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STEPGRAD
СТЕПГРАД

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FLASH FLOODS VULNERABILITY ASSESSMENT OF THE MUNICIPALITY OF ČELINAC, BOSNIA AND HERZEGOVINA

Abstract

This paper analyses the susceptibility of territory of municipality Čelinac to flash floods using the Flash Flood Potential Index (FFPI). All operations related to calculating the FFPI were conducted in a GIS environment. The research results showed that 38.42% of the territory belongs to the category of low susceptibility to flash floods. The category of moderate susceptibility includes 36.86% of the territory, while 18.77% of the territory is classified as highly susceptible to flash floods. The very high susceptibility to flash floods applies to the area occupying 5.95% of the total territory of the Čelinac municipality. This research can be useful to all subjects involved in natural disaster protection, local government, insurance companies, and the general population.

Keywords: FFPI, flash floods, GIS, Čelinac

ПРОЦЈЕНА УГРОЖЕНОСТИ ОПШТИНЕ ЧЕЛИНАЦ БУЈИЧНИМ ПОПЛАВАМА

Сажетак

У овом раду анализирана је угроженост територије општине Челинац од бујичних поплава примјеном индекса потенцијала бујичних поплава (FFPI). Све операције које су се односиле на израчунавање FFPI, урађене су у ГИС окружењу. Резултати истраживања показали су да 38,42% општине припада категорији ниске угрожености бујичним поплавама. Категорија средње угрожености обухвата 36,86% територије, док се 18,77% територије налази у категорији високе угрожености. Веома висока угроженост бујичним поплавама односи се на простор који заузима 5,95% од укупне територије. Ово истраживање може бити од користи свим субјектима који се баве заштитом од природних несрећа, локалној самоуправи и слично.

Кључне ријечи: FFPI, бујичне поплаве, ГИС, Челинац

1. INTRODUCTION

One of the most significant and prevalent natural hazards are flash floods, which cause significant economic damage and in some cases, loss of life [1, 2, 3]. Based on research conducted in Europe during the period from 1950 to 2006, 40% of all flood events were flash floods [4]. What is concerning is the fact that the number of flash floods has increased when observing the period from 1950 to the beginning of the 21st century [5]. However, despite flash floods being one of the most significant natural hazards, occurring in many regions of Europe, the degree of their investigation and documentation is not at a satisfactory level [4, 5, 6, 7]. The level of investigation of flash floods in Republika Srpska, i.e., Bosnia and Herzegovina, is low and not proportional to their significance, especially when considering the economic and other damages caused by flash floods [8]. Flash floods are classified as natural hydrological disasters characterized by the sudden appearance of maximum water flows and the significant transport of suspended and bedload sediment in the beds of flash flood streams. Flash floods can be described as a hydrological phenomenon characteristic of watersheds with steep slopes and relatively small surface areas. Flash floods occur in response to extreme rainfall episodes, which are usually short in duration and high in intensity [9]. In differentiating flash floods, the key determinant relates to the speed of occurrence, which, in the case of intense rainfall episodes, is analogous to the watershed concentration time, typically averaging around 6 to 7 hours [10, 11]. Flash flood streams are defined as natural streams with large and extreme fluctuations in water flow and sediment transport during a hydrological year. The specific and variable characteristics of climate, relief, terrain geology, soil and vegetation cover, as well as changes in socioeconomic conditions such as population migration or land use, represent a wide range of conditions and factors contributing to the occurrence of flash floods. The frequency of flash floods depends on the dominance of those factors and conditions that favor their occurrence. The genesis of flash floods is linked to mountainous areas, while lower areas within the same watersheds, usually inhabited, often become even more vulnerable to flood waves. Natural disasters cannot be prevented, but a better understanding of the processes and clearly defined methodologies can help mitigate their impacts. The Floods Directive 2007/60/EC highlighted the need for preparing flood hazard maps and flood risk maps. However, all activities related to the creation of these maps focused only on larger river channels, while flash flood streams and their watersheds were completely neglected [12]. Given that flash floods in Republika Srpska, i.e., Bosnia and Herzegovina, are one of the most frequent natural disasters, mapping the hazard and risk of flash floods is of particular scientific and societal interest. It should be emphasized that flash floods pose a real challenge when it comes to their detection and forecasting. On one hand, the methodologies used for analyzing flash floods can be very simple, for example, methodologies that only consider precipitation data. On the other hand, there are complex methodologies that utilize sophisticated software, spatial data management, modeling, and forecasting to support them [13]. Observing globally, many countries have developed specific tools used to assess the potential occurrence of flash floods, but the United States, relatively speaking, leads in this regard. In the USA, as part of efforts to enhance flash flood management, a tool has been developed with the aim of better understanding local physical-geographical characteristics that influence the occurrence and development of flash floods [14, 15, 16, 17]. One of the tools commonly used in identifying areas with a high potential for flash floods is the Flash Flood Potential Index (FFPI), first applied by Greg Smith in 2003. This index takes into account numerous factors directly influencing the runoff process, all aimed at identifying areas with a high potential for flash flood development [18]. However, in order to enhance Smith's original methodology, several authors have contributed to modifying the existing methodology to avoid subjective approaches when defining the weighting factors for individual criteria included in the analysis [19, 20, 21, 22, 23, 24, 8, 25].

