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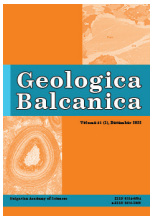

Landslide risk for the territory of Bulgaria by administrative districts

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Abstract. An assessment of the landslide risk (R_{ls}) for the territory of Bulgaria by administrative districts has been made by combining the vulnerability (V) and landslide hazard (H_{ls}) maps. Landslides are a significant part of geological hazards and are widespread throughout the country. In order to assess the landslide risk for the territory of Bulgaria, it is necessary to take into account not only all landslides for a given region, but also its vulnerability, and thus to assess the level of landslide risk for this region, $R_{ls} = f(V, H_{ls})$. Landslide risk is determined by a risk matrix, using selected indicators and weighting coefficient of vulnerability and landslide hazard. Assessing the vulnerability of a region subjected to geological hazards is a key component of risk assessment. These include the exposure of infrastructure, industrial facilities and production capacity, residential buildings, regional GDP per capita and potential for human disability (defined by population density in the district). The data used is combined to create a map showing the vulnerability of each administrative district. Indicators of population density, GDP, length of road and railway networks and number of residential buildings were used to assess the vulnerability. The landslide hazard in each administrative district is determined by the intensity of landslide processes in the district, depending on the level of their activity and the affected area. The normalized (distributed) hazard of landslides for an administrative region is given depending on the area of the given administrative region. Landslides are categorized as active, potential and stabilized. The results express the weighted average hazard. Landslide hazard is rated from 1 to 5, where 1 means no landslide hazard and 5 means that landslide hazard has a very high intensity (very high hazard). The high degree of landslide hazard in turn leads to possible economic losses, social and environmental consequences (landslide risk). The intensity (level) of landslide vulnerability, hazard and risk is assessed as very low, low, medium, high and very high, and is shown on the relevant maps.

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Keywords: landslide risk, vulnerability, landslide hazard, geological hazards, Bulgaria.

INTRODUCTION

The territory of Bulgaria is affected by almost all unfavorable and destructive geological processes and phenomena, which are united under the name of geological hazards: tectonic movements, abrasion, erosion, landslides, collapse, subsidence, swelling, liquefaction of dispersed deposits and others (see Iliev-Broutchev *et al*., 1994; Ivanov *et al*., 2017a, b; Nikolova and Zlateva, 2019). Landslides are one of the main elements of geological hazards in Bulgaria. They are widespread on the country's territory. Their effect causes human casualties, buildings', facilities' and historical monuments' destruction, decay of environmental conditions, reduced soil fertility, all of them causing adverse environmental changes. The area, periodicity, frequency and severity of their effects on humans, material cul-

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ture and the environment vary widely. Landslide risk for the territory of Bulgaria takes into account the landslide hazard for a given region and the vulnerability, expressed via $R_{ls} = f(V, H_{ls})$ or Risk = Hazard×Vulnerability.

Hazard maps represent the intensity and frequency of the landslide hazard for a given area (district), without containing information about its vulnerability. The mapping of landslide hazard passes through a few stages. The first one is connected with the spread of landslides expressed by a landslide inventory map; the possibility of activation or occurrence of a landslide in a given area by a landslide susceptibility map; and the probability of landslide events occurring over time (periodicity, frequency of events) by a landslide hazard map.

Vulnerability represents the conditions determined by physical, social, economic and environmental factors and processes that increase the sensitivity of an individual, a community, assets or systems to the impact of hazards (UNISDR – United Nations Office for Disaster Risk Reduction, http://www.unisdr.org/we/inform/terminology). Vulnerability has the following aspects: economic, social, environmental, physical and demographic. It is determined by the potential of a community to react and withstand a disaster, *e.g.*, its emergency facilities, disaster organization structure, education rate, early warning system, etc. (coping capacity).

Landslide risk maps represent the landslide potential, together with the expected loss of life and property in the event of a landslide. Risk maps combine the information about the probability of the landslide hazard map with an analysis of all possible consequences such as damage to property, victims, infrastructure, loss of services, etc.

METHODS

Landslide risk assessment goes through two stages: vulnerability assessment and hazard assessment. It is based on the following dependence:

$$R = f(V, H),$$

where R – Risk; V – Vulnerability; H – Hazard. The risk levels are determined by a risk matrix.

