S E S   2 0 2 3
Nineteenth International Scientific Conference
SPACE, ECOLOGY, SAFETY
24 – 26 October 2023, Sofia, Bulgaria

WATER-RELATED NATURAL HAZARD ASSESSMENT: A GIS-BASED METHODOLOGY FOR THE RHODOPE MOUNTAIN RANGE IN BULGARIA

Ekaterina Ivanova

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: ivanovae@space.bas.bg

Keywords: *Floods, landslide susceptibility, drought hazard, soil erosion, Rhodope Mountain*

Abstract: *According to the United Nations Environment Programme over 90 percent of "natural" disasters are water-related. Their importance has been steadily growing in recent years due to climate change, which is affecting the hydrological cycle and increasing their frequency and intensity. Using the powerful toolset of GIS, the present study analyzes in a spatial context some of the most significant water-related natural hazards, affecting the Rhodope Mountains region, namely drought, floods, soil erosion and landslides. Drought leads to the degradation of river ecosystems, which are highly dependent on the water availability, and this in turn increases erosion and soil loss. On the other hand, floods and landslides cause devastation and death and result in severe damage to societies, economies and the environment. The study is based on long-term hazard inventory data in the Rhodope Mountain Range, provided by official institutions, regarding past hazardous events such as floods (10 years of measurements, between 2010 and 2020), landslides (5 years of measurements, between 2015 and 2020) and flow-discharge (59 years of measurements, between 1936 and 1995). The purpose of the study is to analyze their temporal and spatial behavior and to divide the territory into risk zones with the possibility of predicting their future occurrence. From the assessment of flood and landslide sites, it is clear that the area is characterized by a high level of risk of occurrence of water-related disasters. This situation calls for intervention from government bodies so that to prepare proper disaster management plans to help mitigate the problem.*

ОЦЕНКА НА ПРИРОДНИТЕ ОПАСНОСТИ, СВЪРЗАНИ С ВОДИТЕ: ГИС-БАЗИРАНА МЕТОДОЛОГИЯ ЗА РОДОПСКАТА ПЛАНИНСКА ВЕРИГА В БЪЛГАРИЯ

Екатерина Иванова

Институт за космически изследвания и технологии – Българска академия на науките
e-mail: ivanovae@space.bas.bg

Ключови думи: *Наводнения, податливост на свлачища, опасност от суша, почвена ерозия, Родопи планина*

Резюме: *Според Програмата на ООН за околната среда над 90 процента от „природните“ бедствия са свързани с водата. Тяхното значение непрекъснато нараства през последните години поради изменението на климата, което влияе върху хидроложкия цикъл и увеличава тяхната честота и интензивност. Използвайки мощния инструментариум на ГИС, настоящото изследване анализира в пространствен контекст някои от най-значимите природни опасности в Родопския планински регион, свързани с водата, а именно засушаването, наводненията, почвената ерозия и свлачищата. Засушаването води до деградация на речните екосистеми, които са силно зависими от наличието на вода, а това от своя страна увеличава ерозията и загубата на почвени ресурси. От друга страна, наводненията и свлачищата причиняват опустошения и смърт и водят до тежки щети на обществата, икономиките и околната среда. Проучването се основава на дългосрочни данни от инвентаризация на опасностите в Родопите, предоставени от официални институции, по отношение на минали опасни събития като наводнения (10 години измервания, между 2010 г. и 2020 г.), свлачища (5 години измервания, между 2015 г. и 2020 г.) и речен отток (59 години измервания, между 1936 и 1995 г.).Целта на изследването е да се анализира тяхното времево и пространствено поведение и да се раздели територията на рискови зони с възможност за прогнозиране на бъдещата им поява. От оценката на местата на наводнения и свлачища става ясно, че районът се*

характеризира с висока степен на риск от възникване на водни бедствия. Тази ситуация изисква намеса от държавни органи и институции, така че да се изготвят подходящи планове за управление на бедствия, за да се помогне за смекчаване на проблема.

Introduction

Water-related natural hazards, so called hydro-meteorological hazards, are a subcategory of natural hazards originating from atmospheric, hydrological or oceanographic processes, which cause severe socio-economic disruptions and damages [1]. The increase in frequency and intensity of them across Europe has been accurately documented and recognized, especially the trends in flood risk [2, 3]. Water-related disasters (floods, storms, landslides, and droughts) occurred globally in the past 20 years account for 73.9% of all natural disasters, while nearly 60% of them are caused by floods and drought [4]. In general, mountainous areas are more sensitive to various natural hazards and threats will be more pronounced in them compared to other areas. In this context, the assessment of multiple hazards, taking into account their possible regional variations in the intensity and frequency of extreme weather conditions, is essential to identify areas potentially more exposed to climate change [2].