This paper analyzes the FFPI for the territory of the Čelinac municipality to gain insight into the spatial distribution of areas vulnerable to flash floods. Geospatial data processing and necessary analyses were conducted using the open-source QGIS 3.17 software package. The analysis results, in the form of a flash flood hazard map, were overlaid with data related to populated areas, all aimed at identifying the most vulnerable inhabited places. Research of this type can be significant for local government units because the local level is a crucial instance in reducing the risk of natural disasters. Additionally, the research results can be beneficial to various sectors such as water management, forestry, agriculture, spatial planning, transportation, environmental protection, and similar fields. Moreover, they can serve as a basis for further in-depth research on this issue.

2. STUDY AREA

The municipality of Čelinac is located in the northwestern, hilly-flat region of the Republika Srpska, within Bosnia and Herzegovina. The municipality covers an area of 362 km2 and shares borders with the city of Banja Luka and the municipalities of Laktaši, Prnjavor, Kotor Varoš, Teslić, and Kneževo. The municipality has a population of 16,974 inhabitants [26]. The municipality of Čelinac comprises 30 inhabited places organized into 17 local communities. It's important to emphasize that Čelinac is situated in the central part of the Banja Luka region, with major arterial roads, regional routes, and railway lines traversing its territory, connecting the entire region. The southern and southwestern parts of the municipality reach elevations up to 760 meters, while the northern part, which is the largest in terms of area, ranges from 300 to 600 meters above sea level. The lowest point in Čelinac is at the confluence of the Jošavka River and the Vrbanja River, at an altitude of 196 meters. The climate in the Čelinac municipality is moderately continental, influenced by the continental climate of the Pannonian Plain and the mountain climate from the Manjača, Vlašić, and Čemernica massifs. The average annual temperature is 10.4°C, with December being the coldest month and July the warmest. The pronounced annual temperature fluctuations, along with high amplitude of absolute extreme temperatures, reflect a high degree of continental climate. The average annual precipitation in Čelinac is around 1000 mm, with the highest rainfall occurring in July and November, and the lowest in February. There are approximately 130 rainy days per year. The northern, central, and western parts of the municipality belong to the Vrbas River basin, while the eastern and southern parts belong to the Ukrina River basin. The most significant watercourse in the municipality is the Vrbanja River, with other major watercourses including the Jošavka, Ukrina, Turjanica, and Švrakava rivers. Looking at the network of permanent and intermittent watercourses, it can be concluded that the hydrographic network is well developed. Forests and forest land dominate the overall land use structure, covering 23,761 hectares or 61.45% of the total area of the municipality. The second most prevalent land use category is agricultural land, spanning 9,791 hectares or 27.12% of the municipality's territory. Within the agricultural land category, arable land is the most prevalent (7,102 hectares), while meadows and pastures cover 2,588 hectares. Other areas in the observed territory include built-up land, water bodies, and other land use categories.

