and remote sensing: case study of western foothills of Pirin Mountain (Bulgaria)

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Debris flows occur in many areas in Bulgaria, but the studies of these cases are mainly for their structure and insensitivity and less attention is given to the susceptibility and risk assessment. Although the development of computer technology, geoinformation approach in debris flows investigation in Bulgaria is still not wide applied. The current study focuses on the geological-geomorphological features of the debris flows areas and their role in mass movement. Morphometric characteristics of the basins and rivers/streams channels are analyzed in relation of slope hydrologic properties and mass movement. Lithological substrate and land cover are also considered. Normalized difference vegetation index is used for assessment of land cover and outlining the debris flows areas. The research is held on the foothills of Pirin Mountains (Bulgaria). In the area steep slopes, deep weathering and many faults are highly presented, which, combined with sparsely vegetation and intensive rainfall determine the frequent occurrence of debris flows. GIS analyses are done on the base of SRTM digital elevation model, Sentinel 2 images (ESA), geological map in scale 1:100 000 and field investigations. Application of GIS technology provides an opportunity for easy performing of spatial analyses and investigating the functional and spatial relations between different aspects of debris flow environment. The results of the research can be used in debris flows susceptibility assessment and mapping which is a first step in disaster risk reduction and management.

debris flows, Pirin Mountains (Bulgaria), GIS

Применение ГИС и данных дистанционного зондирования для анализа селевых потоков на примере изучения западных предгорий Пирина (Болгария)

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Сели сходят во многих районах Болгарии, однако большая часть исследований посвящена изучению структуры селевых потоков и их интенсивности, и гораздо меньше внимания уделяется анализу селевой опасности и оценке селевого риска. Компьютерные технологии и геоинформационные методы в исследовании селевых потоков в Болгарии по-прежнему недостаточно широко применяются. В данном исследовании основное внимание уделяется геолого-геоморфологическим особенностям территорий, подверженных сходу селей, и их роли в массовом движении. Проанализированы морфометрические характеристики бассейнов и русел водотоков, а также взаимосвязь этих характеристик с гидрогеологическими особенностями склонов и склоновыми процессами. Также учитываются литологические особенности и растительный покров. Нормализованный разностный индекс растительности используется для оценки растительного покрова и оценки площадей развития селевых процессов. Исследование проводилось в предгорьях гор Пирин (Болгария). Этот район характеризуется крутыми склонами, высокой степенью выветрелости пород и наличием большого количества разломов, что в условиях разреженной растительности и интенсивных осадков обусловливает сход селевых потоков. В качестве основы для ГИС-анализа использовались цифровая модель рельефа SRTM, снимки со спутника Sentinel 2 (ESA), геологическая карта масштаба 1: 100 000 и данные полевых исследований. Применение технологии ГИС облегчает проведение пространственного анализа и изучения функциональных и пространственных отношений между различными характеристиками территорий развития селевых процессов. Результаты исследования могут быть использованы при оценке и картографировании селевой опасности, что является первым шагом к снижению риска бедствий и управлению ими.

селевые потоки, горы Пирин (Болгария), ГИС

Introduction

The complicated nature of debris flows as a result of interaction between many factors require analysing a great volume of data, considering many cases at different conditions and investigating the interconnection between debris flows triggering factors. A detailed study of the relation between climate, surface properties and geomorphology is done by *Melton* [1957] who gives a special attention to the quantitative indicators and statistical methods in investigations and consider different morphometric parameters that have important role in basin hydrology. Development of geomorphological and hydrological researches and collecting of quantitative information about drainage basins lead to increasing the number of publications about basins morphometry and particularly analyzing the morphometric parameters to identify debris flows prone areas [*Jackson et al., 1987; Bovis and Jakob, 1999; Wilford et al., 2004; Bertrand et al., 2012; Zhou et al., 2015; Jun et al., 2017 etc.*].