Vulnerability analysis by administrative areas (districts)

Vulnerability can be a challenging concept to understand because it tends to mean different things to different people and because it is often described using a variety of terms including “predisposition”, “fragility”, “weakness”, “deficiency” or “lack of capacity” (https://www.preventionweb.net/understanding-disaster-risk/component-risk/vulnerability).

The indicators used to measure vulnerability measure something specific that can be damaged by geological hazards and cover both the potential damage and the capacity to deal with it within the socioeconomic, physical and environmental dimensions (http://gis.mrrb.government.bg/KGR/; see also Ivanov and Berov, 2017; Svalova *et al*., 2020; Frantsova, 2021; Frantzova, 2021a, b). Therefore, assessing the vulnerability is an essential component of risk assessment. Vulnerability is complex and includes many factors such as exposure to infrastructure, industrial facilities and production capacity, residential buildings, regional GDP per capita and the potential for human disability (defined by population density in the area) for a given area. Data related to the existing and potential hazards, as well as the coping capacity, are combined to create a vulnerability map for a given district.

Coping capacity is the ability of people, organizations and systems to manage adverse consequences in case of a disaster or emergency. Coping capacity contributes to the reduction of disaster risks and affects the effective human response in case of a disaster. For our aims and goals, the capacity to cope is expressed in terms of national GDP.

Vulnerability components are divided into five classes, which allow the integration of economic and social vulnerability into one integrated vulnerability index. The sum of the components of vulnerability presents the integrated index of vulnerability for a given area. The statistical data for Bulgaria and its administrative regions are taken from the National Statistical Institute (http://www.nsi.bg/).

Landslide hazard by administrative areas (districts)

The geological hazard in Bulgaria is dominated by the occurrence of landslides, which are widespread throughout the country. The distribution of landslide processes is uneven and depends on the geological, geomorphological, tectonic and other features of the terrain. Taking into account these factors, landslides are widespread in several key regions: the Black Sea coast, the High Danube River Bank, the Rhodope Mts., Cenozoic grabens in Southern Bulgaria and the Fore-Balkan area (Iliev-Broutchev *et al*., 1994; Berov *et al*., 2002, 2020; Konstantinov *et al*., 2003; Bruchev *et al*., 2007; Dobrev *et al*., 2013, 2014;

Ivanov *et al*., 2017a, b; Bruchev, 2018; Ivanov *et al*., 2020a, b).

The landslides that have occurred in recent years along the Black Sea coast and the Danube coast bank, the Rhodope Mts. and other parts of the country, and their severe consequences rightfully cause alarm and concern among the entire population of the country. In addition to economic losses, human casualties are also caused (Haque *et al*., 2016).

Official research on landslide processes shows that a total of 2178 landslides (data from 2020) in settlements, resort complexes, villa areas and roads were registered on the territory of the Republic of Bulgaria, according to data from the Ministry of Regional Development and Public Works. Of these, 830 landslides are still active, 895 are potential (dormant) and the other 453 are stabilized. For each administrative region, their area is determined and the landslide intensity (level) is calculated.

The districts bordering the right bank of the Danube River (Vidin, Montana, Vratsa, Pleven, and Veliko Tarnovo) are mostly affected by landslide phenomena. From a geological and tectonic point of view, the Danube Plain belongs to the structure of the Moesian Platform. Of particular importance for the stability of the High Danube River Bank are the lithological varieties that are exposed on the surface and include sandy, clayey and mixed sandy-clayey layers, which are covered by varieties of loess deposits. The geological structure of this area is built by mainly Neogene and Quaternary clayey sediments resting on erosion-resistant rocky and semi-rocky chalk sediments, which is a prerequisite for the formation of significant large and deep-seated landslides. Intense river erosion, groundwater and human activity cause their periodic activation.

Landslides along the northern Black Sea coast (Varna and Dobrich districts) have a significant spread. Due to the specific geological construction and different neotectonic movements, some of the largest landslide complexes in depth and volume have arisen. The area where the landslides developed is made up of Miocene sediments represented by sands and clays, aragonite sediments, sandstones and limestones. The formation of deep-seated landslides in this area is mainly a result of marine abrasion. The high seismicity of this area is also important. Recent landslides trigger in the bodies of large and deep-seated landslides as a result of the impact of natural and manmade factors. Usually, these landslides are shallow in depth but cause significant losses of properties and economic activities. The percentage of active landslides is highest in Varna District. The number of stabilized and potential deep landslides along the Black Sea coast of Bulgaria is also high.

