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ASSESSMENT OF TORRENTIAL FLOOD SUSCEPTIBILITY USING GIS MATRIX METHOD: CASE STUDY - VRBAS RIVER BASIN (B&H)

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Abstract: Torrential floods are the most frequent natural hazard events in Bosnia and Herzegovina. The increase of intensive rains in Bosnia and Herzegovina over last years, as a consequence of the climate changes, has triggered many torrential floods, which have generated a lot of damages and losses of human lives. This study was focused on development of torrential susceptibility model using GMM Method and GIS in the Vrbas river basin as an attempt to create a new methodological approach which can be used on other river basins in Bosnia and Herzegovina. First, a total of 174 torrential basins were identified in the Vrbas river basin, as a base for creating an inventory map, which was a base map for the assessment of torrential floods susceptibility. The GIS Matrix Method and six influencing factors were used for generation of Torrential Flood Susceptibility Model. Based on the obtained values of Torrential Flood Susceptibility Model for the Vrbas river basin, 45.52% of the study area is within strong and very strong susceptibility category. The Torrential Flood Susceptibility Model was validated using a "degree of fit" method. Validation indicators of the TFSM show that the 80.04% are in the category of strong and very strong susceptibility, while only 4.37% are in the category of very low and low susceptibility. This fact suggests that used methodology based on GMM method and used influencing factors enable delimitation of the area with high and very high susceptibility to torrential floods into the Vrbas basin. Therefore, used methodological approach represents a good base for future research, and it has potential for the practical use and should be tested in other river basins in Bosnia and Herzegovina.

Keywords: natural hazard, flood, torrential basins, GIS analysis, Bosnia and Herzegovina.

1. INTRODUCTION

Torrential (flash) floods are one of the most devastating natural hazards, which caused a serious loss of lives and economic damages (Alcantara, 2002; Schmidt et al., 2006; Toya & Skidmore, 2007). According to Barredo (2007), 40% of the flood events in Europe in the period 1950–2006 are torrential floods. Data concerning a number of torrential flood events that have occured since 1950. have been reported by Gaume et al., (2009). Though they are one of the most significant natural hazards, and their potential is increasingly pronounced in many regions of Europe, torrential floods remain a poorly understood and documented natural phenomenon (Barredo, 2007; Gaume et al., 2009; Marchi et al., 2010; Romanescu, et al., 2011, 2017). Apart from large-scale river floods, torrential floods are the most frequent natural catastrophic events in Bosnia and Herzegovina. Despite the fact that this natural disaster has an extremely destructive effect on the socio-economic sector, the torrential floods in Bosnia and Herzegovina have been poorly hydrologically researched. The torrential floods in Bosnia and Herzegovina during 2014, and particularly torrential floods in the Vrbas river basin in August 2014, when two human lives were lost, indicated that this natural phenomenon requires a detailed study. Torrential floods represent a real challenge for forecasting and detection. The tools available in the analysis vary from simple manual tools that include the existing data on average rainfall and floods in the form of tables and graphs, to complex IT systems that include sophisticated data management, modelling, forecasting and automatic warning distribution. Several tools used by forecasters in assessing the potential occurrence of torrential floods have been developed worldwide (e.g. USA). The tools were used to upgrade Flash Flood Guidance (FFG), in terms of better understanding of the local physical-geographical conditions that contribute to the occurrence and development of torrential floods (Georgakakos, 2006; Drobot & Parker, 2007; Collier, 2007; Borga et al., 2008; Norbiato et al., 2008). The most commonly used both globally and in our region is the Flash Flood Potential Index (FFPI) proposed by Greg Smith 2003. He considered a number of factors that actively influence the process of runoff, with the intention of identifying the areas with a high torrential flood potential in the Colorado basin (USA) (Smith, 2003). Methodological approaches to natural hazard susceptibility are differing across the literature (Guzzetti et al., 2005; Irigaray et al., 2007; Fuchs et al., 2015; Totschnig & Fuchs, 2013; Tsakiris, 2014). Today there are a number of widely accepted methodologies that have been very successfully used in natural hazard mapping. Various methods have been used for torrent flood susceptibility mapping, such as multi-criteria evaluation, decision tree, analysis fuzzy theory, weight of evidence, logistic regression, and others (Sahoo et al., 2006; Mukerji et al., 2009; Kia et al., 2012; Tehrany et al., 2013, 2014; Bajabaa et al., 2014; Zhang et al., 2015; Elkhrachy, 2015; Youssef et al., 2016; Khaleghi & Mahmoodi, 2017). In order to improve Smith's original methodology in terms of more objective results (results do not depend on the subjective attitude of an individual who assigns weight factors), some authors proposed adaptation and improvement of the initial methodology proposed by Greg Smith. This methodological approach was the basis for the development of different Flash Flood Susceptibility assessment methods in many countries worldwide (Fernandez-Lavado et al., 2007; Borga et al., 2007; Abeyta, 2009; Brewster, 2010; Kruzdlo & Ceru, 2010; Zogg & Deitsch, 2013; Teodor & Matreata, 2011; Kourgialas & Karatzas, 2011; Degiorgis et al., 2012; Bryndal, 2014; Kim & Choi, 2015; Papagiannaki et al., 2015; Kostadinov et al., 2017; Albano, et al., 2017; Radevski & Gorin, 2017). Bosnia and Herzegovina has not been included in the most recent studies that have examined torrential flood hazard within the territory of Europe. Hence, this paper presents the significant step towards better understanding of the phenomenon of torrential floods as the most common natural hazard in Bosnia and Herzegovina. The data presented in this paper are also significant to practical issues such as integral water management projects, spatial planning, sustainable land planning, protection of soil, forest ecosystems and environmental protection, sediment management, flood risk management, agriculture and other human activities. The development of flood hazard and flood risk maps for the Vrbas river basin has to involve the problems of torrential floods. The identification of torrential river basins and the formation of the torrential flood susceptibility model for the Vrbas river basin is especially important as an attempt for creating a new methodological approach which could be used on other river basins in Bosnia and Herzegovina. The main objective of this study is assessment of the susceptibility to torrential floods in Vrbas river basin using GMM – GIS Matrix Method, which operates entirely in a GIS environment. This study includes several stages: (i) Development of a Cadastre of Torrential Basins in the Vrbas river basin; (ii) Analysis and selection of factors that determine the susceptibility; (iii) Development of a susceptibility model; (iv) Calibration and validation of the Torrential Flood Susceptibility Model.