Different indices are used considering the topographic, geological, hydrological and climate properties of catchments. The most often used ones are slopes angle, stream slope, catchment area, catchment relief, curvature, physical-mechanical properties of rocks, rainfalls. Having regard, the morphometric properties of catchments, the catchment relief and relief ratio are determined as two important impact factors on the debris flow occurrence because the catchment with larger catchment relief and the relief ratio can afford enough energy for debris flow initiation and transportation [*Zhou et al., 2015*]. Land cover and the role of vegetation in mass movement and debris flows development is investigated by *Barlow et al., 2006; Kuriakose, S. L., 2006*.

The need of processing a great volume of information in investigating the debris flows areas, some ones of which are difficult to be detailed investigated on the field, and development of computer technology determine wider use of geographic information systems (GIS) and remote sensing methods. The possibility of GIS and remote sensing in debris flows investigation is considered by [*Melelli and Taramelli, 2004; Elkadiri et al., 2014; Yin et al., 2017*].

Considering the complicated nature of the debris flows, the aim of the current research is to analyze the geological-geomorphological features of debris flows prone areas in order to assess their susceptibility by using GIS and remote sensing technology. For assessing the debris flows susceptibility, the following morphometric parameters are considered: basin area, basin relief, relief ratio, basin shape and slope of the topographic surface. Vegetation and lithology are also considered.

Study area

The research is done in the foothills of the Pirin Mountains, located in the Southwhest Bulgaria (Fig. 1).

