www.gi.sanu.ac.rs, www.doiserbia.nb.rs
J. Geogr. Inst. Cvijic. 2024, 74(3), pp. 311–327

Original scientific paper

UDC: 528.8:556.53:551.3(497.2)
https://doi.org/10.2298/IJGI2403311T

Received: October 21, 2024
Reviewed: November 2, 2024
Accepted: November 28, 2024

ANALYSIS OF REMOTE SENSING DATA PERTAINING TO DEBRIS FLOWS: INSIGHTS FROM SELECTED DRAINAGE BASINS IN BULGARIA

Ilia Tamburadzhiev[1]*

[1]Sofia University, Faculty of Geology and Geography, Department of Climatology, Hydrology and Geomorphology, Sofia, Bulgaria; e-mail: tamburadzhiev@gea.uni-sofia.bg

Abstract: The present study is focused on remote sensing data analysis of the factors for the formation and development of debris flows in mountain drainage basins in Bulgaria. The rate of debris flow susceptibility in the range of the selected drainage basins was investigated. The relevance of the present study is related to the frequency of adverse hydro-climatic phenomena of natural and anthropogenic origin in the last decade in different parts of Bulgaria. Topographic conditions (slope angle), lithology, and land cover (vegetation) are considered as a complex area factor for the formation and development of debris flows. A morphometric analysis of the relief and the drainage network was carried out in order to analyze the debris flow susceptibility. Morphometric parameters and the Normalized Difference Vegetation Index (NDVI) were calculated in Geographic Information System (GIS) environment. The channel networks were classified by stream ordering. GIS analysis is done on the basis of Digital Elevation Model (DEM), Landsat multispectral satellite images, and geological maps. A complex debris flow susceptibility analysis was carried out. A classification system for debris flow susceptibility was generated. The complex analysis of the slope angle, lithology, and land cover within the studied basins show that drainage basins characterized predominantly by rocks of volcanic igneous complex and to a considerable extent by bare soils and arable lands are more susceptible to debris flows. The percentage of the highest rates of debris flow susceptibility is extremely low for the four studied drainage basins, which is largely due to the smaller slope gradients.

Keywords: debris flow susceptibility; drainage basin; remote sensing; morphometric analysis; Bulgaria

1. Introduction

Debris flows are one of the catastrophic mass movement events, which are a transitional phenomenon between landslides and floods. They are a danger to people's economic activity, and sometimes a serious threat to human life. The main reasons for carrying out the present study are the still relatively insufficient study of debris flow on the territory of Bulgaria and, at the same time, their frequent manifestations of risk phenomena in the last decade. Previous research of debris flows for territories in Bulgaria using mostly, or entirely, remote

---

*Corresponding author, e-mail: tamburadzhiev@gea.uni-sofia.bg

sensing methods were carried out by Baltakova et al. (2018), Krenchev and Kenderova (2019), Nikolova et al. (2021), Stoycheva and Krenchev (2021), and Nikolova et al. (2022).

The present study is based on one of the modern remote sensing methods for studying debris flow susceptibility—Satellite-Based Remote Sensing. Other modern remote sensing methods and techniques related to the analysis of susceptibility to various types of mass movement phenomena are Light Detection and Ranging (LiDAR), Synthetic Aperture Radar (SAR), Unmanned Aerial Vehicles (UAV) and Drones, Hyperspectral Remote Sensing and Ground-Based Remote Sensing Techniques (e.g., Ground Penetrating Radar [GPR] and Terrestrial Laser Scanning [TLS]). TLS was done by Nikolova et al. (2021) for the purpose of morphometric analysis of debris flows in the basins in the Eastern Rhodopes, Bulgaria.

The increase of the frequency of debris flows phenomena is a result of both the negative impact of anthropogenic activity and climate change. A number of hilly and mountainous regions of the country are characterized by the presence of suitable conditions for the formation and development of debris flows. Such areas are the peripheral mountain territories surrounding the Zadbalkan Valleys (especially the southern slopes of Stara Planina Mountain), the Eastern Rhodopes, and the Struma and Mesta drainage basins (Gerdzhikov et al., 2012).

The analysis of debris flows involves a wide range of methods and specialists. The present study aims to investigate the geomorphological and lithological factors, as well as the land cover, for the formation and development of debris flows in the territory of selected drainage basins through the use entirely of remote sensing. Another main aim of the study is to carry out a morphometric analysis of the drainage basins and the drainage network in order to analyze the debris flow susceptibility. In the study of debris flows, remote sensing serves as an essential tool for detecting, monitoring, and analyzing the dynamic processes associated with these catastrophic phenomena. Also, it allows the identification of unique landforms and deposits on the Earth’s surface, shaped or entirely formed by debris flows. It provides insight into the tangible impacts of these events on human activities and infrastructure. Finally, preliminary risk analysis would be useful for the prevention or mitigation of the negative impacts of debris flows in potentially threatened areas. Expanding the spectrum of research on this topic would contribute to the construction of a detailed scientific and information base on the genesis and susceptibility to the development of this phenomenon.

2. Study area

Four representative drainage basins were selected, in the scope of which remote sensing investigations of the susceptibility to debris flows formation and development were carried out. The selection of drainage basins is based on two main principles: 1) territories for which there are data in the scientific literature that are potential for the development of debris flows; and 2) territories in which detailed studies of this risk phenomenon have not been conducted so far. The drainage basins of four mountain rivers were selected—the Turiyska River (in Sarnena Sredna Gora Mountain), the Novoselska River (in the Eastern Stara Planina Mountain), the Dyushundere River (in the Eastern Rhodopes Mountain), and a river in the Eastern Rhodopes, which has no name and is designated as River 4 in the present study (Figure 1).

The selected drainage basins are located in the transition zone between the temperate continental climate and the subtropical climate. The drainage basins of Dyushundere and River 4 fall into a zone with a stronger Mediterranean climatic influence. Regarding the interannual distribution of precipitation, some differences are also observed between the individual drainage basins. The drainage basin of the Turiyska River is characterized by a temperate continental type of interannual distribution of precipitation, the drainage basin of the Novoselska River—by a transitional type, and the drainage basins of the Dyushundere River and the River 4—by a continental-Mediterranean type. The location of the selected drainage basins in the transition zone between the temperate continental climate and the subtropical climate allows the research results to be compared to territories with similar natural conditions not only in Bulgaria and the Balkan Peninsula, but also in other regions of Southern Europe. Regarding the soils, the drainage basin of the Turiyska River is characterized mainly by Cambisols, Luvisols and Planosolsm and to a lesser extent, by Fluvisols. The drainage basin of the Novoselska River is characterized by Cambisols and Luvisols. The drainage basins of the Dyushundere River, and the River 4 are characterized by Luvisols and to a lesser extent, by Fluvisols.