The southern Black Sea coast (Burgas District) encompasses the structures of the Burgas "synclinorium", strongly dominated by an Upper Cretaceous volcanogenic-sedimentary complex cut in places by young intrusives with imposed "Tertiary" depressions and small patches of Middle and Upper Miocene sediments. In this geological situation, more suitable conditions for landslides exist along the coast in the northern part of Burgas District (Nesebar and Sarafovo). To the south of Burgas, the landslides in this area are shallow. They are developed along the coastal escarpment. An exception is the landslide near the town of Chernomorets, which has a volume of about 2 million m^3. Main destabilizing factors here are sea abrasion and fluctuations in groundwater level.

The districts covering parts of the central Fore-Balkan Unit of the Balkan tectonic zone (Lovech, Gabrovo, Targovishte, Shumen, the northern parts of Montana, Vratsa, Veliko Tarnovo districts) are affected by a large number of relatively shallow and significantly smaller in size landslides than the landslides located along the Danube River and the northern Black Sea coast. Marls and siltstones from the Lower Cretaceous, as well as flysch deposits of Paleogene age, are important for the occurrence of landslides. Moistened marls and clayey rocks, with appropriate inclination of the strata and undercutting of the slopes, create conditions for the occurrence of landslides in a number of places in these areas. They are primarily caused by river erosion, rising groundwater levels and anthropogenic activity.

Landslides are widespread in Sofia City, Sofia and Pernik districts. They are distributed mainly along the peripheral frame of the grabens of the same name (Sofia Graben and Pernik Graben). Paleogene, Neogene and Quaternary sediments are affected by landslide processes. The number of stabilized landslides in these districts is significant and is one of the highest in the country.

In the Rhodope Mts. (Smolyan and Kardzhali districts), there are the largest landslides in the country: Peshtera, Smolyan, Broken Mountain, near the village of General Geshevo. Their dimensions are up to several kilometers, and their volumes often reach hundreds of millions of cubic meters. Numerous small but dangerous landslides affect settlements and roads and cause extensive damages. Precipitation and groundwater fluctuations are a major factor, mainly characteristic of shallower landslides in the area (Frangov *et al*., 2017). Major

factors in deeper landslides are slow tectonic movements, tectonic movements along fault structures, seismic effects, and deep erosion (*e.g.*, Dobrev *et al.*, 2005). Different types of rocks are affected by the landslide processes: metamorphic (gneisses, amphibolites, marbles, schists); effusive (mainly rhyolites, trachytes, andesites and various types of tuffs and tuff-breccia), and sedimentary (conglomerates, sandstones, tuffites, limestones and others).

A landslide susceptibility map of Bulgaria is used for assessing landslide hazard (Berov *et al.*, 2002, 2016, 2020; Dobrev *et al.*, 2013; Ivanov *et al.*, 2017b, 2020a, b). The level of hazard (intensity) for each region (district) is defined according to the landslide activity level, landslides area (size) and classified as active, potential and abandoned/stabilized (according to UNESCO-WPWLI 1993). For complete assessment of landslide hazard, we use the following formula:

$$H_{LS} = A_{LS1} \times 1 + A_{LS2} \times 0.8 + A_{LS3} \times 0.5 \qquad (1)$$

where, A_{LS1} is the area in the administrative region (district) affected by active landslides; A_{LS2} is the area in the administrative region (district) affected by potential landslides; A_{LS3} is the area in the administrative region (district) affected by stabilized (abandoned) landslides.

Normalized (distributed) landslide hazard for an administrative region (H'_{LS}) is given by the formula:

$$H'_{LS} = H_{LS}/A \qquad (2)$$

where, A is the area of the given administrative region (district).

The landslide hazard (H'_{LS}) for the given administrative regions of Bulgaria is calculated via formula (2). Landslide hazard is rated from 1 to 5, where 1 means low landslide spread and activity and 5 means high landslide spread and high landslide activity (very high landslide hazard). The results are used to define the class of intensity (I) of the landslide hazard ratio, respectively as very low, low, medium, high and very high.