2. STUDY AREA

The Vrbas river basin is located in the western part of Bosnia and Herzegovina and drains the central part of the Dinaric mountain massif (Fig. 1). Vrbas River is a right tributary of the Sava River. It appears at the southern slope of the Vranica Mountain (1530 m above sea level) and it confluences into Sava River near Srbac. The drainage basin area is 6289.19 km^2. The total length of the watercourse is 235 km, and the average gradient of the main stream is 6 m/km. The average altitude of the river basin is 690 meters above sea level. In the physical-geographical sense, the basin belongs to two morphotectonic units: Pannonian and mountain/valley. The first morphotectonic unit includes low depressions originating from tectonic activities and accumulation processes. The second morphotectonic unit, apart from the significant karst areas that are scattered around and divided into smaller isolated massifs and mountains, includes the Manjača massif in the central part, which covers an area of about 200 km^2. In the area between the mountains, there are tectonic depressions or valleys. The valleys are connected to the gorges and canyons cut into older and more resistant rocks that dominate this morphotectonic unit (Čičić, 2002; Hrvatović, 2006).

In a geomorphological view, the Vrbas river basin is a mountain-hilly relief, while in the geotectonic sense, it is a part of the western zone of fold mountains (Dinaric mountain area) and the Pannonian depression.

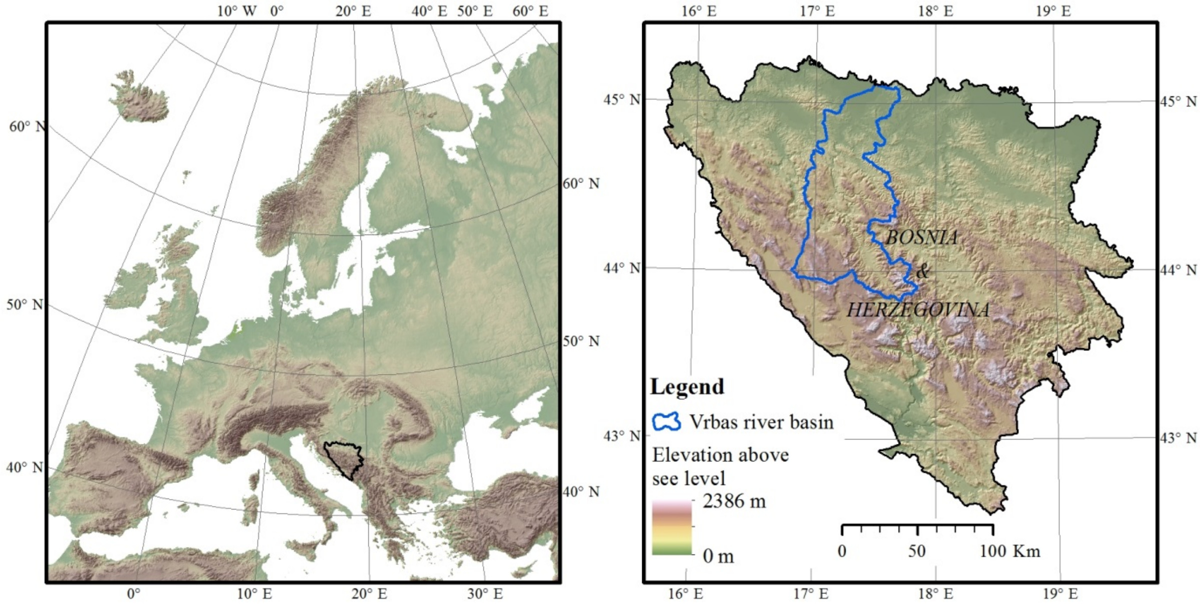

Figure 1. Location of study area - the Vrbas river basin (Bosnia and Herzegovina)

The headwater of Vrbas belongs to the main highest range of the Dinaric Mountains. The rest is mostly developed on the north-eastern slope of the Dinaric Mountains. The lower part of the river basin is on the edge of the Pannonian Basin and in its accumulative plain.

The quantitative characteristics of climate parameters are based on the results of systematic meteorological measurements and observations at several weather stations. Data from 53 precipitation stations were analysed for daily precipitation for the period 1950–2016, and the data from the Banja Luka, Bugojno and Jajce stations that are currently operating in the basin. This analysis concluded that the average precipitation in the Vrbas river basin is 1050 mm per year. The average annual air temperatures are mostly conditioned by the altitude and geomorphological characteristics of the basin. In the Vrbas basin they range from 9.4°C to 10.8°C in the area with temperate continental climate, and from 6°C to 9°C in the areas with sub-mountain and mountain climates.

The hydrographic network in the Vrbas river basin has a close and direct dependence on the geological structure of the land and the hydrogeological function of the rock masses. In an average year with 1050 mm of precipitation, the total precipitation volume is 6704.3×10^6 m^3 and the total runoff is 4062×10^6 m^3. This gives an average runoff coefficient for the entire basin of 0.60 and an average discharge of 128.8 m^3/s. A very important hydrological characteristic is the regime of flood flows. These streams have extremely torrential regimes, with a very short time of concentration of the flood wave (in smaller basins only a few hours) and extremely large runoff modules (1–1.5 m^3/s km^2, and even over 2 m^3/s km^2 on small rivers). Hydrological data (i.e. daily discharges) from 16 hydrological stations in the Vrbas river basin were analysed for this research.

The soils of the Vrbas river basin belong to the order of automorphic and hydromorphic soils. In the group of automorphic soils, there are the following classes: undeveloped soils (A) - C profile; humus-accumulative soils (A - C profile), cambisol (A - (B) - C profile); eluvial-illuvial soils (A - E - B - C profile). In the group of hydromorphic soils, there are the following classes: gleysol (A - Eg - Bg - C profile); fluvisol ((A) - I - II); hypofluvisol (A - G profile); and humofluvisol (A - C - G profile) (Burlica & Vukorep, 1980).