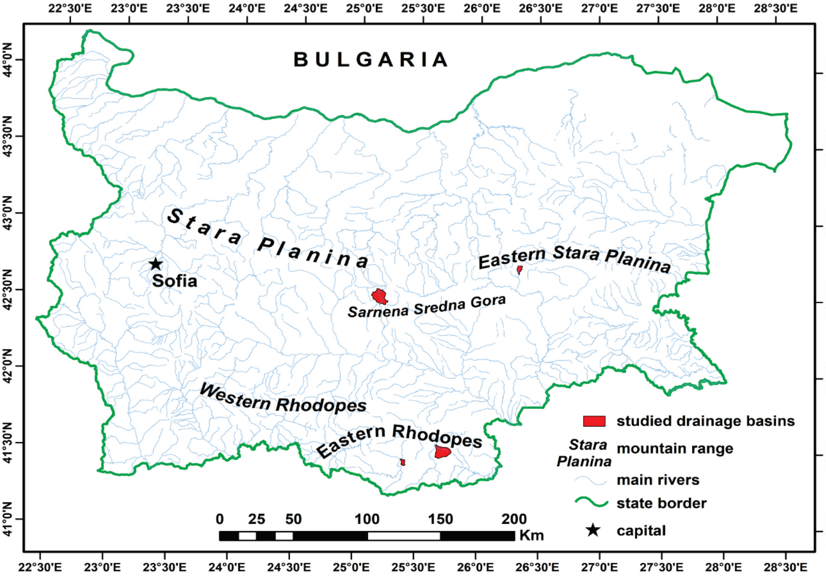

Figure 1. Geographical position of the studied drainage basins.

3. Data and methodology

Remote sensing methods, including analysis of Digital Elevation Model (DEM) and satellite images, were used in the present study. Topographic and geological maps were analyzed using Geographic Information System (GIS). The following data were used, shown in Table 1.

The slopes and the lithological base were the geomorphological and lithological factors taken into account in determining the susceptibility to debris flow formation and development. Lithological factors have a direct relationship with the conditions for the development of erosion and weathering of rocks and with the exchange between surface and groundwater. The slope affects the conditions for transport and accumulation of the destroyed material, as well as the spatial distribution of surface runoff. Basic characteristics of the land cover (vegetation cover) were also analyzed, as well as characteristics of the studied drainage basins and their drainage networks, which also influence the spatial distribution of surface runoff and the conditions for the formation and development of debris flows.

Table 1. Research data

Data		Source
Shuttle Radar Topography Mission (SRTM 1 Arc-Second Global) (DEM, 30 m)	n41_e025_1arc_v3 n42_e025_1arc_v3 n42_e026_1arc_v3	United States Geological Survey, Earth Resources Observation and Science Center (2018)
Geological map of Bulgaria (1:100 000)	Map sheet Kardzhali	Kozhuharov et al. (1989)
	Map sheet Kazanlak	Tsankov et al. (1995)
	Map sheet Krumovgrad and Sape	Kozhuharov et al. (1992)
	Map sheet Sliven	Kanchev (1995)
Landsat 8 and 9 OLI/TIRS Collection 2	Landsat 8 OLI/TIRS Collection 2 satellite image (path 182, row 030), resolution 30 × 30 m, acquired on 09/28/2024 Landsat 8 OLI/TIRS Collection 2 satellite image (path 182, row 031), resolution 30 × 30 m, acquired on 09/28/2024 Landsat 9 OLI/TIRS Collection 2 satellite image (path 183, row 030), resolution 30 × 30 m, acquired on 09/27/2024	United States Geological Survey, Earth Resources Observation and Science Center (2024)

A morphometric analysis of the studied drainage basins and their drainage network was carried out by calculating the following parameters, which are related to the conditions for the formation and development of debris flows: Basin area (*A*), Highest basin altitude (H_{max}), Lowest basin altitude (H_{min}), Mean basin altitude (H_{mean}), Interbasin length (*L*), Total relief (*H*), Relief ratio (R_h), Melton ratio (*R*), Hypsometric integral (H_i), Form factor, Number of streams (*N*), Stream frequency (F_s), Drainage network length, Drainage density (D_d), and Slope angle. The stream order was determined by Strahler's method (Strahler, 1957). The drainage networks were generated in GIS using the method of Tarboton et al. (1991) and DEM (Figure 2). The methods used for the calculation of the specified parameters are described in Table 3.

In the present study (Table 4, Figure 3), the 3-level debris flow susceptibility scale proposed by Baltakova et al. (2018) was adopted in the analysis of slopes, lithology, and vegetation cover. Debris flow susceptibility rates are 1 (very low), 2 (moderate), and 3 (high). Debris flows are formed most often at slopes between 27° and 56° (Blair & McPherson, 2009; Campbell, 1975). Slopes steeper than 56° most commonly are bare bedrock and soil slips on slopes of less than 27° are less common (Campbell, 1975). According to Blair and McPherson (2009), slopes formed of colluvium range from 15° to 56°. Therefore, in the present study, we perceive slopes of 27°–56° with the highest rate of susceptibility (high rate) for the formation and development of debris flows, slopes of 15°–27° with a comparatively lower susceptibility rate (moderate rate), and slopes below 15° and above 56°—with very low susceptibility rate (very low rate).

Rock types and formations (Figure 4) have been grouped into generalized rock groups in order to more easily define their rate of susceptibility to debris flows. The generalized rock groups are unconsolidated sediments, sedimentary rocks, intrusive igneous complex, volcanic igneous complex, metamorphic, and migmatized rocks (Table 5). Most debris flows appeared in hard massive rock (granite) and soil mass (clay, sub clay, fine sand, coarse sand, and gravel soil). Hard bedded rock (limestone) is unlikely to form debris flow disasters (Qin et al., 2019). In confirmation of part of the above are the claims of Esper Angillieri (2020) that the igneous complex is an important debris flows-related factor and the Triassic granites are lithology most vulnerable to debris flows. Lorente et al. (2003) recorded the development of debris flow in the Flysch sector and to a much lesser extent in areas composed of limestone.

Based on the provided data, the unconsolidated sediments, intrusive, and volcanic complexes are classified with a susceptibility rate of 3 for debris flow development. Rate 2 of susceptibility defines metamorphic and migmatized rocks. Regarding the sedimentary rocks, it should be noted that in the investigated drainage basins in the present study, they are represented not only by limestones, but also by dolomites, flysch formations, etc. There are a number of studies proving the formation and development of debris flows in areas composed of dolomites (Berti et al., 1999; Gregoretti et al., 2018). Therefore, we also define the sedimentary rock group with the rate 2 of susceptibility to debris flows development (Table 5).