The Rhodope Mountain Range represent a significant part of the Bulgarian's mountain ecosystems, which play a key role in the national water supply system. On the other hand, the region is vulnerable to water-related natural disasters due to its structural instability, geographical location and topography. The disaster events has risen in the recent years resulting in numerous socio-economic losses and climate change has increasing their frequency and severity. Although various research work and data collections are being executed by national organizations, national plane for their mitigation still not exist.

The Rhodope Mountain Range is located in Southeastern Europe, which suggests that the region suffers extreme disasters events of a different and contradictory nature. On the one hand, the area is prone to streamflow droughts, which is becoming more severe and persistent in Southern Europe resulting from the increased evaporative demands with higher temperatures, while Eastern and Central Europe, opposite, is facing floods and soil erosion due to earlier spring snowmelt and heavy and high-intensity short duration convective storms [2, 5].

Risk assessments imply the combination of hazard, vulnerability and exposure (e.g., population, assets) [3]. This work is aimed at assessing the hazard component of the risk, based on historical data about past events about floods, landslides and water discharge data. The main objective is to analyze their temporal and spatial behavior and to identify areas potentially vulnerable to occurrence of water disaster events, in order to facilitate future research and decision-making for water management.

Study area

The study area includes the Rhodope Mountain Range of the Bulgarian territory, extending on an approximately 15 700 km^2 between longitudes 23º40'E and 26º40'E and between latitudes 40º50'N and 41º14'N (Fig. 1).

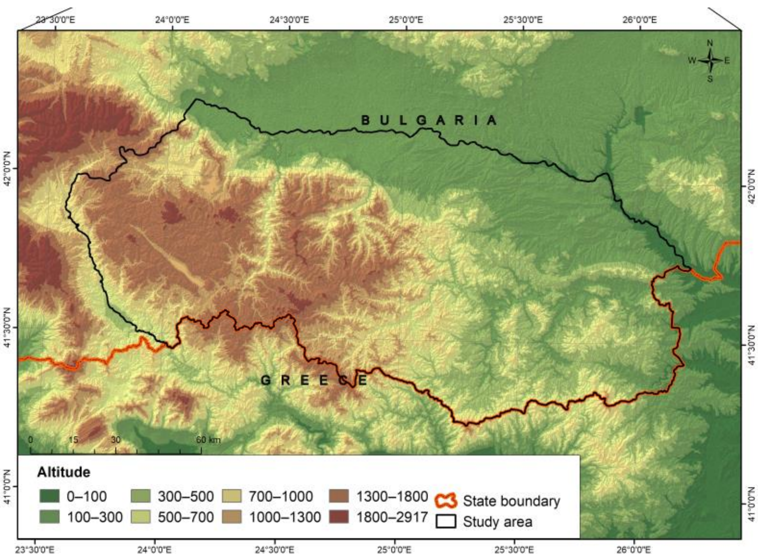

Fig. 1. Study area

The local climate of the region is determined by Mediterranean influence from the south and continental influence from the north. The average annual temperature varies from 5 to 10–13 ºC, whilst the average annual precipitation ranges between 600 and 1,100 mm [7]. The relief differs from 40 to 2,190 m above sea level with an average elevation of 745 m. The highest mountain is Golyam Perelik (2,191 m). The region also has the highest species diversity in the Balkans and includes 17 Natura 2000 protected sites [8, 9]. The region is characterized by a dense and complex river network and climatic and topographic variations determine the contrasts in the flow regime.