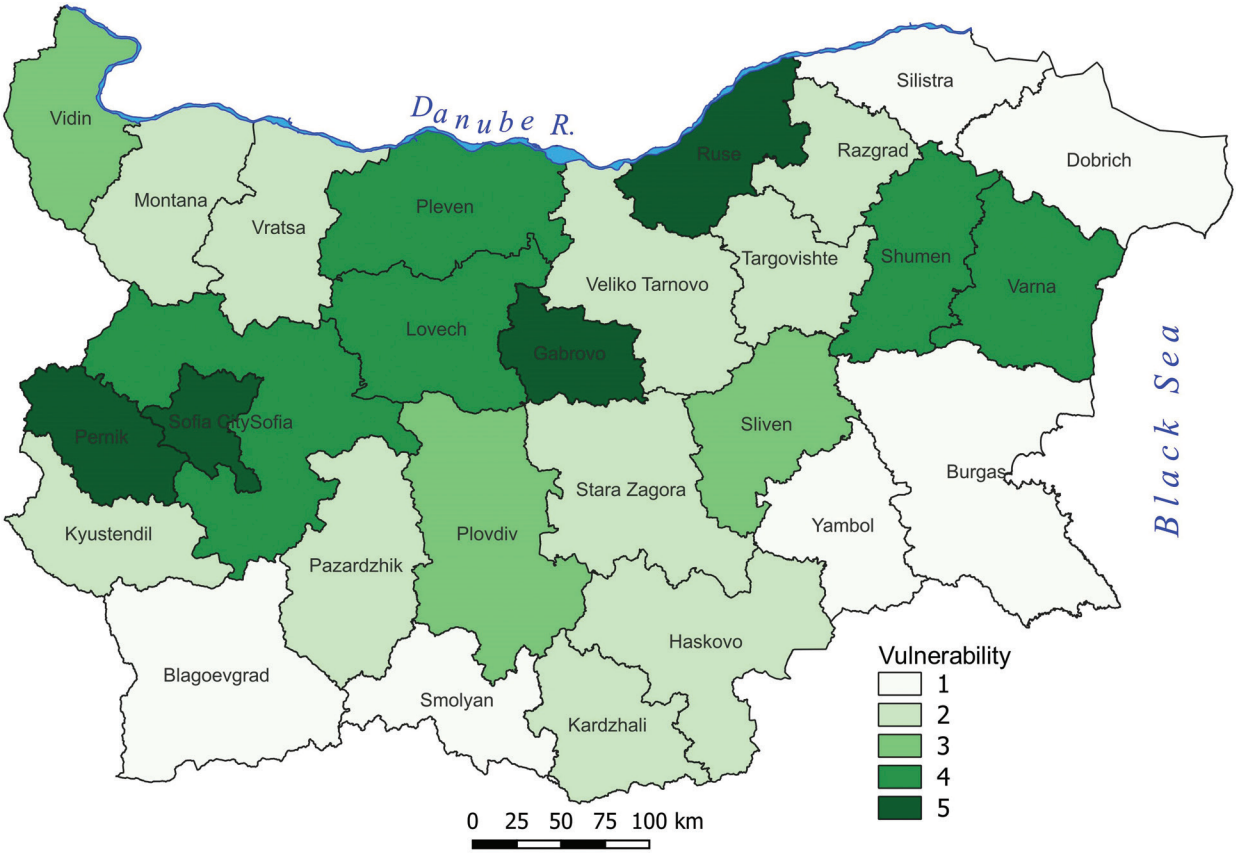

Fig. 1. Vulnerability map to hazardous geological processes by districts (Bulgaria).

RESULTS

Vulnerability map

Four indicators are used for vulnerability assessment. Each indicator used for vulnerability and risk analysis is attached to a weighting coefficient equal for all factors. It is assumed that various factors have equal weight and contribute in changing the magnitude for the assessment of the risk levels (Fig. 1, Table 1).

The districts of Sofia City, Pernik, Gabrovo and Ruse are characterized by very high vulnerability. The districts of Blagoevgrad, Burgas, Dobrich, Silistra, Smolyan and Yambol exhibit very low vulnerability.

Landslide hazard map

The map of the landslide hazard by administrative regions (districts) of Bulgaria with landslide hazard intensity for each of the districts is shown in Fig. 2.