An important factor for the formation and development of erosion and weathering processes, and hence for creation of conditions for formation of debris flows, is vegetation. Land cover and particularly vegetation influence on surface runoff of rainfall and snowmelt (Baltakova et al., 2018). In this sense, the Normalized Difference Vegetation Index (NDVI) was used, the calculation of which allows distinguishing the territories covered with vegetation from the deforested territories or bare soils. The index is calculated in GIS environment using the formula which indicates the ratio between the red (*R*) and near infrared (*NIR*) values (Equation 1). For the LANDSAT 8 and 9 OLI/TIRS satellite images used in the present study, the combination of Band 5 (*NIR*) and Band 4 (*R*) was used to apply the Equation 2 (Landsat Missions, 2024):

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \tag{1}$$

$$NDVI = \frac{Band\,5 - Band\,4}{Band\,5 + Band\,4} \tag{2}$$

Takahashi (2014) associates poor vegetation with the occurrence of very dense shallow landslides and good vegetation with lower landslide density. Barlow et al. (2006) set NDVI threshold of .15 for the separation of objects into vegetated/unvegetated classes. In order to differentiate dense from rare vegetation, and based on the NDVI values proposed by Weier and Herring (2000) and by the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, Department of Atmospheric and Oceanic Sciences of the University of Wisconsin-Madison, USA (CIMSS/SSEC/AOS, 2024), an NDVI threshold of .3 was determined, above which dense vegetation cover is registered. Therefore, rare vegetation is registered in the range .15–.3, and bare soils and arable lands are below .15 (Table 6, Figure 5).

Bare soils and arable lands have the highest debris flow susceptibility rate—(3), rare vegetation—(2), and dense vegetation—the lowest rate (1). Topographic conditions (slope angle), lithology, and land cover (vegetation) are considered as a complex area factor for the formation and development of debris flows (Table 6). The drainage network is considered as a separate, linear factor for the formation and development of debris flows. The weights of importance of the considered factors are determined based on the existing data in the scientific literature. Blais-Stevens et al. (2013) determine slope angle and surficial geology with equal importance in determining debris flow susceptibility—30% each or a total of 60% for both factors. Baltakova et al. (2018) set 50% weight of importance for land cover (vegetation).

In the present study, equal importance is assigned to topographic conditions (slope angle), lithology, and land cover (vegetation) in determining debris flow susceptibility.

A complex debris flow susceptibility analysis was carried out. A classification system for debris flow susceptibility was generated for this purpose, including seven rates. Each rate is obtained after taking into account the debris flow susceptibility rates of the slopes, lithology, and vegetation cover. In Table 2, the seven rates of debris flow susceptibility and their interpretations are shown.

Table 2. Debris flow susceptibility rates and correlation to the rates of debris flow susceptibility of the topography (slope angle), lithology and land cover (vegetation) factors

Susceptibility rate	Correlation to the rates of debris flow susceptibility of the topography (slope angle), lithology, and land cover (vegetation) factors	Risk
7	All three factors are rate 3	Extreme
6	Two factors are rate 3, one factor is rate 2	Very high
5	One factor is rate 3, two factors are rate 2; or two factors are rate 3, one factor is rate 1	High
4	One factor is rate 3, one factor is rate 2, and one factor is rate 1; or all three factors are rate 2	Moderate
3	One factor is rate 3, two factors are rate 1; or two factors are rate 2, one factor is rate 1	Low
2	One factor is rate 2, two factors are rate 1	Very low
1	All three factors are rate 1 of debris flow susceptibility	Minimum or no risk

4. Results

4.1. Morphometric analysis

The methods used for the calculation of the specified parameters are described in Table 3. Wilford et al. (2004) define drainage basin length < 2.7 km as potential for debris flow development. None of the studied drainage basins fall into this category. Regarding the R_h, Wilford et al. (2004) indicate values > .35 for the development of debris flows. Again, none of the studied drainage basins fall into this category.

Table 3. Values of river drainage basins morphometric parameters

Parameter	Formula and method	Unit	Turiyska	Novoselska	Dyshundere	River 4
Area (A)	GIS	km^2	75.9	13.8	69.8	10.4
$Hmax$	GIS	km a.s.l	1.247	1.176	.813	.622
$Hmin$	GIS	km a.s.l	.415	.301	.168	.254
$Hmean$	GIS	km a.s.l	.815	.818	0.47	.439
L	Schumm (1956)	km	8.9	5.6	10.2	4
H	$H = H_{max} – H_{min}$ (Schumm, 1956)	–	.832	.875	.645	.368
R_h	$R_h = H/L$ (Schumm, 1956)	–	.093	.156	.063	.092
R	$R = H/\sqrt{A}$ (Melton, 1965)	–	.096	.236	.077	.115
H_i	$H_i = (H_{mean} – H_{min})/(H_{max} – H_{min})$ (Bishop, 2002)	–	.481	.591	.468	.503
Form factor	$F = A/L^2$ (Horton, 1932)	–	.958	.44	.671	.65

Table 3. Values of river drainage basins morphometric parameters (*continued*)

Parameter	Formula and method	Unit	Turiyska	Novoselska	Dyshundere	River 4
Number of streams	GIS	–				
Total (N)			360	56	252	45
1st order			282	42	200	36
2nd order			58	10	39	6
3rd order			16	3	10	2
4th order			3	1	2	1
5th order			1	-	1	-
F_s	$F_s = N/A$ (Horton, 1945)	number of streams/km^2	4.7	4.1	3.6	4.3
Drainage network length	GIS	km				
Total			180.9	29.2	140.8	21.6
1st order			96.4	12.3	67.5	11.9
2nd order			42.7	7	33.1	5.8
3rd order			23.5	7	23.9	1.8
4th order			11.9	2.9	12.8	2.1
5th order			6.4	–	3.5	–
D_d	D_d = the total drainage network length/A (Horton, 1945)	km/km^2	2.383	2.116	2.017	2.077

Values of Melton ratio $R \leq .30$ indicate that conventional fluvial processes are generally dominant in a watershed (Jackson et al., 1987; Welsh & Davies, 2011; Wilford et al., 2004). All the four studied drainage basins fall into the specified category. According to Welsh and Davies (2011), catchments with values of $R > .50$ are potentially dangerous for generating debris flows. Therefore, the studied drainage basins do not fall into this category.

Highly eroded regions are characterized by low values (with values close to 0) of H_i (Pedrera et al., 2009). The drainage basin of the Novoselska River has the highest value, and the drainage basin of the Dyushundere River has the lowest one. Therefore, the drainage basin of the Dyushundere River is the most eroded. In general, it is noticeable that the values of the integral of all the four drainage basins are close to each other and they (the basins) are relatively moderately eroded.

The Form factor is equal to unity when the basin shape is a square, and decreases according to the extent of elongation (Zavoianu, 1985). Proceeding from the statement that the more circular a basin is, the greater the flood potentiality of the basin (Ogarekpe et al., 2020) and comparing with the degree of elongation, it follows that the drainage basin of the Turiyska River is characterized by the highest flood potentiality and the drainage basin of the Novoselska River—by the lowest. The highest value of F_s is found in the drainage basin of the Turiyska River and the lowest in the drainage basin of the Dyushundere River, which makes the first one the most susceptible to development of debris flows based on this parameter.