Across the vertical profile of Vrbas River, from the confluence to the highest peaks, vegetation differs according to the ecological conditions of habitats, with different types of forest and grass ecosystems, and agroecosystems. In the lowest parts of river valleys and streams with permanent wetlands there are hydrophilic forests of black alder and willow. In the middle course of the Vrbas River, there are forest communities of sessile oak and hornbeam. In slightly lower and humid areas there are some pedunculate oaks, while Turkey oak is very rare. The most common shrubs are: hazel, common spindle, viburnum and hawthorn (Stefanović et al., 1983).

3. DATA AND METHODOLOGY

3.1. Data collection methodology

The institutions responsible for water have no official cadastre or register of torrential watercourses (basins) floods, as an integral part of the Bosnia and Herzegovina water management information system (WMIS_B&H), i.e. module WMIS_B&H. Despite the fact that torrential floods have extremely destructive effects on the socio-economic sector, they are scarcely documented and their monitoring is often non-existent. This especially refers to work in torrential basins and channels. The lack of data has determined a specific methodological approach to meet the requirements set forth in this Study, which relates to: defining and identifying torrential basins in the Vrbas river basin, and the development of the Torrential Flood Susceptibility Model (TFSM).

The field survey was carried out to address the lack of relevant data on torrential basins and floods in the Vrbas river basin. The field studies of torrential basins and streams in the Vrbas river basin included: studying the basins and collecting data on factors that influence the formation of torrential floods; soil erosion mapping to define the source zones of sediments; studying the hydrographic network through which the transit of the torrential flow passes; studying sediment deposition zones, studying sediment flows at the mouth of the local base level; determination of hydraulic traces of flood flows formed during the passage of torrential flood waves; the frequency and extent of previous torrential flood waves; the type of torrential flood wave; the parameters of torrential flood wave (depth, width, hydraulic traces); causes of torrential flood wave (shower, long rainfall, sudden snow melt, etc.); data on the duration of the event; the destructive force of the torrential flood wave (types of damage caused); identification of torrential basins, mapping with a GIS/GPS device; development of a Torrential Basins Cadastre and a Geospatial database (GDB).

The plan for field survey in the basins was defined in the office, including the preparation of topographic maps and their integration into the GIS/GPS device. After this, the field work commenced in the Vrbas river basin. The following indicators for torrential regimes were identified, examined and documented in the field: potential for sediment transport; cascades in the channel, parent rock outcrops; meandering of the channel; sediment deposited on convex sides; connection of the profile with source of sediments; blocks at the stream bed; material in the channel; traces of undercutting in the channel; backwater in the channel; tributaries, alluvial fans; ravines and gullies (appearing in the area of the river source or laterally further down the stream); visible traces on the channel sides; structures in the channel; biotechnical works in the basin; torrential debris on the banks; vegetation on the banks; traces of flood flows on the banks; visible processes in the basin; traces of sediment at the confluence with the main stream; infrastructure along the channel; population survey; type of torrential stream; photo reference, digital photo, referenced with the ID. These indicators, together with the Soil Erosion Map were the basis for the identification of torrential basins in the Vrbas river basin and the development of the Cadastre of Torrential Basins in the Vrbas river basin.

Torrential watercourses were classified according to the origin of their bedload: “underminers” (U) which are torrential watercourses whose river channel passes through ground that can be easily eroded, developing intensive downward and headward erosion; “washers” (W) which are torrential watercourses that flow through rocky channels, so downward erosion is not pronounced, but they transfer enormous amounts of sediment washed into the channel (surface erosion - denudation work of water in the basin); “mixed” (M) torrential watercourses characterized by undermining the channel and also transporting material from surface erosion. Additionally, torrential watercourses are divided into 4 hydrograph classes (Hk) (Gavrilović, 1972):

Class A – torrential large rivers: all torrential watercourses whose Hk is over 20 km^2. These are hilly streams with relatively wide channels and long watercourses with a developed network of torrential tributaries (small rivers, brooks and dry valleys).

Class B – torrential small rivers: all torrential watercourses whose Hk ranges between 10 and 20 km^2. These are hilly streams with extremely varying channel widths, and a significant number of tributaries, brooks and dry valleys.

Class C – torrential brooks: all torrential watercourses whose Hk ranges from 0.1 to 10 km^2. These are hilly streams with relatively narrow and uneven cross-sections. They have a negligible network of tributaries, mainly dry valleys and ravines with perennial or intermittent streams.

Class D – dry valleys and small torrential brooks: all torrential watercourses whose Hk ranges from 0.1 to 1.0 km^2. These are hilly streams with relatively short watercourses and a small number of tributaries, ravines and gullies. The definition and identification of adequate determination factors for torrential floods is the first step in the process of developing the Torrential Flood Susceptibility Model, i.e. the process of identifying certain areas and spaces which are differently sensitive (susceptible) to torrential floods. The selection of the parameters of the future torrential flood susceptibility model in the Vrbas basin was based