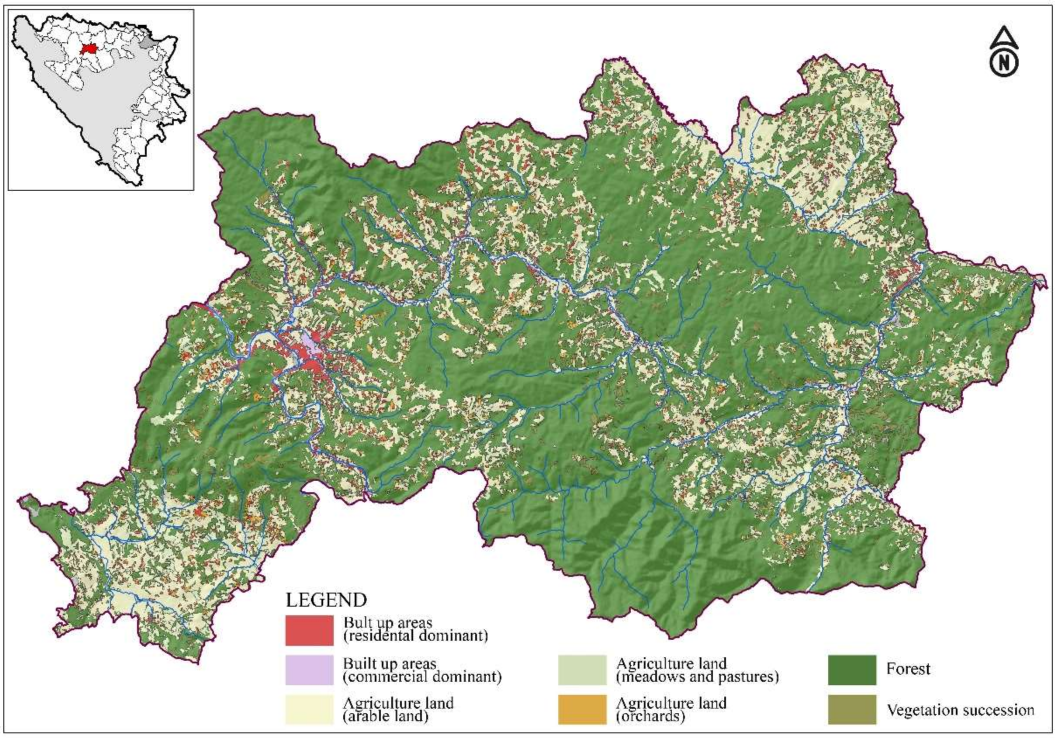

Figure 1. The territory of the Čelinac municipality

3. MATERIALS AND METHODS

The method used in this study to determine the susceptibility to flash floods involves calculating the Flash Flood Potential Index (FFPI). The original Flash Flood Potential Index (FFPI), developed within the framework of the National Weather Service for the Colorado River basin, utilized variables related to terrain slope, vegetation cover, soil texture, and land use [18]. Due to the absence and unavailability of certain data, this study analyzed variables related to terrain slope, geological substrate, land cover, and vegetation index. The coefficient values for each variable range from 1 to 10, where the lowest value (1) represents areas least vulnerable to flash floods. Standardization of the coefficients is performed for each specified variable based on predefined values. The Flash Flood Potential Index is calculated based on the formula:

$$FFPI = (S + L + G + V) / 4 \quad (1)$$

where S represents terrain slope, L represents land cover, G represents geological characteristics, and V represents vegetation cover.