A value of 2.74 for D_d is an indicator for poorly drained basin and a value of .73—for well-drained (Horton, 1945). Low permeability of the outcropping soils and high erosive activity are indicated by high D_d values (Grelle et al., 2019). Therefore, all the studied drainage basins are characterized by a relatively high erosion potential and high susceptibility to debris flows—the highest is for the Turiyska River basin and the lowest is for the Dyushundere River basin. The basins of the 1st and 2nd order are more susceptible to debris flows than the higher-order basins (Nikolova et al., 2022). The drainage basin of the Turiyska River is characterized with the largest number of the 1st and 2nd order streams and with the longest 1st and 2nd order drainage network. On the opposite side is the drainage basin of the River 4. Therefore, the drainage basin of the Turiyska River is characterized by the highest susceptibility to debris flows

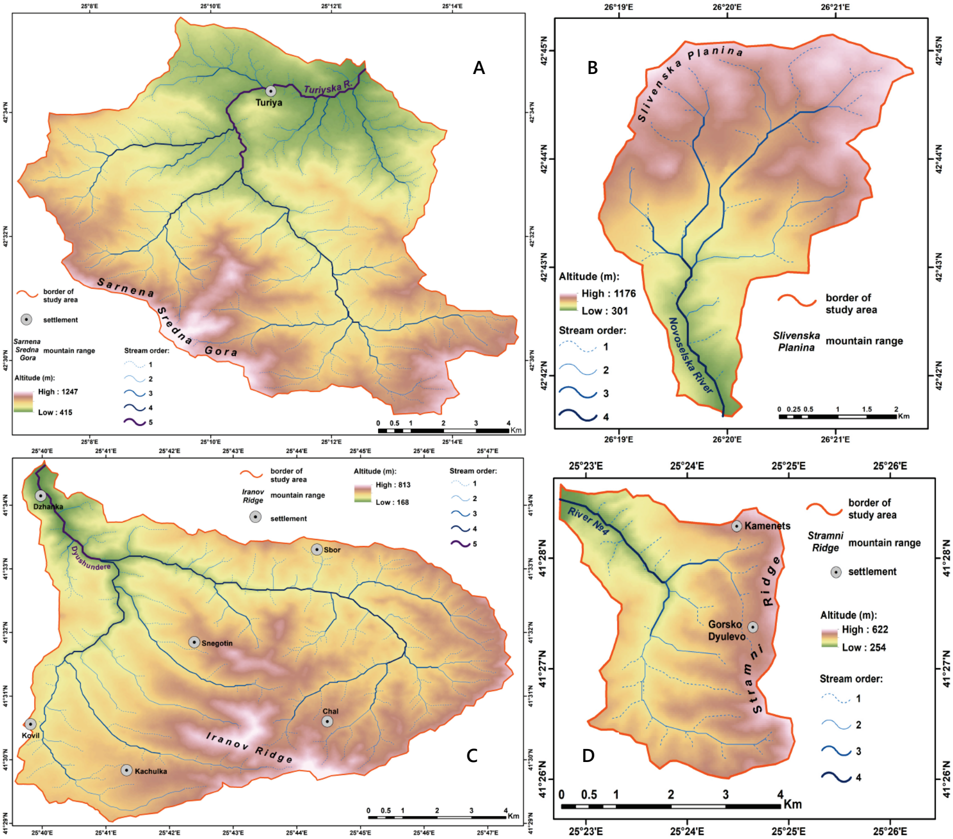

Figure 2. Hypsometric and stream ordering maps of the studied drainage basins.
Note. Panel A: Turiyska River. Panel B: Novoselska River. Panel C: Dyushundere River. Panel D: River 4.

4.2. Slope analysis

The low percentage of slopes with the highest rates of debris flow susceptibility in all the four studied drainage basins is striking. The drainage basin of the Novoselska River is characterized by the highest percentage of the highest rate of debris flow susceptibility from the point of view of the slope analysis. However, slopes from 27° to 56° occupy a very small part of the basin’s territory (7.66%, Table 4).

Table 4. Debris flow susceptibility rates by slopes

Slope	Debris flow susceptibility rate	Turiyska (% of the basin area)	Novoselska (% of the basin area)	Dyushundere (% of the basin area)	River 4 (% of the basin area)
0°–15°	1	74.4	46.5	74.3	80.5
15°–27°	2	24.1	45.82	25.3	19.3
27°–56°	3	1.5	7.66	.4	.2
> 56°	1	–	.02	–	–

The percentage of the highest rate of debris flow susceptibility is the lowest for the drainage basin of the River 4, and the percentage of the the Dyushundere River drainage basin is very close to its values. The percentage of slopes with the lowest rate of debris flow susceptibility in the drainage basins of the rivers Turiyska, Dyushundere, and River 4 is significant, with the latter having the highest value (80.5%, Table 4).

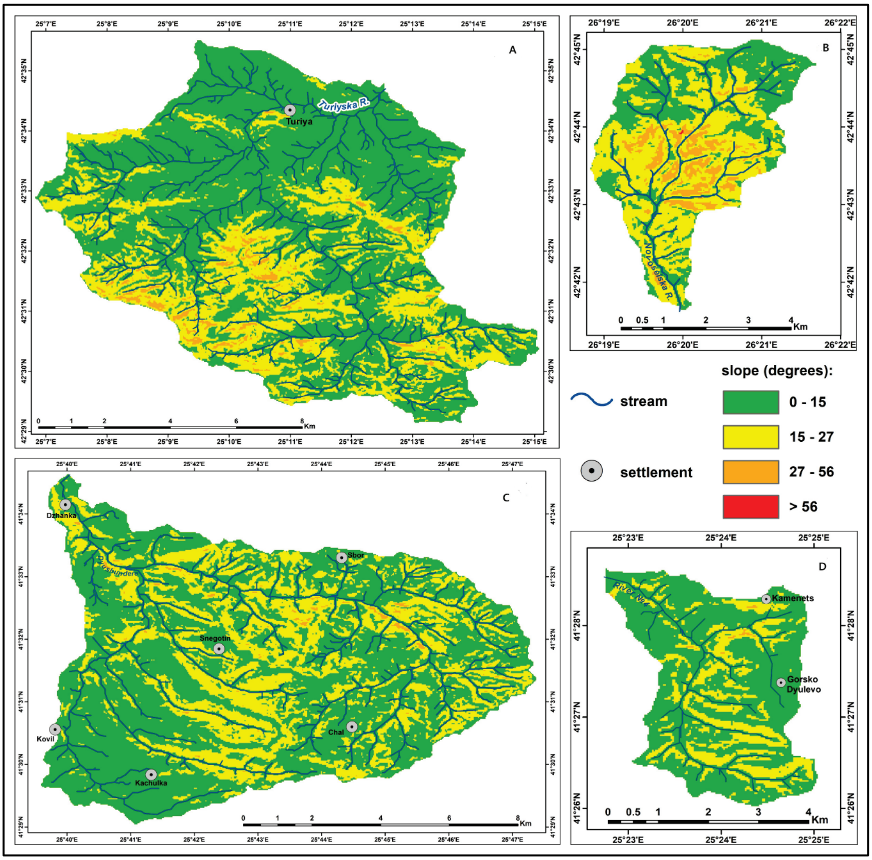

Figure 3. Slope maps of the studied drainage basins.
Note. Panel A: Turiyska River. Panel B: Novoselska River. Panel C: Dyushundere River. Panel D: River 4.