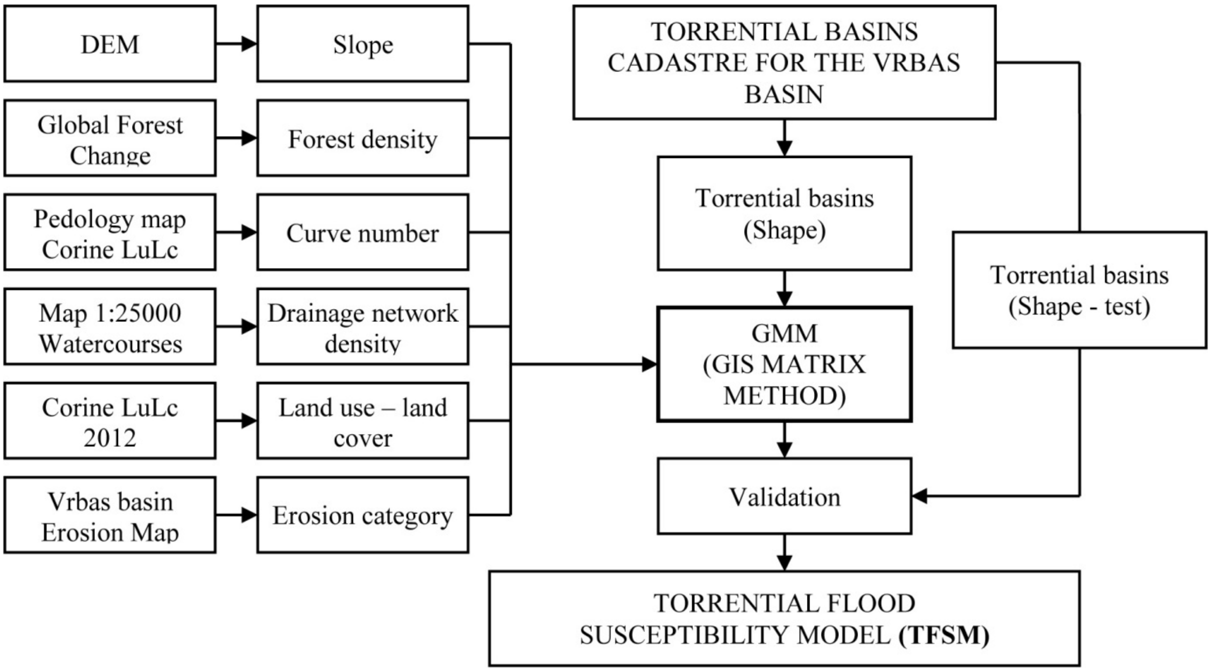

Figure 2. Procedure for the development of the Torrential Flood Susceptibility Model in the Vrbas river basin

on the following criteria: that they were well documented in the literature as a factor with significant impact on the runoff and formation of torrential floods; that they allow the evaluation of the predisposition of the basin to torrential floods; that there is sufficient data to define those parameters and that they are of adequate spatial resolution; that they respect the specificities of geological and geomorphologic material (karst), hydrography, and pedological and vegetational characteristics of the Vrbas basin. Given the specificity of the geological-geomorphological structure (karst), specific hydrology, and soil and vegetation characteristics of the Vrbas basin, six factors, that play an important role in the runoff from the ground surface, have been selected. The following factors are used in the preparation of the Torrential Flood Susceptibility Model (Fig. 2): the angle of the slope (S) generated from the Digital Elevation Model (DEM), the Curve Number (CN) determined on the basis of the pedologic map, reference soil profiles and land use (hydrological soil group), drainage network density (DND) determined on the basis of the existing watercourses at the map scale of 1:25000, land use – land cover (LULC) determined on the basis of CORINE Land Cover (Coordination of Information on the Environment – EEA) supplemented with a digital orthophoto (DOF), erosion category (EC) determined by use of the Erosion Map of Vrbas River, and forest density (FD) obtained from Global Forest Change data (Burlica & Vukorep, 1980; CLC, 2007; Tošić et al., 2012; Hansen et al., 2013).

The collection and preparation of the data of the above specified factors used ArcGIS 10.4 software. All data prepared for the analysis have vector data format. They were reclassified depending on the type of data and histogram distribution of the analysed data.

3.2. Methods

Torrential floods are defined as a rapid onset of flood flow in the river channel with a high concentration of the solid phase (sediment). In extreme cases, two-phase liquid flow spills over the river banks with great destructive power. The two-phase liquid flow of a torrential flood contains solid fractions of different grain size distribution that make up to 60 % of the total volume. Also, torrential floods are often defined as floods in which up to 50 – 60 kg of erosion sediment appear in 1 m^3 of flowing water and whose flood wave lasts less than 6 hours, especially after a rainfall of short duration (Tk<24 hours), but high intensity (i>0.5 mm/min; and>1mm/min). The sediment production and transport regime of torrential watercourses is in accordance with the hydrological regime. Most of the annual sediment transport (over 70 %) takes place in torrential flood waves. However, the phenomenon of torrential floods is very complex. It is a set of processes and phenomena taking place in a torrential watercourse and riparian area when a flood wave arrives (Gavrilović, 1972; Jevtić, 1978; Norbiato et al., 2008; Marchi et al., 2010; Ristić et al., 2012; Petrović et al., 2015).

Mentioned before in the literature, one of the first attempts to evaluate the torrential flood potential of a basin was carried out by Flash Flood Potential Index (FFPI) (Smith, 2003). In order to improve Smith's original methodology in terms of more objective results (results do not depend on the subjective attitude of an individual who assigns weight factors), this study proposed adaptation and improvement in terms of creating a new methodological procedure for the development of the Torrential Flood Susceptibility Model (TFSM) in the Vrbas river basin. It includes several stages: development of a Cadastre of Torrential Basins in the Vrbas river basin; analysis and selection of factors that determine the susceptibility; development of a susceptibility model; calibration and validation of the Torrential Flood Susceptibility Model.

One of the methods most commonly used in physical-geographical, geological and geomorphological studies of these phenomena is the matrix method (Irigaray et al., 1999, 2000, 2007). This is a quantitative method which uses a statistical analysis to establish the susceptibility model index to this phenomenon in an observed area. Although this model cannot define susceptibility in absolute terms, it can recognize a potential relative susceptibility, which is calculated for the entire observed surface using a series of measurable relevant factors of this phenomenon.

GMM (GIS Matrix Method), which operates entirely in a GIS environment, is based on the analysis of three matrices: torrential basin matrix (TM), total surface of the study area matrix, i.e. the Vrbas river basin (TSSASM) and torrential susceptibility matrix (TSM). This model is based on the determination of all possible combinations between different types of factors that influence the occurrence and development of torrential floods (Fig. 3). The result is a differentiated space in which each unit area indicates its estimated relative susceptibility, which corresponds to a combination of determination factors within that area.

Each SM value shows the percentage of source area in each combination in relation to the entire observed surface, which is presented through a combination of determination factors of the phenomenon and development of torrential floods. The use of a classification method in the ArcGIS environment (natural breaks method) will obtain results that can be further reclassified.

Based on these, different levels of susceptibility to torrential floods can be shown visually (very low 0–2; low 2–10; medium 10–30; strong 30–50; very strong 50–100) (Irigaray et al., 1999, 2000, 2007).