The districts in northwestern Bulgaria along the High Danube Bank are characterized by a very high hazard of landslides: Vidin, Montana, Vratsa, Pleven, and Veliko Tarnovo. The district of Varna (northern Black Sea coast) is also at a very high risk of landslides. The districts with a very low landslide risk are Pazardzhik, Plovdiv, Stara Zagora, Sliven, Haskovo and Yambol.

Landslide risk map

The landslide risk for each administrative area is determined using the results of the vulnerability and landslide hazard assessments. The levels of risk are calculated via a risk matrix (Fig. 3) that compares the results obtained for vulnerability and landslide hazard. The obtained landslide risk map of Bulgaria by administrative regions (districts) is shown in Fig. 4.

The districts of Sofia City, Pleven and Varna are characterized by a very high landslide risk, where a large part of the area of the district is occupied by numerous manifested active and potential landslides, and the vulnerability is also high. There is a high landslide risk in the districts of Vidin, Montana, Vratsa, Veliko Tarnovo, Gabrovo, Ruse and Pernik. The district of Yambol, where there are no registered landslides, is defined as having the lowest landslide risk.

DISCUSSION

The definition of vulnerability, hazard and risk is relative and depends on what the level is in a given country or region. The obtained results refer to Bulgaria and show where (in which administrative regions) we can expect the most damage from landslide processes and where the least (landslide risk map). In the present study, the most important indicators for assessing vulnerability were taken, such as population density, Gross Domestic Product (GDP), length of road network, number of residential buildings. Vulnerability assessment indicators and their weight in the overall assessment may be different. Other metrics may be added. The landslide map is constantly being developed and supplemented. Some landslides move from one category to another.

The need for periodic updating of the assessment of natural destructive processes on the territory of the country, leading to disaster and catastrophic conditions in a number of areas, is motivated by their high activity in recent years.

As of December 31, 2021, a total of 2,207 landslides were registered in the country, of which 829, or 37.6%, were in an active state. Only in the last year, 30 new landslides were registered. The tendency is for their number to grow, while the share of manmade activated landslides also grows.

Solving the landslide, erosion and sea erosion problems in Bulgaria will be a long-term process

Table 1
Vulnerability levels for the selected indicator

Population density (inhabitants per km^2)	GDP BGN million/km^2	Road network km/ km^2	Residential buildings, number/km^2	Vulnerability level
<50	>1	<0.2	<15	**1**
50–75	0.75–1	0.20–0.225	15–20	**2**
75–100	0.5–0.75	0.225–0.25	20–25	**3**
100–150	0.25–0.5	0.25–0.275	25–50	**4**
>150	<0.25	>0.275	>50	**5**