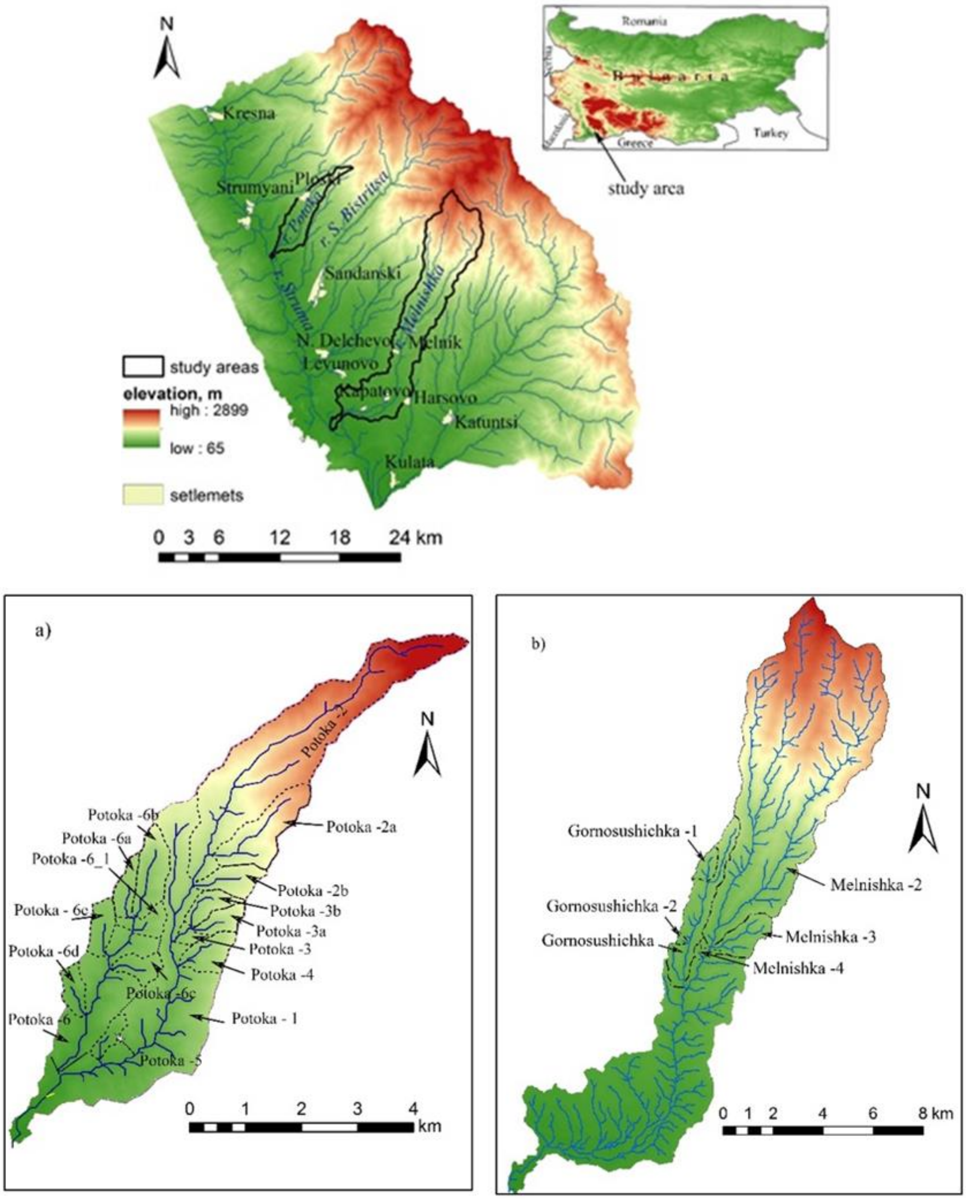

Fig. 1. Study area – basins and subbasins: a) subbasins of river Potoka; b) subbasins of river Melnishka

The catastrophic character of debris flows in the region was first recognized by M. *Glovnja* [1958] who described debris flows from the river Blagoevgradska Bisritsa catchment (north from the studied area). Debris flows in the Middle Struma Valley were studied regarding their type, climatic conditions and partly their mitigation by [*Kenderova and Vassilev, 1997; 2002*] and [*Kenderova et al., 2013a; 2013b, 2014*]. In some sources the studied catchments were characterized as torrential [*Marinov, 1984; Zakov, 2001; Bruchev et al., 2001*], but in recent 20 years there are no records about debris flows occurrence.

Potoka River (18.3 km^2) heads from 1300 m a.s.l. and flows into the river Struma at 220 m. It has SW direction which follows the main slope orientation of this part of the Pirin Mountains. Almost all the catchment area is located in Neogene sandstones and conglomerates [*Zagorchev, 1990*].

River Melnishka (95.6 km^2) catchment is spreading from 2500 to 80 m a.s.l. and also mouths at the river Struma. The lowest part is covered by contemporary alluvial deposits.

Neogene sandstones and conglomerates takes the lower slopes of the mountain in the periphery of the Sandanski Depression [*Kanev 1989*]. The higher catchment parts are built by gneisses, migmatites and granites, part of the Pirin southern pluton body [*Zagorchev, 1990*].

Climate in this part of Pirin is mountainous with strong Mediterranean influence in the higher parts and Mediterranean with continental influence in the lower parts [*Ratchev, Nikolova 2009*]. Annual precipitation values are between nearly 690 mm in the higher parts and about 530 mm in the lower parts.

Data and Methods

The current research is done by applying basin approach in analysing debris flows prone areas. Having regard, the complex character of this hazardous phenomenon this is the most logical approach because in the frame of river/drainage basin the interaction between all landscape forming factors is the strongest. For the purpose of the research 2 river basins are considered (described above, section Study area, and presented on Figure 1). The both basins are divided of several subbasins and morphometric parameters for each one of them are calculated.

Morphometric parameters of the drainage basins are determined on the base of 30 meters SRTM digital elevation model (DEM) [*USGS, NGA, NASA*]. The first step in DEM processing is to convert the geographic coordinate system of the initial file into the projected coordinate system (we used UTM projection) to be able to do the next calculations. Drainage network and watersheds are delineated in ArcGIS environment by Hydrology Spatial Analyst Tool (ESRI Inc.). The drainage network is generated from flow accumulation raster by Map Algebra. Having regard, the complicated mountain relief of the study areas and the characteristics of the investigated phenomena (debris flows) which are mostly related to gully erosions, and also aiming to include all streams (both with a permanent and temporal flow) in the model we accepted that the threshold area to create a stream is 0.1 km^2. In 30 m DEM the number of cells corresponding to 0.1 km2 area is 111 and in this case the stream raster is generated from flow accumulation raster where all cells with a value greater than 111 received a value 1 and present streams, and all other were set to null.