In this study, torrential flood susceptibility maps were validated using a "degree of fit" method. The degree of fit (DF) is defined as follows:

$$DF_i = \frac{\frac{m_i}{t_i}}{\sum \frac{m_i}{t_i}} \qquad (1)$$

where m_i is the area occupied by the source areas of the torrential basin at each susceptibility level i, and t_i is the total area covered by the susceptibility level.

The degree of fit for each susceptibility level represents the percentage of mobilized area located in each susceptibility class. This model was validated using a "degree of fit" method.

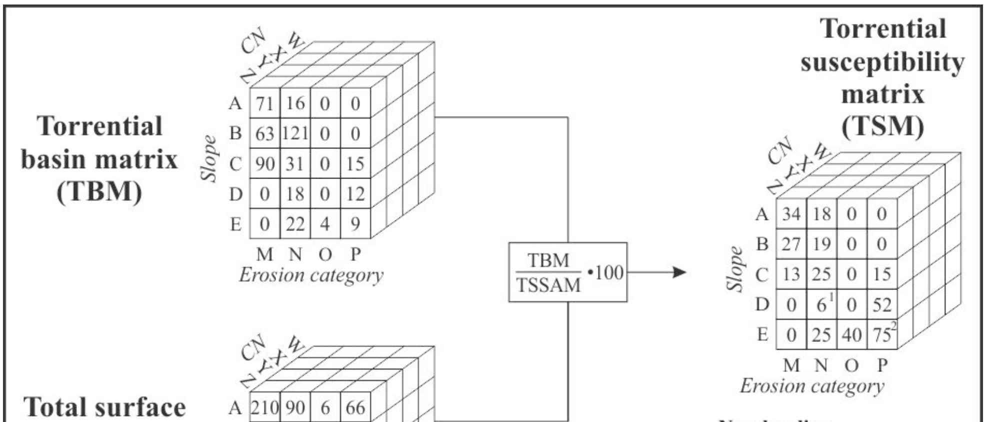

Figure 3. Illustration of the determination of torrential flood susceptibility by the GIS matrix method

This method assesses the relationship between torrential basin surfaces (sample from the torrential basins register that was not used in the preparation of the preliminary model) and the developed torrential flood susceptibility model. The quality of the model was estimated using spatial autocorrelation technique and measuring the degree of fit between the validation data set and the resulting susceptibility model. The ultimate goal was to assess the quality of the susceptibility model, as a predictive resource used to explain the spatial distribution (location) of torrential basins in the project area (Irigaray et al., 1999; Fernandez et al., 2003; Remondo et al., 2003; Jiménez-Perálvarez et al., 2009; Tošić et al., 2014; Lovrić & Tošić, 2017).

Torrential basins have a complex structure of important factors for the formation of runoff, where the time of concentration (T_c) is an indicator of the intensity of this process. Therefore, the time of concentration (T_c) is one of the most important indicators of the potential for the basin to form rapid surface runoff, and thus, the development of torrential flooding. In this study, the following equation was used to determine the time of concentration (Ristić, 2006; Ristić et al., 2012):

$$T_c=0.502\bullet A^{0.506}(h) \quad (2)$$

where A is area of torrential basin in km^2.

4. RESULTS

4.1. Torrential basin inventory (cadastre of torrential basins)

Through the detailed field survey, 174 torrential basins were identified in the Vrbas river basin. The total surface area of the torrential basins is 1753.33 km^2, which is 27.87 % of the total area of the Vrbas river basin (Table 1). The spatial distribution of torrential basins in the Vrbas river basin is given in inventory map (cadastre of torrential basins in the Vrbas river basin), which is also a base map for development of torrential floods susceptibility model (TFSM). By analyzing the spatial distribution of torrential basins in the Vrbas river basin, it is possible to distinguish five zones dominated by torrent basins (Fig. 5).

The first zone of torrential basins (I) represents the foothills of the Motajica mountain in the northeastern part of the Vrbas river basin. The torrential basins at the foot of the Motajica have pronounced indicators of torrential regime. There are plenty of sediments on convex sides of the channel. In the upper part of the basin, the processes of undermining are dominant, while in the lower part the process of washing and mixed torrential activity dominates. Backwater in the channel and numerous culverts (pipes and bridges) are a major problem in the outflow of flood flows (torrential water). Because of this, many households and local roads have been flooded during torrential events. According to the survey of the local population, torrential streams are most active during the spring and autumn, when very strong flood flows are formed in a short period of time, but they are of short duration and they quickly recede back to the channel. There are visible traces of sediments, muddy material and trees on the banks of these river flows, which clearly indicate previous very strong torrential activity. In this part of the basin there are two characteristic basins: the Stojkovića basin as a typical underminer, and the Bogdanuša as a typical washer. Very similar characteristics of torrential streams are recorded in the Husrpovačka, Crkvena, tributary of Turjanica and others torrential streams in this torrential zone.

The second zone of torrential basins (II) represents the wider urban area of Banja Luka. Few torrential watercourses, mainly small, are registered in the area around Banja Luka. Of the 16 watercourses, nine flow in their lower course through the central part of the town, while seven are either in the immediate vicinity of the town or they flow through the suburbs.

Three of them stand out by the intensity of their erosion processes: Đurđevac, Dubravski and Gluvi. These are typical torrential watercourses with a pronounced linear erosion. Four torrential watercourses have strong erosion accompanied by the undermining of stream bed and banks and transporting large quantities of materials: Dubočajac, Sedra, Rujišnjak and Suvi. These jeopardize the road infrastructure from Banja Luka to Jajce. Other torrential watercourses in the area of Banja Luka have weaker intensity of erosion. Among them stand out: Crkvena, Ularac, Rebrovac and Rebrovački located on the slopes of Starčevica, Podstranac on the slopes of Petrićevac, and Pećinski, Močila, Zmajevac, Sitarski and Dubočaj.