4.3 Lithology analysis

In terms of lithology, the River 4 drainage basin has the highest rate of debris flow susceptibility. The entire basin's territory has rate 3 of susceptibility. Approximately 93.82% of the territory of the drainage basin of the Dyushundere River has rate 3 of debris flow susceptibility (Table 5).

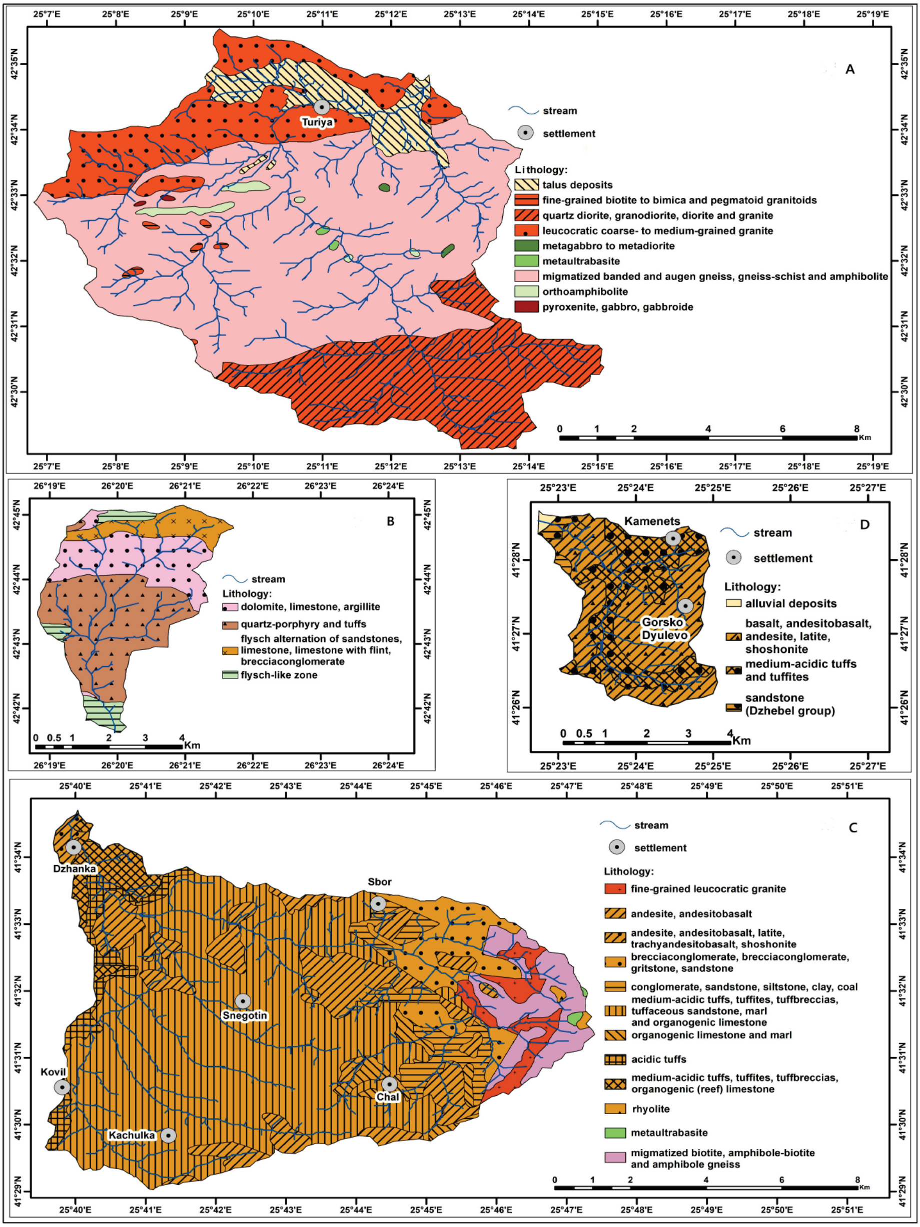

Figure 4. Lithological maps of the studied drainage basins.
Note. Panel A: Turiyska River. Panel B: Novoselska River. Panel C: Dyushundere River. Panel D: River 4.

Almost two-thirds (62.47%) of the territory of the drainage basin of the Novoselska River is characterized by rate 3 of susceptibility. The drainage basin of the Turiyska River has the lowest rate of debris flow susceptibility—less than a half (44.03%) of the basin's territory is characterized by rate 3 of susceptibility (Table 5).

Table 5. Debris flow susceptibility rates by lithology and % of the drainage basin area

Rock types and formations	Generalized rock group	Debris flow susceptibility rate	Turiyska	Novoselska	Dyushundere	River 4
Alluvial deposits Talus deposits	Unconsolidated sediments	3	6.54	–	–	0.96
Dolomite, limestone, argillite Flysch-like zone	Sedimentary rocks	2	–	37.53	–	–
Fine-grained biotite to bimica and pegmatoid granitoids Fine-grained leucocratic granite Leucocratic coarse–to medium-grained granite Pyroxenite, gabbro, gabbroide Quartz diorite, granodiorite, diorite and granite	Intrusive igneous complex	3	37.49	–	3.2	–
Acidic tuffs Andesite, andesitobasalt Andesite, andesitobasalt, latite,trachyandesitobasalt, shoshonite Basalt, andesitobasalt, andesite, latite, shoshonite Brecciaconglomerate, conglomerate, gritstone, sandstone Conglomerate, sandstone, siltstone, clay, coal Flysch alternation of sandstones, limestone, limestone with flint, brecciaconglomerate Medium-acidic tuffs and tuffites Medium-acidic tuffs, tuffites, tuffbreccias, organogenic (reef) limestone	Volcanic igneous complex	3	–	62.47	90.62	99.0

Table 5. Debris flow susceptibility rates by lithology and % of the drainage basin area (*continued*)

Rock types and formations	Generalized rock group	Debris flow susceptibility rate	Turiyska	Novoselska	Dyushundere	River 4
Medium-acidic tuffs, tuffites, tuffbreccias, organogenic (reef) limestone Medium-acidic tuffs, tuffites, tuffbreccias, tuffaceous sandstone, marl and organogenic limestone Organogenic limestone and marl Quartz-porphyry and tuffs Rhyolite Sandstone (Dzhebel group)	Volcanic igneous complex					
Metagabbro to metadiorite Metaultrabasite Migmatized banded and augen gneiss, gneiss-schist and amphibolite Migmatized biotite, amphibole-biotite and amphibole gneiss Orthoamphibolite	Metamorphic and migmatized rocks	2	55.97	–	6.18	–

4.4. Land cover analysis

The drainage basin of Dyushundere River has the highest percentage of bare soils and arable land and therefore is characterized by a higher rate of debris flow susceptibility compared to the other studied drainage basins. The predominant part of the drainage basin is occupied by rare vegetation. The percentage of bare soils and arable lands is the lowest in the drainage basin of the Turiyska River (Table 6).