Morphometric parameters, vegetation features and rocks properties used for characterizing the basins are described in Table 1.

Field investigations and data about geological and geomorphological properties of the study area are a basis of the current research. Geological map in a scale 1: 100 000 [*Zagorchev, 1990*] is used for presenting the role of lithology as a debris flow triggering factor. For this purpose, rocks are grouped according their physical-mechanical properties in the following groups: 1) intrusive rocks (manly granite); 2) gneiss and amphibolites; 3) conglomerates and sandstones, and 4) alluvial - gravel, sands and clay. The different susceptibility to weathering of the rocks influence to the ability to be detached and to be involved in the debris flow process.

Table 1. River basins parameters used in debris flow susceptibility assessment

Parameter	**Description and relation to debris flows**
Basin area, km^2	Catchment area, determined on the base of 30 m DEM. Polygon attribute table in GIS environment is used for calculating geometry. The size of the catchment area influence on the variability of the hydro-climatic and geomorphic conditions, and in this regard on the debris flows occurrence. It affects the total amount of the surface runoff and its distribution.
Basin relief, km	The vertical distance between the highest point in the basin and the mouth of the basin (Melton, 1957). It is an indicator for the geodynamics of the area and development of the erosion processes.
Relief Ratio, km	Basin relief divided by the basin length (Schumm, 1954; Strahler, 1958). It is a measure of the general steepness of the basin.
Melton index	Calculated by dividing the basin relief by the square root of the basin area. It is considered as an indicator for the ruggedness. Watersheds prone to debris flows has Melton ratios (indices) >0.3 (Jackson et al., 1987) and > 0.53 according to Bovis and Jakob (1999).

Parameter	Description and relation to debris flows
	Melton index should be considered and interpreted together with the other morphometric parameters.
Basin length, km	Measured along the long axis of the basin, longest dimension measured parallel to main stream channel. Calculated in GIS environment on the base of stream direction raster as downstream distance along the flow path (Flow length – ArcGIS Hydrology Tool).
Basin Shape Factor	A ratio between basin length and basin width. Basin shape directly impacts the size of peak discharge and the time of its arrival at the basin outlet. The peak discharge is higher and the time is shorter at circular basins.
Basin area with a slope <12°	Topographic surface sloped < 12° in % of the total area of the basin. Includes the transition between mountain relief and low land (sloped to horizontal surface) which influence the transportation and accumulation of colluvial material.
Basin area with a slope >25°	Topographic surface sloped >25° in % of the total area of the basin. The areas with higher energy of mass movement.
Stream density, km/km^2	The total length of streams in the catchment area divided by the total area of the catchment. It is an indicator for the development of erosional processes, incl. gully erosion which is a prerequisite for debris flow occurrence.
NDVI - bare soils, arable land, %	Bare soils and arable lands are considered as more prone to debris flows. The area is determined by values of NDVI between 0 and 0.2
NDVI -forest, %	Forest areas are less prone to debris flows. They have retention role to the flows. Forest areas are determined by the values of NDVI > 0.5
Rocks type	Physical – mechanical properties of the rocks influence on the water permeability and runoff distribution as well as on the saturation and mass movement, and in this regard impact on the debris flow occurrence.

Land cover and particularly vegetation influence on surface runoff of rainfall and snowmelt and together with the topographic factors and climate impact on debris flows occurrence. The effect of vegetation on debris flows development is considered through the normalized difference vegetation index (NDVI). It is calculated on the base of Copernicus Sentinel data [*2017, European Space Agency*] considering red (B04) and near infrared (B08) bands. In the current research Sentinel 2 images are used, acquisition date 16 October 2017. The following equation is applied in Map Algebra to the both bands images:

$$NDVI = (B08 – B04) / (B08 + B04). \qquad (1)$$

In the interpretation of NDVI values we accepted that negative values present areas of water bodies, clouds, snow cover that reflect red band greater than infrared. Values close to 0 (0 – 0.2) present bare soils and arable land, which are more prone to debris flows. These areas reflect nearly in the same rate red and infrared bands. Rare vegetation has values of NDVI between 0.2 and 0.5, and values greater than 0.5 present forest areas. The highest values are for the densest vegetation (forest) cover. The time of image acquisition should be considered in the analysis and interpretation of NDVI. The results of NDVI for the study areas in October are lower than in June but considering that debris flows are more possible to happen on bare soils or rare vegetation and following the precautionary principle in debris flow susceptibility assessment we used images of autumn period. Using images of winter month is not applicable in this case because of snow and clouds.

After entering the data about the relief, land cover and lithology in the GIS environment, data processing and calculating the above described indices the next step is to determining and assessing the debris flows prone basins/ subbasins using the morphometric parameters. For this purpose, we used the following parameters: basin relief, relief ratio, Melton index, basin length, basin shape factor and stream density and area with a slope greater than 25°. Each one of these parameters was rated in 3 classes (1, 2 and 3) presenting the debris flow susceptibility rates (1 – very low and low; 2 – moderate and 3 – high). The values are determined by expert views and considering the physical-geographical properties of the study basins as well as the publications in the field of debris flows investigations, cited in the Introduction section of this paper. A complex assessment is done accepting that the considered morphometric parameters have equal influence on debris flows occurrence. The second step is to add the information about the land cover and lithology to the complex morphometric assessment. Weighted sum overlay (ArcGIS Spatial Analyst Tool) is used. The weights of importance of the considered parameters are determined by expert evaluation as follow: for land cover (vegetation) – 50%; lithology – 25% and morphometric indices – 25%.

Results

The river basin morphometry is calculated on the DEM basis and presented in Table 2. The most important values are marked in bold.

The basin area influences on the total amount of the surface runoff which entered from the rainfall and on the drainage time. In larger basins the total rainfall is bigger than in the small ones and in this regard, it could be a prerequisite for intensive surface erosion. On the other hand, the time for drainage is longer and the probability for flash floods and debris flows is lower. Numerous investigations show that debris flows are more typical for small basins. Because of the contradictory character of the basin area to the surface runoff and debris flows occurrence this parameter is not directly considered in debris flow prone assessment, but it is an important basin characteristic and is considered in calculating of other parameters (for instance Melton index). Basin relief, basin ratio and basin length are indicators for steepness of the study areas and should be considered together with the basin area. In the particular cases of the investigated basins, the river Potoka catchment area is more susceptible to debris flows. Although the values of basin relief for some parts of river Melnishka are higher, they are received for larger areas. A complex parameter presenting the basin relief and area is Melton index. According to this parameter the river Potoka subbasins show a higher susceptibility again. Basin shape factor impacts on the discharge of the area and indirectly effect the hydro-geomorphological processes in the basin. The discharge of circular basins is faster than in the elongated basins of the same area because the tributary runoff flows into the main stream nearly in the same time. Regarding the basin shape factor the investigated basins and subbasins are rather low and moderately prone to debris flows than high. The stream density indicates the rate of the development of erosion processes and the drainage network as a whole. On the other side in the analysis of debris flows areas this indicator should be considered and interpreted in relation to the number of streams (particularly 1st order streams – these that have not tributaries), basin area, relief and other morphometric parameters. In the investigated cases the values of stream density show more favorable conditions for debris flows in the river Potoka subbasins than in the subbasins of the river Melnishka.

Analysing the role of the topographic surface in debris flows occurrence, we considered 2 slope intervals: < 12^{o} and > 25^{o}. The limit of 12^{o} is chosen because in many geomorphological classifications and in Bulgarian Regulation about large scale topographic maps this value is used as a limit for delineating mountain areas. Having regard that debris flows are mass movement in wet, saturated environment they could arise even at small degree of the sloping surface. Although that, the higher degrees of slopes are stronger presented as debris flows triggering factors. *Wilford et al.* [2004] consider slopes greater than 30^{o} and particularly between 30^{o} and 40^{o}. According *Zhou et al.* [2015] debris flow prone catchments have slopes between 25^{o} and 45^{o}. In the current paper study areas have slopes until 50^{o}, but the areas steeper than 40^{o} take very small part of the investigated basins. In debris flow prone assessment we accepted that the slopes greater than 25^{o} have greater importance. Slope raster is generated in GIS environment on the base of DEM and reclassified in the three rates. The values show that basin/subbasins of river Melnishka are more prone to debris flow according to the slope parameter.