Terrain slope data were obtained based on the analysis of a digital terrain model generated from the digitization of topographic maps at a scale of 1:25,000. This digital terrain model has a spatial resolution of 25 meters. Terrain slopes were initially calculated in percentages, after which the following formula was applied [27]:

$$S = 10^{n/30} \quad (2)$$

where "n" represents the slope in %. If "n" is greater than or equal to 30%, then the value of S is always 10. Slopes ranging from 0-30% are assigned values from 1-9 using a simple classification method of equal intervals. Geological substrate data were obtained through the digitization of basic geological maps at a scale of 1:100,000. Specific types of geological substrates were assigned corresponding coefficients based on the characteristics of the rocks themselves (e.g., strength, permeability). Land cover data relate to the Corine Land Cover and were obtained from the European Environment Agency portal. The FFPI values assigned to each land cover class depend on the influence of that class on the occurrence of floods [28, 24]. The highest FFPI values (10, 8, 7) are assigned to built-up areas and areas used for agricultural production. On the other hand, areas covered by forests or pastures have lower values due to their infiltration capabilities, which affect the runoff rate.

The vegetation index is calculated based on the NDVI in the QGIS environment, for the period from May to October, using Landsat 8 satellite imagery with a spatial resolution of 30 meters. The calculation of NDVI (Normalized Difference Vegetation Index) is based on the following formula:

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

where NIR represents the value of the near-infrared band and R represents the value of the red band. The NDVI values for the Čelinac municipality range from 0.02 to 0.66. Values closer to zero represent built-up areas and usually have low vegetation presence (0-0.2). Moderate NDVI values (0.2-0.5) indicate the presence of sparse vegetation (pastures, shrub vegetation, etc.). High NDVI values (above 0.5) indicate the presence of forests and other dense vegetation.

Table 1. Coefficient Values for Different Variables and Their Categorization According to FFPI

Slope (%)	Land cover (CLC)	Vegetation index	Geology	FFPI
≤ 3	-	0,55 – 0,66	Carbonate rocks	1
6	131, 311, 312	0,52 – 0,55	Alluvial sediments	2
9	313	0,49 – 0,52	Dykes, peridotites, hornfels	3
12	-	0,46 – 0,49	Flysch, lapor,bBreccia	4
15	231	0,43 – 0,46		5
18	324	0,39 – 0,43	Metamorphic rocks	6
21	243	0,35 – 0,39	Proluvium	7
24	242	0,30 – 0,35	-	8
27	-	0,22 – 0,30	-	9
≥ 30	112	0,02 – 0,22	-	10

After standardizing the coefficients for each individual variable and calculating the Flash Flood Potential Index, the classification process is undertaken to identify areas based on their susceptibility to flash floods. In this study, four classes of susceptibility to flash floods have been identified: low, moderate, high, and very high susceptibility to flash floods. The susceptibility class may indicate the possibility of flash floods occurring under appropriate conditions. However, whether flash floods will occur and at what intensity depends on numerous factors.

4. RESULTS AND DISCUSSION

Flash floods represent one of the most prevalent natural hazards across much of the territory of Bosnia and Herzegovina, including the Republika Srpska. The increase in rainfall due to climate change, particularly the rise in extreme rainfall events and the increase in the number of days with rainfall exceeding 20 mm [29], has resulted in an increase in the frequency of flash floods of varying intensities. Hydrological and meteorological data, as well as flood data, are often available for large rivers and basins, while such data usually do not exist for small basins. Small basins have their own characteristics and play a role in runoff formation, making it very important for them to be the subject of hydrological analyses [30]. Intense rainfall is an important but not decisive factor influencing the formation of flash floods. Some of the factors essential for flash flood formation were analyzed in this study, and the Flash Flood Potential Index was calculated to identify areas with different characteristics related to flash flood susceptibility. The variables analyzed include terrain slope, geological substrate, land cover, and vegetation index. Appropriate coefficient values were assigned to each individual variable to standardize them. All analyzed layers were converted into raster data models, and layers related to terrain slopes and NDVI were subsequently reclassified according to defined values.