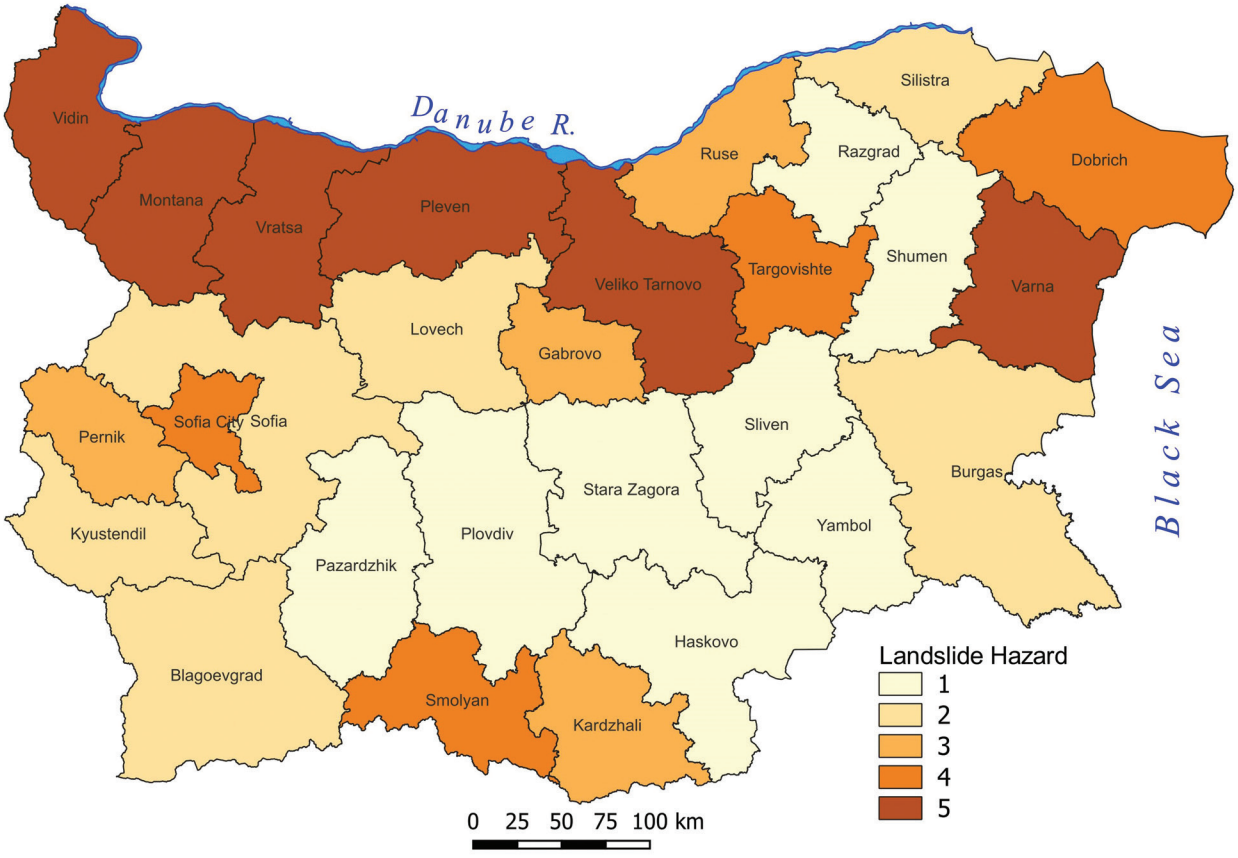

Fig. 2. Landslide hazard map of Bulgaria by districts.

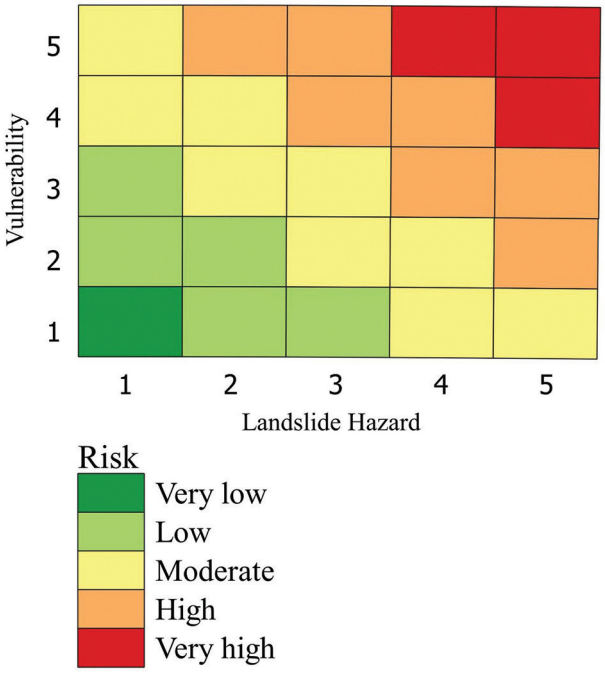

Fig. 3. Landslide risk matrix.

throughout the 21st century, due to the presence of a large number of landslides, erosion and sea erosion areas.

The practical use of such research is related to stakeholders and municipal and state institutions when making decisions about constructions of different purposes and sizes, such as road infrastructures, industrial zones or residential districts. In this way, it is easier to work with such important decisions of the Council of Ministers of the Republic of Bulgaria, the Ministry of Regional Development and Public Works, as well as all municipal authorities.