The described morphometric parameters of the basins are rated according to their importance for debris flow occurrence (Table 2) and the assessment of debris flow susceptibility by morphometric parameters is calculated and presented on Figures 2a and 2b.

Table 2. Values of river basins morphometric and landover parameters

Basins/ Subbasins	Basin area, km^2	Basin relief, km	Relief Ratio, km	Basin length, km	Melton index	Basin Shape Factor	Stream density, km/km^2	Basin slope <12 (% of the basin area)	Basin slope >25 (% of the basin area)	NDVI – bare soils, arable land (% of the basin area)	NDVI – forest (% of the basin area)
River Potoka											
Potoka basin	18.3272	1.2380	0.0825	15.0000	0.2892	12.2768	2.04	45.57	6.10	6.36	29.49
Potoka – 1	13.3360	1.1950	0.0906	13.1900	0.3272	13.0456	2.04	39.29	7.55	4.34	39.47
Potoka – 2	6.4588	0.9610	0.1232	7.8000	0.3781	9.4197	1.86	26.96	12.51	0.17	70.53
Potoka 2a	1.1219	0.4170	0.1709	2.4400	0.3937	5.3066	2.06	26.99	9.85	0	41.79
Potoka 2b	0.4831	0.2230	0.1593	1.4000	0.3208	4.0571	1.84	35.02	3.79	2.99	13.95
Potoka – 3	0.7746	0.2700	0.1500	1.8000	0.3068	4.1830	2.39	30.23	4.01	0.71	21.47
Potoka - 3a	0.3038	0.2300	0.2018	1.1400	0.4173	4.2778	1.94	23.50	8.75	1.45	17.17
Potoka - 3b	0.3371	0.2140	0.1507	1.4200	0.3686	5.9821	2.35	26.68	1.35	0.06	33.63
Potoka – 4	0.4847	0.2370	0.1823	1.3000	0.3404	3.4869	1.85	30.47	8.75	5.57	21.19
Potoka – 5	0.2119	0.1410	0.1294	1.0900	0.3063	5.6071	2.38	59.07	2.49	21.93	0
Potoka – 6	4.3400	0.4180	0.0760	5.5000	0.2006	6.9701	1.88	60.19	2.55	11.28	3.00
Potoka - 6_1	1.3684	0.2910	0.1293	2.2500	0.2488	3.6995	1.95	49.25	4.33	12.98	6.83
Potoka - 6a	0.3260	0.1160	0.0829	1.4000	0.2032	6.0129	2.04	98.61		2.18	0
Potoka - 6b	0.7343	0.2760	0.1415	1.9500	0.3221	5.1783	1.76	29.47	7.86	11.73	11.72
Potoka - 6c	0.3249	0.1250	0.1136	1.1000	0.2193	3.7242	1.98	65.27		16.02	0
Potoka - 6d	0.3008	0.1140	0.1009	1.1300	0.2079	4.2457	1.93	54.04	3.28	13.55	0
Potoka - 6e	0.3719	0.1080	0.0915	1.1800	0.1771	3.7444	1.69	95.70		1.90	1.22
River Melnishka											
Melnishka basin	95.6221	2.3740	0.0673	35.2700	0.2428	10.3735	1.99	43.35	20.76	7.68	52.75
Melnishka – 2	52.4606	2.1010	0.1161	18.1000	0.2901	6.2449	1.76	12.00	36.00	1.29	84.30
Melnishka – 3	2.3607	0.3360	0.1087	3.0900	0.2187	4.0446	1.91	26.00	16.00	6.71	44.68
Melnishka – 4	0.1749	0.1260	0.1575	0.8000	0.3013	3.6589	1.84	20.00	21.00	24.06	7.25
Gornosushichka	6.2381	0.6060	0.0739	8.2000	0.2426	10.7790	1.94	34.00	10.00	1.08	32.90
Gornosushichka - 1	0.8455	0.2700	0.1588	1.7000	0.2936	3.4180	1.84	30.00	8.00	2.19	37.53
Gornosushichka - 2	0.1518	0.1160	0.1450	0.8000	0.2977	4.2154	1.90	28.00	9.00	0.13	22.39