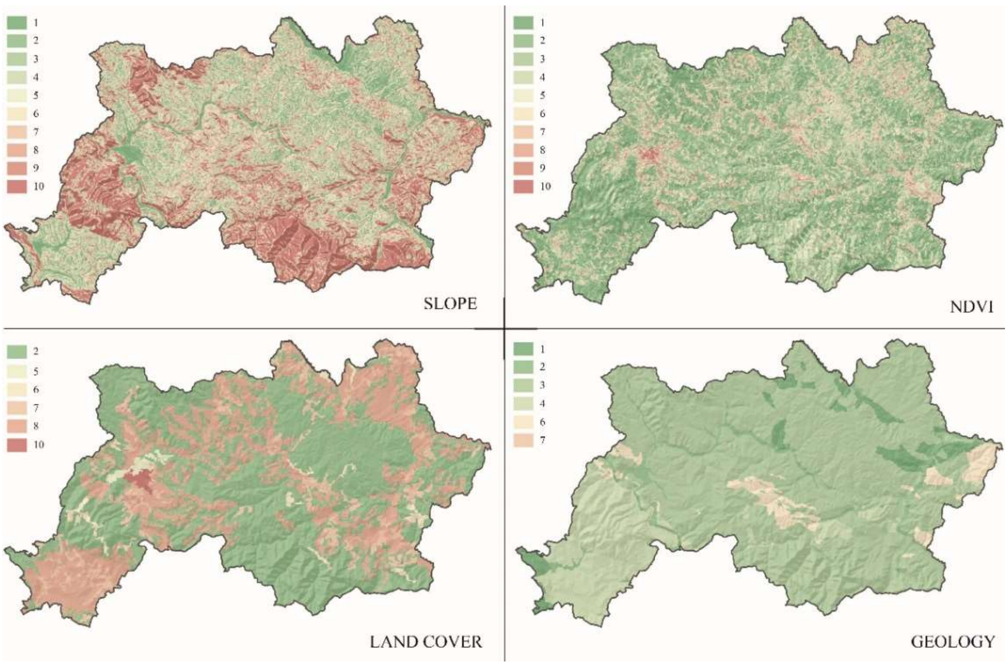

Figure 2. Analyzed variables with standardized values

After standardizing the analyzed variables, a final layer was created using the raster calculator. On the final layer, or the synthesis map, values were grouped into four categories: low, moderate, high, and very high susceptibility to flash floods. Based on the FFPI values, the most prevalent category is low susceptibility to flash floods, covering 137.4 km2 or 38.42% of the Čelinac municipality's territory. Following the low susceptibility category, large areas are covered by the moderate susceptibility category, extending over 131.8 km2 or 36.86% of the Čelinac municipality's territory. The high susceptibility category to flash floods covers 67.1 km2 or 18.77% of the total municipality's territory, while the very high susceptibility category is recorded on 21.3 km2 or 5.95% of the Čelinac municipality's territory. The values related to the high and very high susceptibility categories are closely related to the physical-geographical characteristics of the observed area.