Table 6. Debris flow susceptibility rates by land cover and % of the drainage basin area

NDVI value	Land cover	Debris flow susceptibility rate	Turiyska	Novoselska	Dyushundere	River 4
< .15	bare soils, arable lands	3	.4	3.7	22.69	1.44
.15–.3	rare vegetation	2	32.23	39.19	60.68	83.85
> .3	dense vegetation	1	67.37	57.11	16.63	14.71

On the other hand, the drainage basin of the Turiyska River has the highest percentage of dense vegetation and therefore is characterized by a low rate of debris flow susceptibility. The percentage of dense vegetation is the lowest in the drainage basin of the River 4 (Table 6).

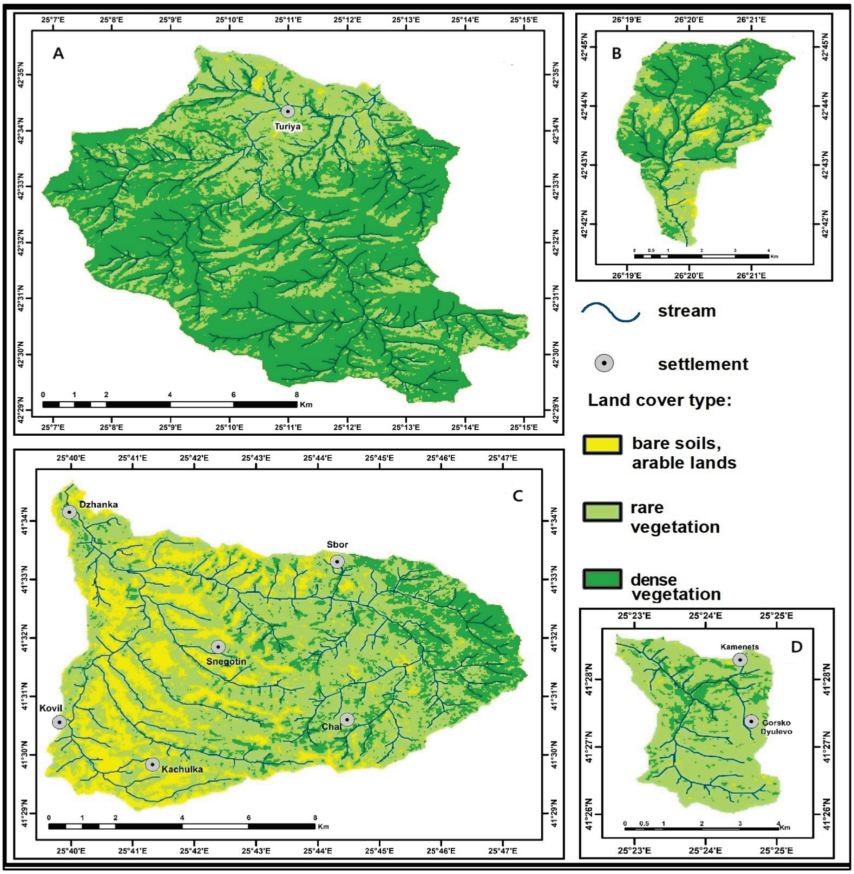

Figure 5. Land cover maps of the studied drainage basins.
Note. Panel A: Turiyska River. Panel B: Novoselska River. Panel C: Dyushundere River. Panel D: River 4.

4.5. Complex debris flow susceptibility analysis

Based on the complex analysis of the topographic, lithological factors, and the land cover, it was established that there are no registered areas with rate 1 of debris flow susceptibility on the territory of the investigated drainage basins. The drainage basin of the the Dyushundere River is characterized by the highest percentage of rate 7 of debris flow susceptibility and the drainage basins of the Turiyska River and the River 4—by the lowest. The percentage of rates 6 and 7 of debris flow susceptibility, however, is extremely low for the four studied drainage basins (Table 7).

The drainage basin of the Dyushundere River is characterized by the largest area and the highest percentage (more than one third) of rate 5 of debris flow susceptibility, which makes it the basin with the highest risk of formation and development of debris flows compared to the other drainage basins. The drainage basin of the Turiyska River is characterized by the highest percentage of the lowest registered rate of debris flow susceptibility (rate 2), and together with rate 3 the percentage of very low and low rates of debris flow susceptibility is more than 70%. This, in turn, determines the drainage basin of the Turiyska River with the lowest risk of formation and development of debris flows compared to the other drainage basins.

Table 7. Complex debris flow susceptibility rates and % of the drainage basin area

Debris flow susceptibility rate	Turiyska	Novoselska	Dyushundere	River 4
1	–	–	–	–
2	30.43	17.42	3.00	–
3	39.74	29.95	10.88	10.89
4	25.71	25.75	47.36	72.71
5	3.85	20.42	35.12	15.88
6	.25	5.41	3.61	.50
7	.02	1.05	.03	.02

The drainage basin of the Novoselska River is characterized by the relatively even distribution of areas with very low, low, moderate and high rates of debris flow susceptibility. A significant area of the River 4 drainage basin has a moderate rate of debris flow susceptibility (Table 7, Figure 6).