Data and methods

The study is based on long-term hazard inventory data in the Rhodope Mountain Range, provided by official institutions, regarding past hazardous events such as floods (10 years of measurements, between 2010 and 2020), landslides (5 years of measurements, between 2015 and 2020) and flow-discharge (59 years of measurements, between 1936 and 1995). A spatial database was created to assess water-related hazards in the Rhodope Mountain Range which also include digital elevation model (DEM) and the shapefiles of streams, gauging stations, roads and settlements, derived from 1:50,000 scaled topographic maps. One of the most devastating natural disasters that occur frequently in the Rhodope Mountain region is flood. Flood inventory database for past events, provided by East Aegean River Basin Directorate in Bulgaria, was utilized for flood hazard assessment. The data comprise information on 622 floods occurred in 207 locations in the investigated area over 10 years of observation, between 2010 and 2020. The average frequency of an event is 3 times. The minimum frequency is 1, while the maximum is 22. The database also contains information on their impact on society, infrastructure, human health, the economy and the environment. Flood frequency was applied in this study to calculate the probability (in percentages) of a future disaster occurrence. Geostatistical kriging and IDW interpolations were then enforced in order to identify flood hazard areas. For the landslide hazard assessment this study adopts the meaning of "landslide hazard" as a synonym of "landslide susceptibility", i.e. probability of landslide occurrence in a given area for a certain time interval. Analytic Hierarchy Process (AHP) [10] was applied to identify landslide hazard areas, which is based on Multi-criteria Decision Analysis (MCDA) and calculating the weights of the landslide causal factors. The method stands on a subjective assessments of the relative importance of a range of factors (criteria) in a network of digital values (weights). ASTER-GDEM v.003 was used to derive independent variables of the important landslide causal factors, which is freely shared by the Distributed Active Archive of Earth Processes of the NASA Center (https://lpdaac.usgs.gov/). The spatial database for landslide hazard assessment included slope, stream power index (SPI), topographic wetness index (TWI), distance from rivers, distance from roads and land use/cover (LULC) data. To determine water availability, long term flow inventory data was employed in this study, including monthly minimum, maximum and mean discharge records [11]. Low-flow index Q90 (daily flows exceeding 90% of the time), calculated in a previous study, was used for defining minimum flow indispensable for riverine ecosystems [12]. The values for Q90 were extracted from the flow duration curves and expressed in percentage of the mean annual flow (MAF). Then obtained values were interpolated, using the kriging geostatistical method and IDW method, in order to define drought hazard areas. Other hazardous event occurring in the Rhodope Mountain Range is soil erosion. Regarding soil erosion assessment, this paper used Global Soil Erosion Map, provided by the ESDAC of the JRC of the European Commission [13, 14], which had been re-scaled to a regional level. The measurement unit of the map is t/ha/yr.

Water-related natural hazard assessment

The flood assessment shows that during the last 10 years a significant part of the Rhodope Mountain region (approximately 20% of the territory) is exposed to a high and very high risk of adverse events in the future, mainly in the eastern and southeastern parts of the region (Fig. 2). In terms of public significance and human health, 3% of events are of medium (2.4%) and high (0.6%) impact. While, in terms of infrastructure and real estate, high and medium impact events exceed 30%. The economic impact of floods in the region, assessed with a medium and high degree of risk, is about 8% of the events. Floods with adverse environmental consequences of medium and high risk are between 7 and 8 percent. The total economic value of the damage amounts to about BGN 2 million. Seven factors with the strongest influence on landslide occurrence were selected for landslide susceptibility assessment of the Rhodope Mountain Range. These are average slope gradient, land cover, distance from rivers, distance from roads and two indexes extracted from DEM, which characterize the spatial differentiation of hydrological conditions and the distribution of soil moisture: Topographic Wetness Index (TWI) [16] and Stream Power Index (SPI) [17].