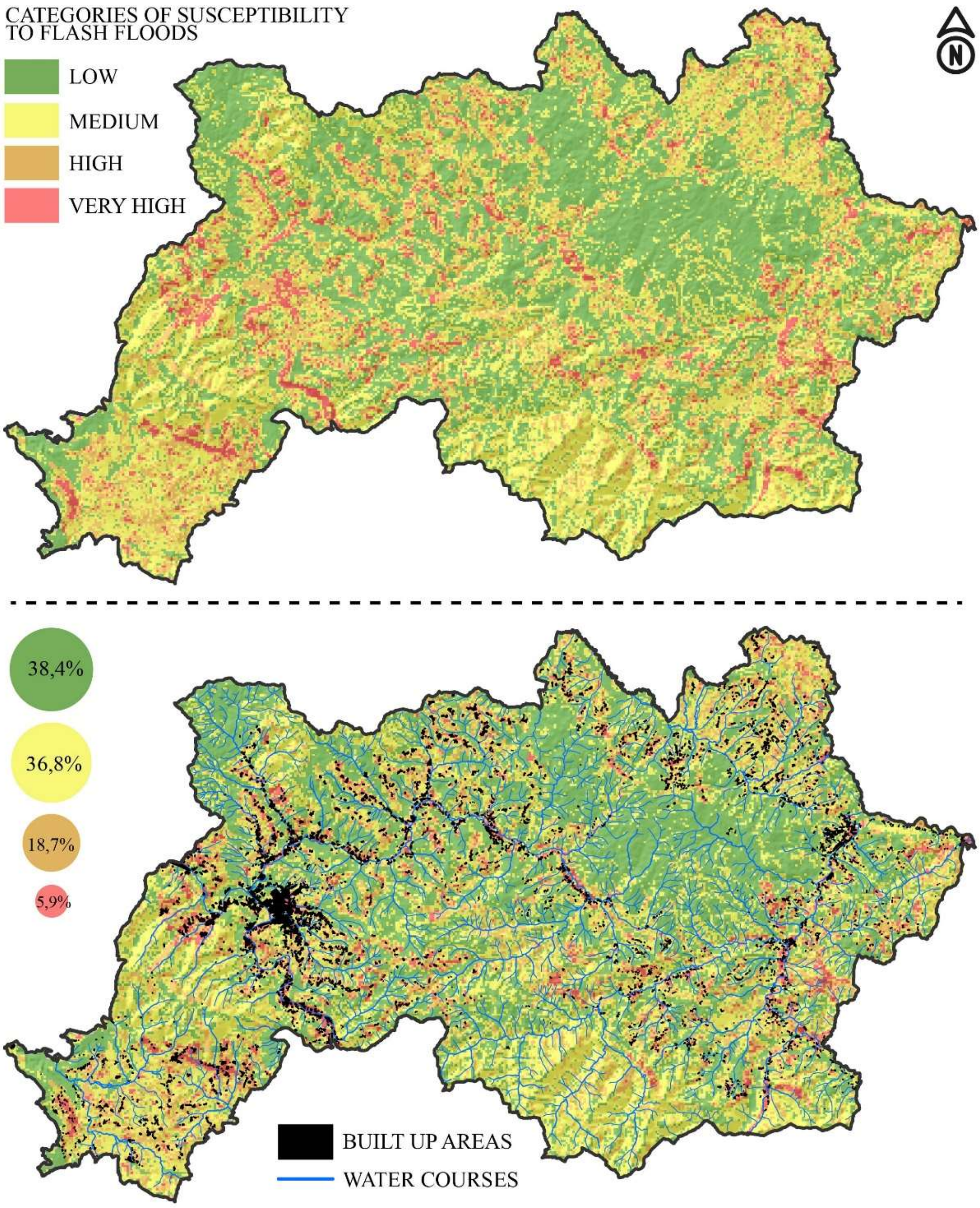

Figure 3. Categories of susceptibility to flash floods calculated based on FFPI

When it comes to geological characteristics, the territory of the Čelinac municipality is mostly characterized by rocks that are, conditionally speaking, resistant to erosion. However, due to a combination of different factors, areas with moderate and strong erosive processes have been identified in the observed area. Moderate erosive processes are identified in the southwest, central, and northeast parts of the municipality, while strong erosive processes are identified in several locations in the wider surroundings of the municipal center, as well as in the north and east of the observed area. On the other hand, forest complexes located in the northwest, central, and southern parts of the municipality are partially degraded. It is important to note that pure deciduous forests are the most prevalent in the forest structure, occupying about 80% of the total forested area. Looking at the vertical breakdown of the relief, higher values are recorded in the northwest, west, south, and east parts of the municipality. These characteristics, combined with other physical-geographical characteristics, have influenced the formation of flash flood catchments in the observed area. A larger number of flash streams in the observed area belong to the mixed category of flash streams, with an emphasis on surface erosion type. Previous research in the Ukrina River basin also identified the mixed category of flash streams as the most dominant type in the basin [30]. In the southern, western, and eastern parts of the observed area, characterized by hilly-mountainous terrain, flash streams with large longitudinal slopes and pronounced linear erosion have been identified. In these areas, erosion is concentrated only in the beds of flash streams. Due to their location, these flash streams do not currently pose a threat to settlements or infrastructure, so they are not the focus of activities related to protection from the harmful effects of flash floods. Using zonal statistics, the mean FFPI values were calculated for each individual inhabited place. Five classes were identified in total to observe differences in FFPI values at the level of inhabited places.