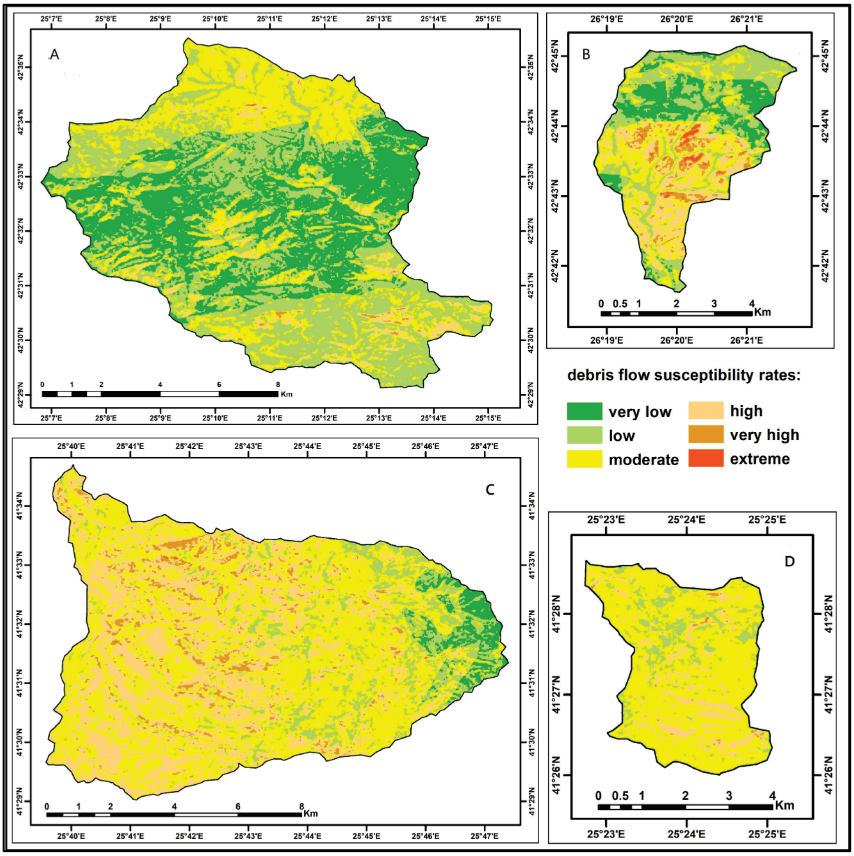

Figure 6. Debris flow susceptibility maps of the studied drainage basins.
Note. Panel A: Turiyska River. Panel B: Novoselska River. Panel C: Dyushundere River. Panel D: River 4.

5. Discussion and conclusion

The results of the morphometric analysis show that the larger area and length of the drainage basins predetermine lower values of the R_h and the Melton ratio (R), which in turn is a factor for low debris flow susceptibility rates. Based on the Hypsometric integral calculation, it became clear that all the four drainage basins are relatively moderately eroded. The drainage basin of the Turiyska River is characterized by the highest flood potentiality based on the Form factor. The same drainage basin is the most susceptible to development of debris flows based on the F_s, D_d and number of streams of 1st and 2nd order. All other studied drainage basins are also characterized by a relatively high erosion potential and high susceptibility to debris flows based on the D_d parameter.

The complex analysis of the topographic conditions (slope angle), lithology, and land cover (vegetation) within the studied drainage basins show that drainage basins characterized predominantly by rocks of volcanic igneous complex, and to a considerable extent, by bare soils and arable lands are more susceptible to debris flows. The percentage of rates 6 and 7 of debris flow susceptibility is extremely low for the four studied drainage basins, which is largely due to the smaller slope gradients. The drainage basin of the Dyushundere River is characterized by the largest area and the highest percentage (more than one third) of rate 5 of debris flow susceptibility, which makes it the basin with the highest risk of formation and development of debris flows compared to the other drainage basins. The drainage basin of the Turiyska River is characterized by the highest percentage of the lowest registered rate of debris flow susceptibility (rate 2), and together with rate 3 the percentage of very low and low rates of debris flow susceptibility is more than 70%. This, in turn, determines the drainage basin of the Turiyska River with the lowest risk of the formation and development of debris flows compared to the other drainage basins.

The remote sensing analysis of debris flow susceptibility is an initial step. For the overall study of the susceptibility for the formation and development of debris flows and about the results of the manifestation of this phenomenon, complex studies are required, including data on the tectonic, hydrological and climatic features of the investigated territory, as well as field research, including taking samples for sedimentological analysis. The main challenges facing this type of research are access to the necessary data and equipment, as well as data quality. For example, for better detail and precision of the study, it is necessary to perform atmospheric corrections to the satellite images used. At the same time, remote sensing methods for studying debris flow susceptibility are an important and necessary tool in the process of preventing this risk phenomenon. The practical application of the results obtained should be part of territorial management at national, regional, and local level in order to reduce the consequences of the formation and development of debris flows.

References

Baltakova, A., Nikolova, V., Kenderova, R., & Hristova, N. (2018, October 1–5). *Analysis of debris flows by application of GIS and remote sensing: case study of western foothills of Pirin Mountains.* 5th International Conference "Debris Flows: Disaster, Risk, Forecast, Protection". Tbilisi, Georgia. https://shorturl.at/vXYMx

Barlow, J., Franklin, S., & Martin, Y. (2006). High Spatial Resolution Satellite Imagery, DEM Derivatives, and Image Segmentation for the Detection of Mass Wasting Processes. *Photogrammetric Engineering & Remote Sensing*, *72*(6), 687–692. https://doi.org/10.14358/PERS.72.6.687

Berti, M., Genevois, R., Simoni, A., & Tecca, P. R. (1999). Field observations of a debris flow event in the Dolomites. *Geomorphology, 29*(3–4), 265–274. https://doi.org/10.1016/S0169-555X(99)00018-5

Bishop, M. P., Shroder, Jr. J. F., Bonk, R., & Olsenholler, J. (2002). Geomorphic change in high mountains: a western Himalayan perspective. *Global and Planetary Change*, *32*(4), 311–329. https://doi.org/10.1016/S0921-8181(02)00073-5

Blair, T. C., & McPherson, J. G. (2009). Processes and Forms of Alluvial Fans. In A. J. Parsons & A. D. Abrahams (Eds.), *Geomorphology of Desert Environments* (2nd ed., pp. 413–467). Springer. https://doi.org/10.1007/978-1-4020-5719-9_14

Blais-Stevens, A., Lipovsky, P., Kremer, M., Couture, R., & Page, A. (2013). Landslide Inventory and Susceptibility Mapping for a Proposed Pipeline Route, Yukon Alaska Highway Corridor, Canada. In C. Margottini, P. Canuti, & K. Sassa (Eds), *Landslide Science and Practice* (pp. 215–221). Springer. https://doi.org/10.1007/978-3-642-31319-6_30

Campbell, R. H. (1975). *Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California* (Geological Survey professional paper 851). United States Government Printing Office. https://pubs.usgs.gov/pp/0851/report.pdf

Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, Department of Atmospheric and Oceanic Sciences of the University of Wisconsin-Madison, USA. (n.d.). *Vegetation Index – NDVI*. University of Wisconsin-Madison. Retrieved November 05 2024 from https://profhorn.aos.wisc.edu/wxwise/satmet/lesson3/ndvi.html

Esper Angillieri, M. Y. (2020). Debris flow susceptibility mapping using frequency ratio and seed cells, in a portion of a mountain international route, Dry Central Andes of Argentina. *Catena*, *189*, Article 104504. https://doi.org/10.1016/j.catena.2020.104504

Gerdzhikov, I., Vangelov, D., & Glabadanidu, I. (2012). Edin podcenen geoložki risk: debritnite potoci [One underestimated geological hazard: the debris flows]. *Review of the Bulgarian Geological Society*, *73*(1–3), 85–104. https://bgd.bg/REVIEW_BGS/REVIEW_BGD_2012/PDF/05_Gerdjikov_BGS_Rev_2012.pdf

Gregoretti, C., Degetto, M., Bernard, M., & Boreggio, M. (2018). The Debris Flow Occurred at Ru Secco Creek, Venetian Dolomites, on 4 August 2015: Analysis of the Phenomenon, Its Characteristics and Reproduction by Models. *Frontiers in Earth Science*, *6*, Article 80. https://doi.org/10.3389/feart.2018.00080