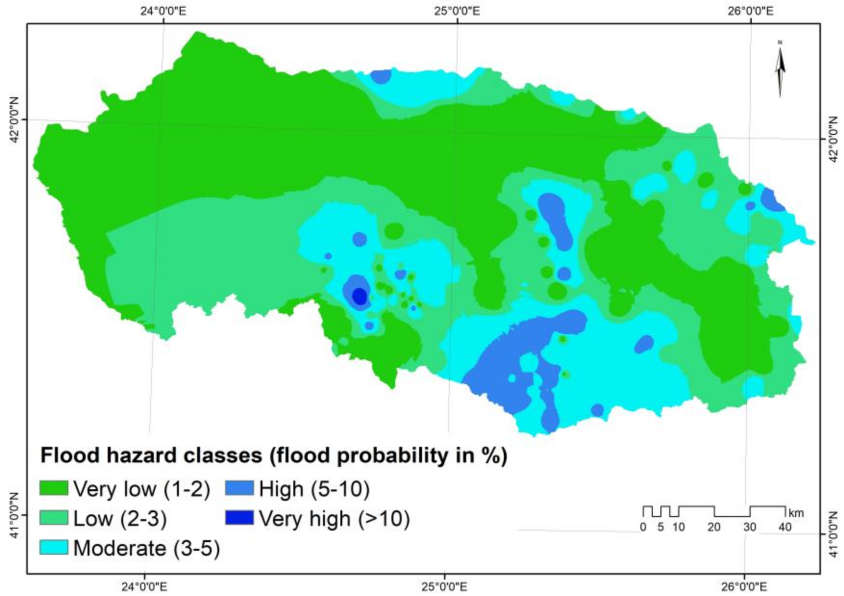

Fig. 2. Flood hazard map of the Rhodope Mountain Range, Bulgaria

Then, they are weighted according to AHP model developed in a previous study [18], so that to develop landslide susceptibility map for the Rhodope Mountain region. Based on this map, the landslide probability in percentages was calculated, which was subsequently used to assess the landslide hazard. The area was divided into 5 hazard zones (Fig. 3). The results show that the areas with high and very high landslide hazard classes are located close (up to 200 km) to riverbeds and roads.

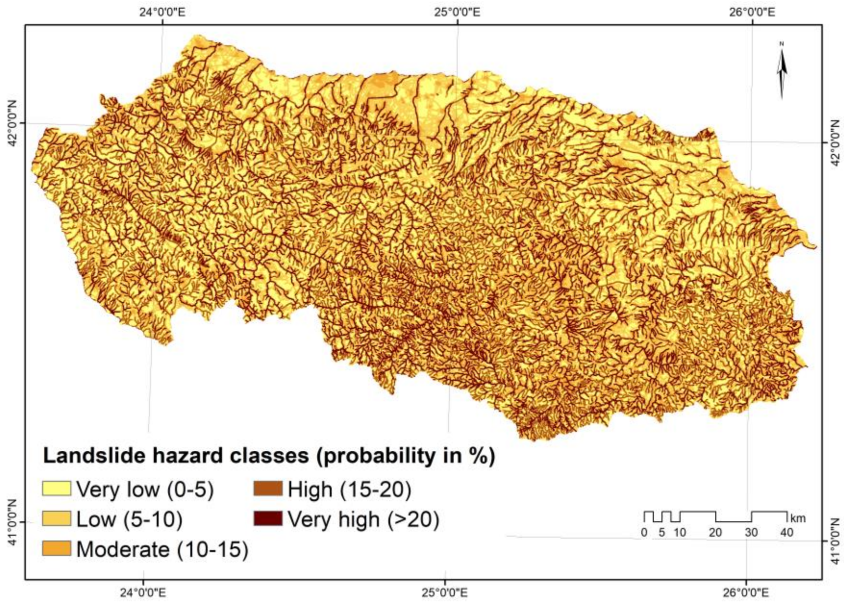

Fig. 3. Landslide hazard map of the Rhodope Mountain Range, Bulgaria

Since the rivers are now facing increasing pressure to provide water as a result of rapidly growing global human population and global climate change, the assessment of low flow has become an essential for achieving sustainable management of natural resources, especially in drought-prone areas. Considering that water availability is critical for the natural ecosystems and control numerous functions and processes, as well as the ecological balance in the aquatic, riparian and floodplain communities, the Q90 low flow index was selected to assess drought hazard in the Rhodope Mountain Range. The Q90 index was calculated as a percentage of mean annual flow (MAF) and then divided into 5 drought hazard zones, as Q90 values are indicative of habitat quality in these zones (Fig. 4). The results show that the entire south-eastern half of the Rhodope region is subject to water shortages and is characterized by a high and very drought hazard classes.

However, a particular surface area subject to the same hazard can face a variety of consequences, depending on land cover types, thence, to provide risk map for disaster mitigation, the risk classes need to be taken in consideration. For example land cover information, settlement data, transportation networks, social economic data, etc. [19].