Besides basins morphometry physical-mechanical properties of the rocks also impact on the possibility for debris flows. Granites, gneiss, amphibolites, marbles, shale, conglomerates and sandstones build the study area. Because of the mountainous relief the alluvial gravel, sands and clay are distributed in limited areas in the low parts of the river basins. Most susceptible to debris flows are conglomerates, sandstones and heavily weathered granites. Non-consolidated gravel and sands are also prone to movement but having regards their high-water permeability, small areas and location on slightly sloping terrains they are not rated in high values (Table 3). Intrusive rocks take the largest area of the investigated basins in Melnishka River catchment – nearly 65%, and 30% are for conglomerates and sandstones, while conglomerates and sandstones cover 92 % of the studied areas in Potoka River catchment.

Table 3. Rates of morphometric parameters according to their importance for debris follow occurrence

Parameter	**Value**	**Rates of susceptibility***
Basin relief, km	< 0.2 0.2 – 1 >1	1 2 3
Relief Ratio, km	0.06 – 0.15 0.15 – 0.20 > 0.20	1 2 3
Melton index	0.17 – 0.29 0.29 – 0.35 > 0.35	1 2 3
Basin length, km	0.8 – 3 3 – 10 >10	3 2 1
Basin Shape Factor	3 – 5 >5	2 1
Stream density, km/km^2	1.5 – 2 >2	2 3
Basin area with a slope >25^o, % of the total basin area	< 5 5 – 20 >20	1 2 3

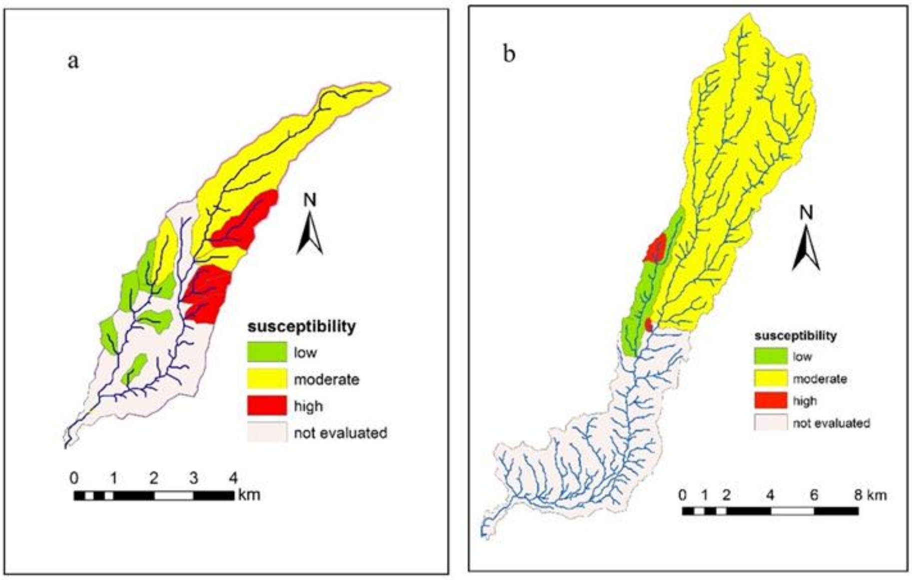

Fig. 2. Debris flow susceptibility according to basins morphometry: a) r.Potoka; b) r. Melnishka

The lithology data is considered together with the results of NDVI interpretation and morphometry in the complex debris flows susceptibility assessment. The determined classes of land cover are rated according to their susceptibility to debris flows (Table 4).