Table 1. Quantitative and qualitative indicators of torrential basins in the Vrbas river basin

Number of torrential basins	Area (km^2)			Hydrograph classes				Type			Tc (h)		
	Min	Max	Average	A	B	C	D	U	W	M	Min	Max	Average
174	0.20	119.52	10.08	45	23	80	26	88	22	64	0.22	5.65	1.30

The third zone of torrential basins (III), represents the torrential basins in the basin of Vrbanja River (the total surface area of the Vrbanja basin is 791 km^2), the right tributary of the Vrbas River. The Jošavka is a typical torrential basin in the Vrbanja basin. Its tributaries bring huge amounts of material, visible in confluences. The Josavka has the largest basin surface in the Vrbas basin. Due to the intense erosion processes in the basin and large quantities of sediments in the channel and in places of backwater, it makes sense to start the erosion control works in the channel of this river.

Of the other torrential basins in the Vrbanja Basin, the headwater area of the Kruševica stands out, where there are well-defined traces of undermining with a lot of material in the channel and in the confluences of its tributaries. Likewise, torrential streams in the headwaters of the Vrbanja stand out. They are mainly underminers which bring significant amounts of material to the Vrbanja.

The left valley side of the Vrbanja has less torrential basins, since this part of the basin is predominantly carbonate rocks, with prevailing karst relief and hydrography. The fourth zone of torrential basins (IV), represents the torrential basins in the central part of the Vrbas river basin. In the Ugar basin there are several smaller torrential streams (Ugrić, Osmanovac, Kukavički and others), with undermining processes particularly pronounced in their headwater areas. Several torrential basins have been identified in the Crna Rijeka basin. Few torrential watercourses were identified in the Pliva basin. The strongest erosion processes with the most sediment in the channel are in the Pliva's left tributaries: Vrbica, Perućica, Jošavka and Lubovačka. The torrent Milski flows directly into the Pliva Lake. In the town of Šipovo the Lubovačka flows into the Pliva, which caused great damage by overtopping in the center of the town which has been often flooded and covered with erosion material.

The fifth zone of torrential basins (V), represents the torrential basins in the source of the Vrbas River. The most characteristic ones are: Komotinski, Sokolinski, Glasinac, Ćupinac, and torrential streams in the headwater area of the Vrbas. Indicators of torrential activity are clearly visible in the channels of these torrential streams. The torrential watercourses in this zone are characterized by large gradients, large amounts of precipitation, impermeable rocks and sparse vegetation. Unlike the basins where the torrential flood regime is a consequence of land degradation and plant cover and where the erosion is surface and linear, in this high-altitude zone the erosion is concentrated only on river channels (dominant undermining). However, since the torrential floods in these basins do not directly threaten settlements and do not cause enormous damage to infrastructure, the monitoring and identification of torrential floods and other processes are virtually non-existent.

4.2. Torrential Flood Susceptibility Model (TFSM)

As we mentioned before, many authors suggested that torrential (flash) floods may occur in almost every basin and hydroclimatic region of Europe. According to these data three regions characterised by high torrential flood potential are: Mediterranean, Alpine Mediterranean and Inland Continental Europe region (Borga et al., 2008; Norbiato et al., 2008; Marchi et al., 2010). The main meteorological factors for the occurrence of torrential floods are certainly extreme rainfall events. In this regard, the conclusion is that extreme rainfall is the main trigger for torrential floods, as most torrential flood analyses show. However, many analyses of torrential flood events point to the significance of other causes of torrential floods.

The definition and identification of influence factors for torrential floods is the first step in the process of developing the Torrential Flood Susceptibility Model (TFSM). In this study, six influencing factors were considered (Fig. 4): the angle of the slope (S), the Curve Number (CN), drainage network density (DND), land use – land cover (LULC), erosion category (EC) and forest density (FD). The influence of listed factors on the formation of floods (torrential) is widely discussed in hydrological literature (Merz & Plate, 1997; Shakya & Chander, 1998; Brown et al., 1999; Naef et al., 2002; Weingartner et al., 2003).

Relief as influencing factor was characterized by angle of slope (S). The slope was reclassified into five classes: (1) 0–5°, (2) 5–15°, (3) 15–25°, (4) 25–35°, (5) >35°. Slope angle affects the timing of runoff and the infiltration process, the steeper slope and the steeper the drainage channels, the quicker flow response and the higher the peak flow.

How rapidly precipitation infiltrates into the soil is a critical factor in evaluating a torrent flood threat. The Curve Number (CN) parameter (SCS, 1972), is calculated on the basis of soil map and land use map. This data enabled assess predisposition of a catchment in terms of transformation of rainfall into runoff. The Curve Number (CN) was reclassified into four classes: (1) 33–49, (2) 50–77, (3) 78–89, (4) 90–100.

Hydrological conditions as influencing factor were characterized by the drainage network density (DND). The data of drainage network density were divided into five classes: (1) 0–1 km/km^2, (2) 1–2 km/km^2, (3) 2–3 km/km^2, (4) 3–4 km/km^2, (5) 4–10 km/km^2. This parameter is one of the most important characteristics for evaluating potential runoff. Land use – land cover (LULC) practices have a significant influence on torrential flooding through runoff volume and flow velocity. Vegetation, respectively forest, cover intercept precipitation and create more porous soils due to their roots. The land use – land cover practices were reclassified according to Corine Methodology (CLC) into five classes: (1) 112, 121, 122, 124, 311, 312, 313, (2) 142, 231, 243, 321, 324, (3) 132, 211, 222, 242, (4) 131, 333, 334, (5) 411, 511, 512.