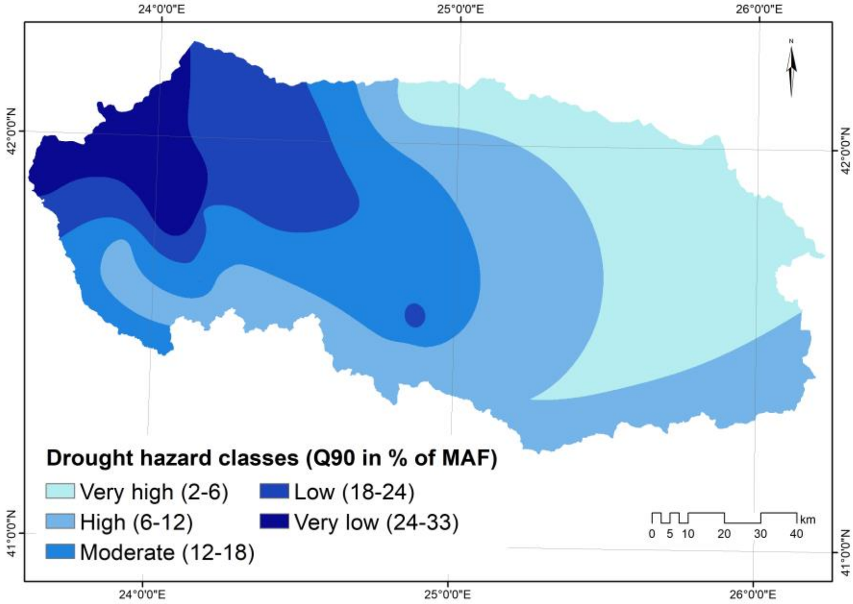

Fig. 4. Drought hazard map of the Rhodope Mountain Range, Bulgaria

Soil erosion by water is one of the most significant forms of land degradation and leads to desertification, especially in arid areas [20]. Agriculture is the sector most affected by water erosion and leads to loss of cultivable, fertile land and soil structure degradation. Nonetheless the soil erosion can also result in destruction of infrastructures, pollution of surface water, flood risk, etc. In this study, the assessment of soil erosion reveals that large areas of the eastern and southeastern parts of the Rhodope Mountain Range are also affected by soil erosion (Fig. 5).

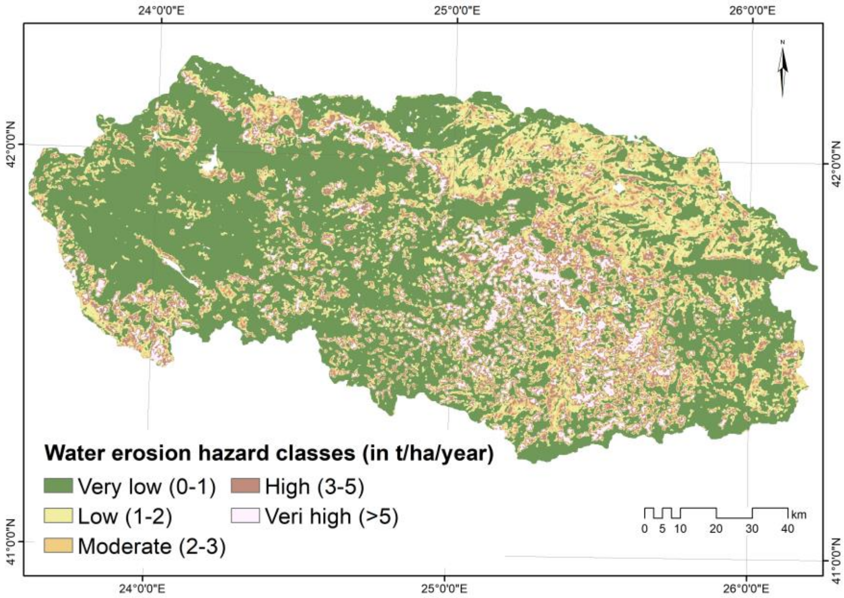

Fig. 5. Water erosion hazard map of the Rhodope Mountain Range, Bulgaria

The soil erosion map was divided into 5 water erosion hazard categories. Owing to the large forest areas, in the western part of the region water erosion shows a stable trend, below 1 t/ha/year. While, the majority of the southern and southeastern parts are characterized by a medium, high and very high water erosion hazard categories (over 3 t/ha/year).

Conclusion

The study assessed the water-related hazardous probability in the Rhodope Mountain Range of the territory of Bulgaria based on long-term hazard inventory data for historical events, regarding floods, landslides, drought hazard and soil erosion by water. That work is an attempt to analyze their temporal and spatial behavior and to identify areas potentially vulnerable to occurrence of water-related disaster events. Four hazardous maps were developed using GIS and remote sensing data and the territory was divided into different hazard zones, so that to facilitate future detailed research and analysis. The results find that the Rhodope Mountain region, in particular, its eastern and southeastern parts are exposed to risk from various water-related disaster events in the future. To reduce disaster losses, more efforts must be made to manage disaster risk in the future, given climate change and an increase in vulnerable populations. All these disaster management measures have an important spatial component. In this line, the use of earth observation products and geographic information systems (GIS) has become an important approach in disaster-risk management and hazard and risk assessments.