CONCLUSIONS

An assessment of the hazard and risk of landslides has been made for the territory of Bulgaria by administrative regions. To assess the vulnerability of a given administrative area to losses due to hazardous geological processes, the so-called indicators of vulnerability, which are defined by means of the social, economic and ecological characteristics of the

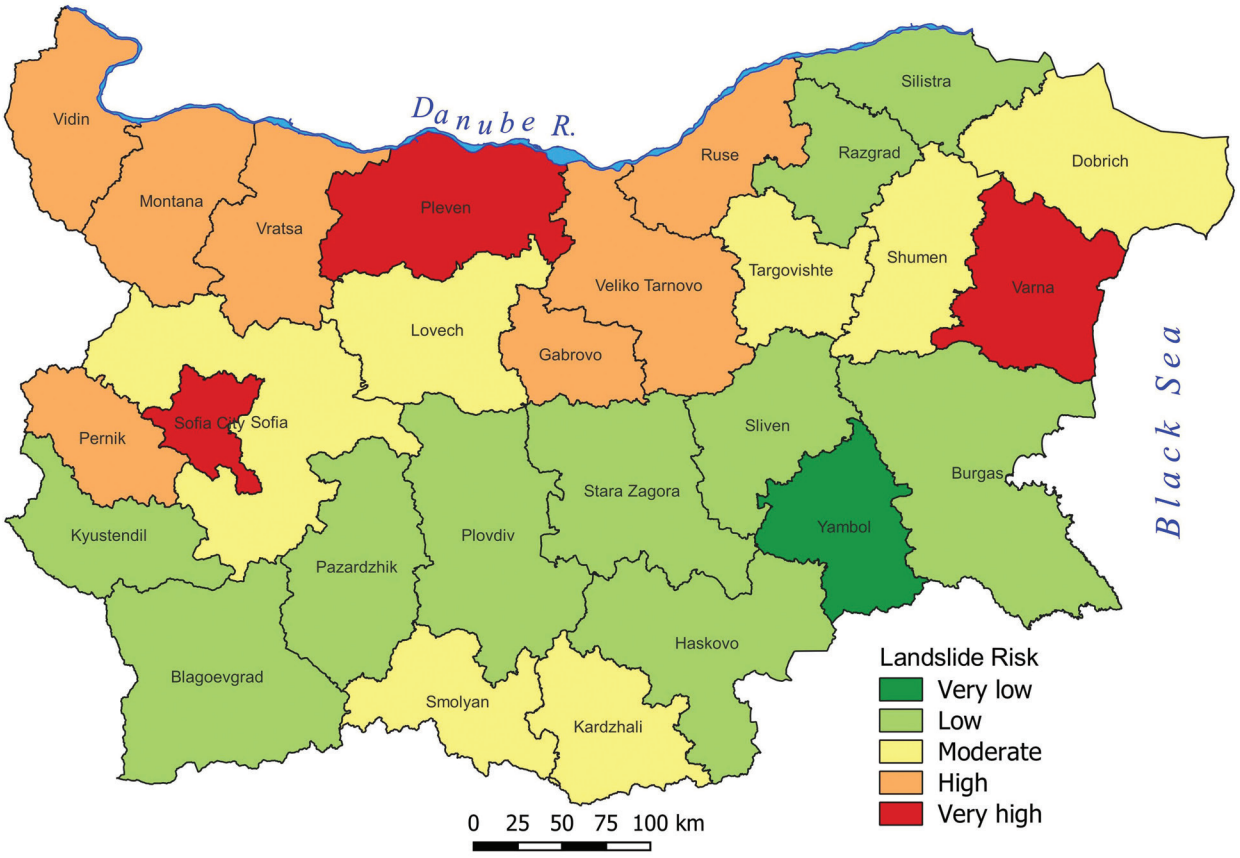

Fig. 4. Landslide risk map of Bulgaria by districts.

area, are used. Based on significance criteria, five degrees of vulnerability are determined: very low, low, medium, high and very high. To determine landslide hazard, data on the distribution of landslides in different areas of the country, the activity of landslide processes and their area were used. Five degrees (levels) of landslide hazard are defined: very low, low, medium, high and very high.

The landslide risk assessment was carried out based on the results of the vulnerability assessment and the hazard assessment. To determine the landslide risk for the territory of Bulgaria by regions, a selected risk matrix was used, and the level was also assessed in 5 degrees: very low, low, medium, high and very high. The districts of Sofia City, Pleven and Varna have the highest landslide risk, and Yambol District has the lowest risk. Of the remaining districts, ten are at low risk, seven are at medium risk, and seven are at high risk.

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