Grelle, G., Rossi, A., Revellino, P., Guerriero, L., Guadagno, F. M., & Sappa, G. (2019). Assessment of Debris-Flow Erosion and Deposit Areas by Morphometric Analysis and a GIS-Based Simplified Procedure: A Case Study of Paupisi in the Southern Apennines. *Sustainability*, *11*(8), Article 2382. https://doi.org/10.3390/su11082382

Horton, R. E. (1932). Drainage basin characteristics. *Eos, Transactions American Geophysical Union*, *13*(1), 350–361. https://doi.org/10.1029/TR013i001p00350

Horton, R. E. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *GSA Bulletin*, *56*(3), 275–370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Jackson, L. E., Kostaschuk, R. A., & MacDonald, G. M. (1987). Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. In J. E. Costa & G. F. Wieczorek (Eds.), *Debris Flows/Avalanches: Process, Recognition and Mitigation* (pp. 115–124). Geological Society of America. https://doi.org/10.1130/REG7-p115

Kanchev, I. (1995). Geoložka karta na Bulgaria, M 1:100 000, karten list Sliven [Geological map of Bulgaria, Scale 1:100 000, Map sheet Sliven]. Committee for Geology and Mineral Resources, Bulgaria.

Kozhuharov, D., Boyanov, I., Goranov, A., & Kozhuharova, E. (1992). Geoložka karta na Bulgaria, M 1:100 000, karten list Krumovgrad i Sape [Geological map of Bulgaria, Scale 1:100 000, Map sheet Krumovgrad and Sape]. Committee for Geology, Bulgaria.

Kozhuharov, D., Boyanov, I., Goranov, A., Yanev, Y., Shilyafova, Z., & Ruseva, M. (1989). Geoložka karta na Bulgaria, M 1:100 000, karten list Kardzhali [Geological map of Bulgaria, Scale 1:100 000, Map sheet Kardzhali]. Committee for Geology, Bulgaria.

Krenchev, D., & Kenderova, R. (2019). Morphometric analysis of debris-flow catchments in Middle Struma Valley (Zheleznitsa Gorge, Bulgaria). *Review of the Bulgarian Geological Society*, *80*(3), 233–235. https://bgd.bg/REVIEW_BGS/REVIEW_BGD_2019_3/PDF/71_Krenchev_GeoSci_2019.pdf

Landsat Missions. (2024). *Landsat Normalized Difference Vegetation Index*. United States Geological Survey. https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index

Lorente, A., Begueria, S., Bathurst, J. C., & Garcia-Ruiz, J. M. (2003). Debris flow characteristics and relationships in the Central Spanish Pyrenees. *Natural Hazards and Earth System Sciences*, *3*(6), 683–691. https://doi.org/10.5194/nhess-3-683-2003

Melton, M. A. (1965). The Geomorphic and Paleoclimatic Significance of Alluvial Deposits in Southern Arizona. *The Journal of Geology, 73(1)*, 1–38. https://doi.org/10.1086/627044

Nikolova, V., Kamburov, A., & Rizova, R. (2021). Morphometric analysis of debris flows basins in the Eastern Rhodopes (Bulgaria) using geospatial technologies. *Natural Hazards, 105*(1), 159–175. https://doi.org/10.1007/s11069-020-04301-4

Nikolova, V., Sachkov, D., & Rizova, R. (2022). Morphometric indicators for erosion and debris flows propagation: a case study of the river Byuyukdere watershed, northwest of Kardzhali town (Bulgaria). *Review of the Bulgarian Geological Society, 83*(3), 303–306. https://bgd.bg/REVIEW_BGS/REVIEW_BGD_2022_3/PDF/71_Nikolova-V_Rev_BGS_2022-3.pdf

Ogarekpe, N. M., Obio, E. A., Tenebe, I. T., Emenike, P. C., & Nnaji, C. C. (2020). Flood vulnerability assessment of the upper Cross River basin using morphometric analysis. *Geomatics, Natural Hazards and Risk, 11*(1), 1378–1403. https://doi.org/10.1080/19475705.2020.1785954

Pedrera, A., Pérez-Peña, J. V., Galindo-Zaldívar, J., Azañón, J. M., & Azor, A. (2009). Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain). *Geomorphology*, *105*(3–4), 218–231. https://doi.org/10.1016/j.geomorph.2008.09.026

Qin, S., Lv, J., Cao, C., Ma, Z., Hu, X., Liu, F., Qiao, S., & Dou, Q. (2019). Mapping debris flow susceptibility based on watershed unit and grid cell unit: a comparison study. *Geomatics, Natural Hazards and Risk, 10*(1), 1648–1666. https://doi.org/10.1080/19475705.2019.1604572

Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *GSA Bulletin, 67*(5), 597–464. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Stoycheva, V., & Krenchev, D. (2021). Morphometric analysis of debris flow basin of Harsovska river (Southwest Rila, Bulgaria). *Review of the Bulgarian Geological Society, 82*(3), 247–249; https://doi.org/10.52215/rev.bgs.2021.82.3.247

Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union*, *38*(6), 913–920. https://doi.org/10.1029/TR038i006p00913

Takahashi, T. (2014). *Debris Flow. Mechanics, Prediction and Countermeasures* (2nd ed.). CRC Press.

Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel networks from digital elevation data. *Hydrological Processes*, *5*(1), 81–100. https://doi.org/10.1002/hyp.3360050107

Tsankov, T., Filipov, L., & Katskov, N. (1995). Geoložka karta na Bulgaria, M 1:100 000, karten list Kazanlak [Geological map of Bulgaria, Scale 1:100 000, Map sheet Kazanlak]. Committee for Geology and Mineral Resources, Bulgaria.

United States Geological Survey, Earth Resources Observation and Science Center. (2018). *Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data* [Data set]. https://doi.org/10.5066/F7PR7TFT

United States Geological Survey, Earth Resources Observation and Science Center. (2024). *Landsat 8 and 9 OLI/TIRS Collection 2* [Data set]. https://doi.org/10.5066/P9OGBGM6

Weier, J., & Herring, D. (2000, August 30). *Measuring Vegetation (NDVI & EVI)*. NASA Earth Observatory. https://earthobservatory.nasa.gov/features/MeasuringVegetation

Welsh, A., & Davies, T. (2011). Identification of alluvial fans susceptible to debris-flow hazards. *Landslides, 8*(2), 183–194. https://doi.org/10.1007/s10346-010-0238-4

Wilford, D. J., Sakal, M. E., Innes, J. L., Sidle, R. C., & Bergerud, W. A. (2004). Recognition of debris-flow, debris-flood and flood hazard through watershed morphometrics. *Landslides, 1*(1), 61–66. https://doi.org/10.1007/s10346-003-0002-0

Zavoianu, I. (1985). *Morphometry of Drainage Basins*. Editura Academiei & Elsevier Science Publishers.