Figure 4. Average FFPI values per inhabited places

The most vulnerable inhabited places to flash floods are Čelinac, Miloševo, Popovac, Lipovac, Kablovi, and Basići. Inhabited places with slightly lower average FFPI values include Šahinovići, Balte, Mehovci, Čelinac Gornji, Ospječko, Branešci Gornji, Vijačanji Gornji, Šnjegotina Velika, Šnjegotina Srednja, and Šnjegotina Donja. Approximately 67% of the total population of the municipality resides in these inhabited places. However, when comparing the average FFPI values for inhabited places with the values defined for susceptibility categories to flash floods, it is observed that, on average, all inhabited places in the Čelinac municipality fall into the moderate susceptibility category to flash floods.

5. CONCLUSION

More significant and systematic research on flash floods in Republika Srpska, i.e., Bosnia and Herzegovina, is not adequately represented in numbers. In order to predict flash floods, it is not sufficient to analyze only meteorological data; it is necessary to include in the analysis multiple physico-geographical characteristics that influence the occurrence and development of flash floods. In practice, the influence of geological substrate, relief, density of the hydrographic network, land use, density of vegetation cover, erosive processes, and other factors affecting runoff and the creation of conditions for the occurrence of flash floods is often analyzed. Identifying areas at risk of flash floods, i.e., producing a hazard map, is crucial for preventive flood protection activities. If the local community, or any other administrative level of governance, has developed preventive measures related to protection from flash floods, there is a greater chance of avoiding material damages, disruptions in economic activities, or, in the worst case, loss of human lives. There are many different original and modified methodological approaches aimed at identifying areas vulnerable to flash floods. One of the simpler methodologies that yields solid results is the Flash Flood Potential Index (FFPI). This study applied a methodology for calculating the FFPI for the territory of the municipality of Čelinac. The research results showed that 38.42% of the municipality belongs to the category of low susceptibility to flash floods. The category of moderate susceptibility to flash floods encompasses 36.86% of the municipality's territory, while 18.77% of the municipality's territory is classified as highly susceptible to flash floods. Very high susceptibility to flash floods refers to an area occupying 5.95% of the total territory of the Čelinac municipality. Furthermore, in order to gain insight into the vulnerability of individual settlements to flash floods, overlays were created between the layers representing the FFPI values and the layers representing the boundaries of populated areas with population figures. Average FFPI values indicate that Čelinac, Miloševo, Popovac, Lipovac, Kablovi, and Basići have a higher susceptibility to flash floods than other populated areas in the municipality. Considering both natural and anthropogenic factors influencing the occurrence and development of flash floods, there is a need to establish a system for periodic or continuous monitoring and control of flash floods. With the help of new technologies, it is possible to gather detailed field data that can be analyzed and incorporated into predictive models. These activities may not be able to eliminate the occurrence of flash floods, but they can provide timely information regarding the onset of danger, thereby helping to avoid more serious damages to people and property. The concept of FFPI has certain limitations, but its application in conditions where analysts are constrained by the quantity and quality of data still yields usable results. Of course, efforts should be made to use the most relevant data for analysis in terms of accuracy and detail, and to continuously improve and adapt the methodology to the specific characteristics of the areas under investigation. Additionally, if possible, it is desirable to validate the results of the analysis to determine whether the applied model is adequate for the given task. The results of this research can serve relevant institutions involved in natural disaster protection as well as local communities. Furthermore, this research can serve as a starting point for further and more detailed investigations into this issue.

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