References:

1. UNISDR, Sendai framework for disaster risk reduction 2015–2030. Proceedings of the 3rd United Nations World Conference on DRR, Sendai, Japan, 2015, pp. 14–18.
2. Forzieri, G., L. Feyen, S. Russo, M. Vousdoukas, L. Alfieri, S. Outten, M. Migliavacca, A. Bianchi, R. Rojas, A. Cid. Multi-hazard assessment in Europe under climate change. Climatic Change, 137, 2016, pp. 1–15.
3. IPCC. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 2018, pp. 1–594.
4. Lee, J., D. Perera, T.Glickman, L.Taing. Water-related disasters and their health impacts: A global review. Progress in Disaster Science, 8, 2020, 100123.
5. Kumar, P., S. Debele, J. Sahani, L. Aragão, F. Barisani, B. Basu, E. Bucchignani, N. Charizopoulos, S. Di Sabatino, A. Domeneghetti, A. Sorolla Edo, L. Finér, G. Gallotti, S. Juch, L. Leo, M. Loupis, S. Mickovski, D. Panga, I. Pavlova, F. Pilla, A. Prats, F. Renaud, M. Rutzinger, A. Basu, M. Shah, K. Soini, M. Stefanopoulou, E. Toth, L. Ukonmaanaho, S. Vranic, T. Zieher. Towards an operationalisation of nature-based solutions for natural hazards. Science of the Total Environment, 731, 2020, 138855.
6. Ban, N., J. Schmidli, C. Schär. Heavy precipitation in a changing climate: does shortterm summer precipitation increase faster? Geophysical Research Letters, 42(4), 2015, pp. 1165–1172.
7. Yordanova, M., S. Velev, I. Drenovski. Characteristic features of the physical geographical regions. In Kopralev, I. (Ed.): Geography of Bulgaria: Physical and Socio-Economic Geography, BAS, Sofia, Bulgaria, 2002.
8. Tsiftsis, S., I. Tsiripidis. Orchids of Rodopi Mountain-Range National Park. Management Body of Rodopi Mountain-Range National Park, Mesochori, Paranesti, Greece, 2012.
9. Natura 2000 Network and Protected Areas Database. Ministry of Environment and Water, 2015 Bulgaria [online] http://natura2000.moew.government.bg/Home/Documents.
10. Saaty, T. The Analytic Hierarchy Process. John Wiley, New York, 1980.
11. Myronidis, D., E. Ivanova. Generating regional models for estimating the peak flows and environmental flows magnitude for the Bulgarian-Greek Rhodope Mountain Range torrential watersheds. Water, 12(3), 2020, 784.
12. Ivanova, E., D. Myronidis. Application of an integrated methodology for spatial classification of the environmental flow in the Bulgarian-Greek Rhodope Mountain Range. International Journal of Sustainable Agricultural Management and Informatics, 8(1), 2022, pp. 84103.
13. Panagos, P., M. Van Liedekerke, P. Borrelli, J. Köninger, C. Ballabio, A. Orgiazzi, E. Lugato, L. Liakos, J. Hervas, A. Jones, L. Montanarella. European Soil Data Centre 2.0: Soil data and knowledge in support of the EU policies. European Journal of Soil Science, 73(6), 2022, e13315.
14. Panagos, P., M. Van Liedekerke, A. Jones, L. Montanarella. European Soil Data Centre: Response to European policy support and public data requirements. Land Use Policy, 29(2), 2012, pp. 329–338.
15. European Soil Data Centre (ESDAC), esdac.jrc.ec.europa.eu, European Commission, Joint Research Centre
16. Beven, J., M. Kirky.A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24 (3), 1979, pp. 43 – 69
17. Moore, I., P. Gessler, G. Nielsen, G. Peterson. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal, 57(2), 1993, pp. 443–452
18. Ivanova, E. Landslide Susceptibility Mapping using Frequency Ratio and Analytic Hierarchy Process (AHP): Comparative study of two areas in Bulgaria. Proceedings of the International Conference “Analysis and Management of Changing Risk for Natural Hazards”, 18–19 November, 2014, Padua, Italy, pp. AP23-1–AP23-9
19. Pradhan, B. Flood susceptible mapping and risk area delineation using logistic regression, GIS and remote sensing. Journal of Spatial Hydrology, 9(2), 2009, article 4.
20. Stefanidis, S., C. Chatzichristaki, P. Stefanidis. An ArcGIS toolbox for estimation and mapping soil erosion. Journal of Environmental Protection and Ecology, 22(2), 2021, pp. 689–696.