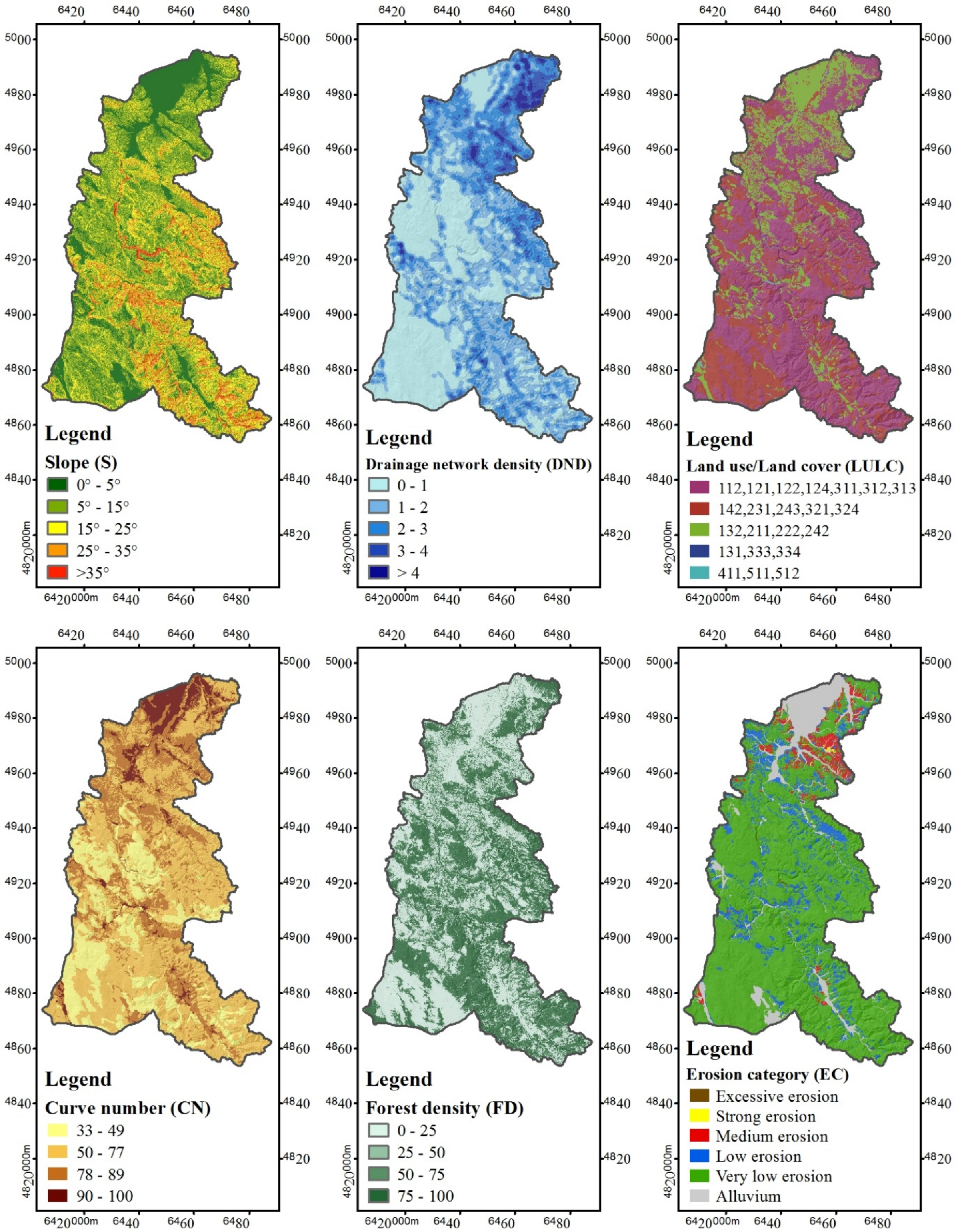

Figure 4. Thematic maps of influencing factors used in development of Torrential Flood Susceptibility Model (TFSM)

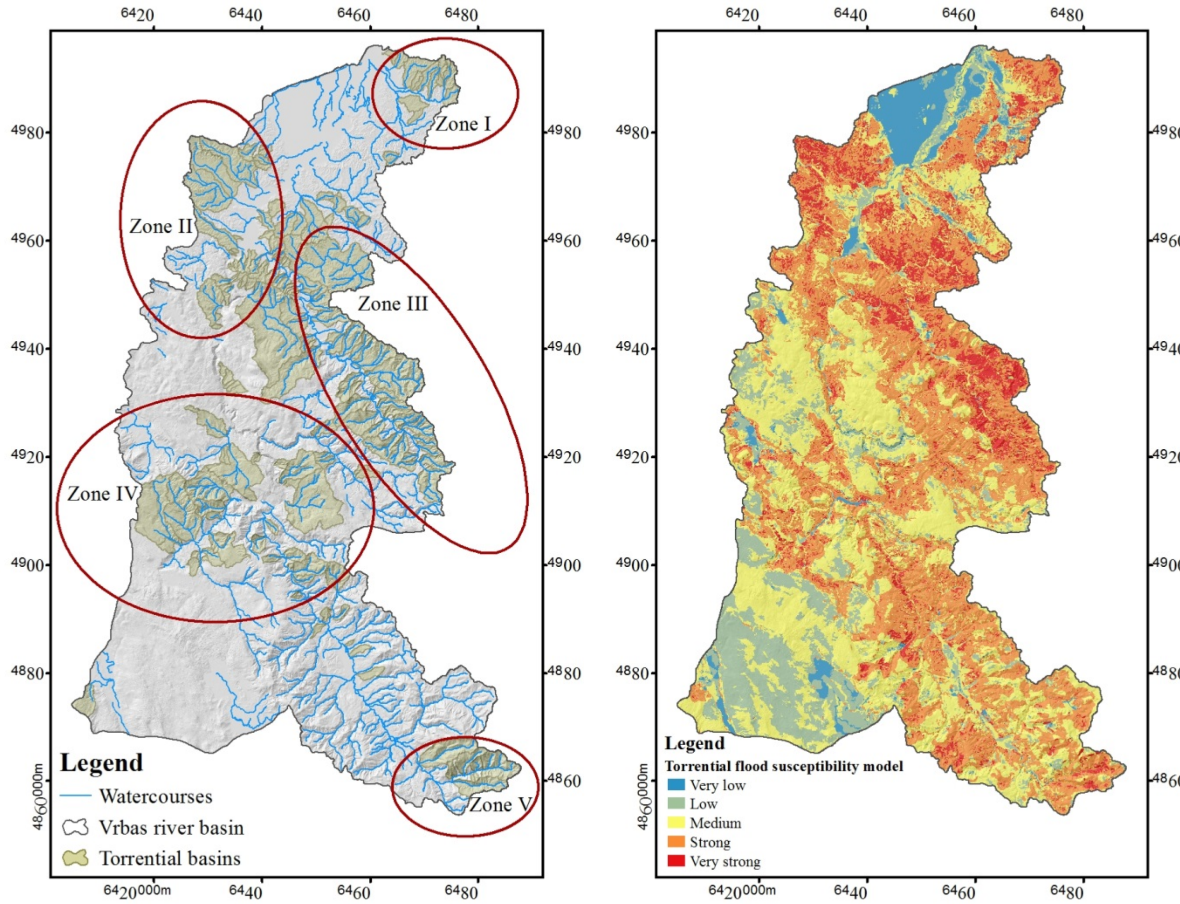

Figure 5. Identified torrential basins in the Vrbas basin with torrential zones in Vrbas basin (left) and Torrential Flood Susceptibility Model for the Vrbas basin (right)