The ArcGIS layers about the susceptibility rates of morphometric parameters, rocks and land cover / vegetation are converted in raster files and are used as input rasters in overlay analysis. Weighted sum is applied. The results are presented on Fig. 3a and 3b.

Table 4. Debris flow susceptibility rates by lithology

Rocks	**Susceptibility***
Granites	2
gneiss and amphibolites	2
conglomerates and sandstones	3
alluvial - gravel, sands and clay	2

*1 -very low and low; 2 – moderate and 3 – high

Table 5. Debris flow susceptibility rates by land cover/vegetation

Land cover	**Susceptibility***
bare soils, arable lands	3
rare vegetation	2
forest	1

*1 -very low and low; 2 – moderate and 3 – high

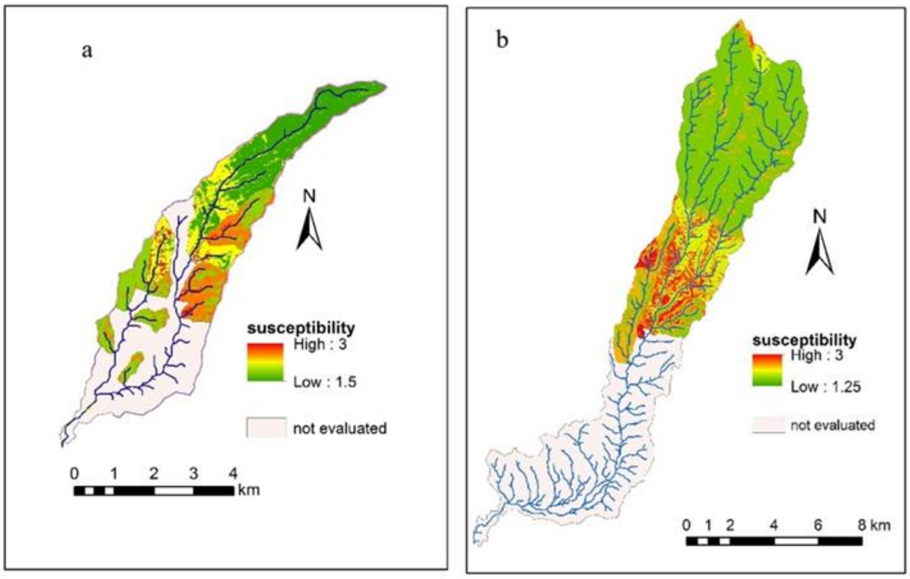

Fig. 3. Complex debris flow susceptibility assessment: a) r. Potoka; b) r. Melnishka

Conclusions

The debris flows susceptibility of two river basins located on the western slopes and foothills of the Pirin Mountain (Bulgaria) is analysed. Three groups of factors are considered: basin morphometry, physical-mechanical properties of rocks and land cover. Analysing river basins morphometry require a complex approach and considering the morphometric indices in interconnection. Reliable results are received by using Melton index which is not considered in geomorphological publications in Bulgaria for the aim of debris flows investigation until now. The results based on morphometric parameters show higher susceptibility to debris flows of the subbasins in river Potoka catchment while it is mainly moderate in the river Melnishka catchment. Due to the lithology and land cover variability the complex susceptibility shows that middle part of the river Melnishka basin is more prone to debris flows. The high susceptibility of subbasins of river Potoka are slightly decreased in the complex assessment.

As a result of the research a GIS data base for the river Potoka and river Melnishka basins is built including DEM, drainage network, lithology and land cover. Application of GIS technology allows processing of big volume of data and easily updating of the information. Using remote sensing data facilitate research of wide areas and save time and resources for field investigation and mapping. The generated model of debris flows susceptibility was validated regarding the previous field and laboratory investigations of these areas [*Kenderova et al., 2014*] and shows good results. However future researches will be in direction to the development of the model, entering more debris flows triggering factors (for instance climate and seismic data) and minimizing the data imperfection.

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