Table 2. The percentage share of torrential flood susceptibility categories in the Vrbas river basin and validation indicators of the Torrential Flood Susceptibility Model in the entire Vrbas river basin

Susceptibility category	Basin surface area (km^2)	Basin surface area (%)	Degree of fit (%)
Very low	317.09	5.06	1.07
Low	862.04	13.71	3.30
Medium	2246.03	3571	15.59
Strong	2261.57	35.96	30.97
Very strong	601.56	9.56	49.07
Total	6289.19	100.00	100.00

Low value of forest density (FD) represents an increased torrent flood potential, while the highest forest density value represents a reduced torrent flood potential. In this study forest density (FD) was divided into four classes: 1) 0–25 %, (2) 25–50 %, (3) 50–75 %, (4) 75–100 %.

Physical-geographic and anthropogenic factors and their connection to torrential basins also determine the threshold and are indirect factors for the occurrence of torrential floods due to severe/extreme rainfall events. This causality is very well indicated by erosion maps (erosion category - EC) of river basins, because when it comes to torrential floods it should be kept in mind that they are a consequence of the fluvial erosion process. Therefore, if a watercourse has characteristics of a torrential regime, its basin must be affected by intense erosion processes. The erosion was reclassified into five categories: (1) Excessive erosion (2) Strong erosion (3) Medium erosion (4) Low erosion (5) Very low erosion (6) Alluvium.

After defining influencing factors, the GMM was used for generated Torrential Flood Susceptibility Model (Fig. 5). According to the Torrential Flood Susceptibility Model for the Vrbas river basin, 45.52 % of the area is within strong and very strong susceptibility category (Table 2). If we analyze the spatial distribution of these categories, we can see that it corresponds to the basins in which it is realistic to expect the appearance of torrential floods considering the intensity of erosion processes, specific runoff and other relevant factors.

The basic characteristics of torrential watercourses in the Vrbas river basin are determined by the specific dynamics of torrents. If we look at the characteristics of this phenomenon, we will see that all torrential streams in the Vrbas basin have specific geomorphological characteristics, that is, pronounced vertical relief dissection, great valley side and stream gradients, significant intensity of erosion processes (surface and linear), while the lower parts of the course are in alluvial planes where torrential watercourses flow into a larger river, which often passes through urban areas. Due to the size of the river channel and its capacity, which is not sufficient for the passage of torrential flood waves, most often the water overtops the banks and torrential floods occur.

The validation of this model randomly split the existing register of torrential basins into two groups: one group was used to create the susceptibility model and the other for the validation of the model. By achieving a certain level of quality, the resulting susceptibility model can be regarded as an acceptable predictive tool for assessing the occurrence and development of torrential floods within the observed area (Table 2).

According to the validation indicators of the Torrential Flood Susceptibility Model, 80.04 % are in the category of strong and very strong susceptibility, while only 4.37 % are in the category of very low and low susceptibility, which are very good results of the validation.

The Torrential Flood Susceptibility Model allowed us to identify the areas of the Vrbas river basin that are susceptible to torrential floods, i.e. that have a strong or very strong potential for the torrential floods. If we use the WSR-88D Doppler radar to determine the amount of precipitation that will potentially fall in an area, and if we have a torrential flood susceptibility model for that area (such as this model for the Vrbas river basin), we can very quickly warn all institutions responsible for the protection of people and goods. The Torrential Watercourses Cadastre for the Vrbas river basin and the Torrential Floods Susceptibility Model, together with the information of the Hydrometeorological Institute on expected precipitation (especially precipitation exceeding 20–30 mm/24h), are basic tools in timely reporting, warning and preventive action in case of potential flood events. A good example is the case from 2014, when an orange warning was issued by the RS Hydrometeorological Institute, stating that torrential floods may occur in northern and north-western parts of the Republika Srpska. If at that time there was a torrential watercourses cadastre or torrential flood susceptibility model for the Vrbas river basin, the relevant institutions would focus their attention on the identified basins with strong and very strong torrential flood susceptibility. The consequences would certainly be mitigated since there were human casualties in that event.

5. CONCLUSIONS

The development of flood hazard and flood risk maps (Implementation of European Flood Directive 2007/60EC) for the Vrbas river basin has to include the problem of torrential floods. Unfortunately, there was no torrential basins cadastre in Bosnia and Herzegovina, hydrometeorological data and historic information about torrential floods events, which we can use in identifying basins at risk of torrential flooding, the main aim of the study was to develop a methodology that identifies torrential flood prone zone in Vrbas river basin.

The first task was to identify the torrential basins, that is, to create the Cadastre of Torrential Basins in the Vrbas basin. After detailed field reconnaissance and analyses, whose methodology is given in the chapter Data and Methodology, 174 torrential basins have been identified, occupying 1753.33 km^2 of the Vrbas basin. The second task was to create the Torrential Floods Susceptibility Model for the Vrbas basin. According to the results of the Model, 45.52 % of the Vrbas basin area is in the categories of strong and very strong susceptibility to torrential floods. Validation indicators of the Torrential Flood Susceptibility Model show that the 80.04 % are in the category of strong and very strong susceptibility.

The used methodology based on GMM method and used influence factors, show good results in delimitation of the area with high and very high susceptibility to torrential floods into the Vrbas basin. Its general conclusion is that the used methodological approach represents a good base for future research, and it has potential for the practical use and should be tested in other river basin in Bosnia and Herzegovina.

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