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Determination of Flash Flood Hazard Areas in the Likodra Watershed

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Abstract: Climate change has a direct impact on flash floods, and indirectly on the environment, society, and economy, due to the rapid development and difficulty of predicting this hydrological phenomenon. The main objective of this study is to assess the potential flash flood hazard areas in the Likodra watershed (218.62 km^2), one of the most vulnerable parts to flash floods in Serbia, using the flash flood potential index (FFPI) and analytic hierarchy process (AHP) method. Recurring events from 1995 to this day and the devastating impact on settlements of the analyzed area show that this territory is extremely vulnerable. The data used include hydrological statistics (maximum daily rainfall) and spatial data on watershed geographical characteristics (slope, soils, land use, vegetation, drainage density) obtained or derived from various sources (maps, satellite images, digital databases) which were integrated into the GIS environment. The results indicate a severe flash flood hazard level, with high flash flood susceptibility classes occupying 76.20%, 87.78%, and 91.73% of the area, depending on the considered criteria and weights assigned to them.

Keywords: natural hazard; flash floods; hazard zoning; FFPI; AHP

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1. Introduction

Climate change directly affects the intensity and frequency of extreme precipitation [1,2], and indirectly affects regional security and development [1]. Flash floods (torrential floods) occur on small torrential flows as a result of intense rainfall and are characterized by the rapid formation of the torrential wave [3,4]. Throughout the world, floods represent one of the most devastating and destructive natural hazards [5] that have an impact on the safety of people and infrastructure [6]. According to van Loenhout et al. [7], the international disasters database (EM-DAT) recorded 7348 disaster events in the period 2000–2019, worldwide, out of which 3254 were floods (44%). Furthermore, the same author emphasizes that the economic loss was estimated at 651 billion, and the number of people affected by floods in this period amounts to 1.65 billion.

Throughout the world and in the continental part of Europe, the consequences of the heavy rainy season are flash floods [8]. Historical data indicate the great vulnerability of the Balkans to devastating and very frequent flash floods [9–13], while Kostadinov et al. [14] and Ristić et al. [15] point out that only in the territory of the Republic of Serbia there are between 11,500 and 12,500 torrential streams. Flash floods are the most frequent type of natural hazard in Serbia [16,17]. Based on the latest research, in the period 1915–2019, 2122 events of large flash floods were registered on the territory of Serbia in which more than 193 people lost their lives [18].

In May 2014, the Republic of Serbia (Krupanj, Šabac, Obrenovac, Bajina Bašta) was affected by intense rainfall which caused major floods and the activation of many landslides. This was initiated by a low-pressure system "Yvette (Tamara)" that formed over the Adriatic [13,19]. Total material damage in the Republic of Serbia was estimated at 1.7 billion euros [20,21]. In western Serbia, Krupanj municipality, 428 mm of rain fell in a 3-day period, leaving behind totally destructed houses, bridges, and sections of roads, flooding both urban and rural areas, and losing lives [22]. Likodra watershed is one of the most affected areas by flash floods in Serbia. With their outlet profile in the center of the Krupanj, the four torrents, Bogoštica, Kržava, Čađavica, and Brštica, have caused flooding many times throughout history. The biggest floods in the last 30 years were in 1995, 1999, 2001, 2014, 2016, 2020, and 2021 [18]. According to the damage report filed by the municipality of Krupanj to the Commission for determining damages from natural disasters (the Government of the Republic of Serbia), the total estimated damage amounts to 13.7 million euros.

To prevent and reduce destructive floods around the world, Smith [23] created the flash flood potential index (FFPI) model for the detection of potentially endangered areas, based on site-specific information (slope, land use, soil type, and vegetation). Selected parameters had equal weights (1), except slope which was given slightly higher weight due to its significance in flash flood development. Throughout the years, many researchers used this method to detect potentially endangered areas by flash floods all over the world: USA, China, Japan, Romania, Moldova, Serbia, and other countries [24–28]. Some of them used the original formula developed by Smith [23], and some used equal weights for slope, land use, vegetation cover, and soil index [29,30]. Others introduced new parameters for FFPI calculation and used different weights of the corresponding parameters (weighted flash flood potential index—WFFPI) [25,26,28,31–37]. Zeng et al., analyzed flash flood risk using the FFPI method as an initial analysis and added additional criteria such as rainfall (maximum 24 h, 6 h, and daily average) to determine the flash flood hazard index (FFHI) and found that model provides considerably accurate and reliable results on flash flood estimations in terms of spatial distribution [25].

The criteria for determining the potential flash flood index must be defined for each watershed, based on the natural conditions. Since all criteria do not contribute equally to flash flood problems, criteria weights must be determined using a subjective, objective, or integrated approach [38]. The subjective approach is based on expert knowledge and experience, an objective approach uses initial data (each alternative's performance on each criterion) and a mathematical model, while the integrated weighted models combine the previous two approaches. In practice, subjective weights are more commonly used, in which the analytic hierarchy process (AHP) finds wide applications [39–41]. In AHP, criteria weights reflect criteria importance obtained through pairwise comparison by decision makers. AHP is simple, and it can be incorporated with a GIS (Geographic Information System), which enables the users to rapidly determine the weights of the criteria. The main purpose of using AHP was to obtain more realistic results. Risk assessment and hazard assessment are the most popular areas of research where this method is often used [42].

The main objective of this paper is to assess the potential flash flood hazard areas in the observed watershed. This work provides a scientific basis and an improved methodology that enables the determination of the potential hazard zones from flash floods. Furthermore, this paper provides a basis for making preventive and timely decisions and measures aimed at preventing the destructive consequences of floods. For integrated flood risk management, creating hazard maps is a crucial tool. It can be used for increasing public awareness of flood-prone areas and for assisting local communities in formulating plans to lower these risks via both structural and non-structural measures. Moreover, decision makers in regional public institutions can use it for the construction of a clearer legislative framework corresponding to adaptive management. The maps may be used for emergency response programs, and for designing flood insurance products. Additionally, this can be used for sustainable land-use planning and spatial planning. Such actions can reduce damage caused by flash floods.

2. Materials and Methods

2.1. Study Area

The municipality of Krupanj is located in the northwestern part of the Republic of Serbia (Figure 1), on the right bank of the river Drina (Podrinje). Krupanj belongs to the Rađevina microregion, which geomorphologically coincides with the Likodra River watershed. The Likodra River is the left and largest tributary of the Jadar River. It is 32.96 km long and is formed by four torrents connecting in Krupanj (Bogoštica, Kržava, Čađavica, and Brštica). The watershed area of the Likodra River is 218.62 km^2, and the perimeter is 78.86 km long. The physical characteristics of the Likodra River watershed are presented in Table 1. Mountains Sokolske (973 m), Jagodnja (939 m), and Boranja (856 m) represent the natural border of the Likodra River watershed.

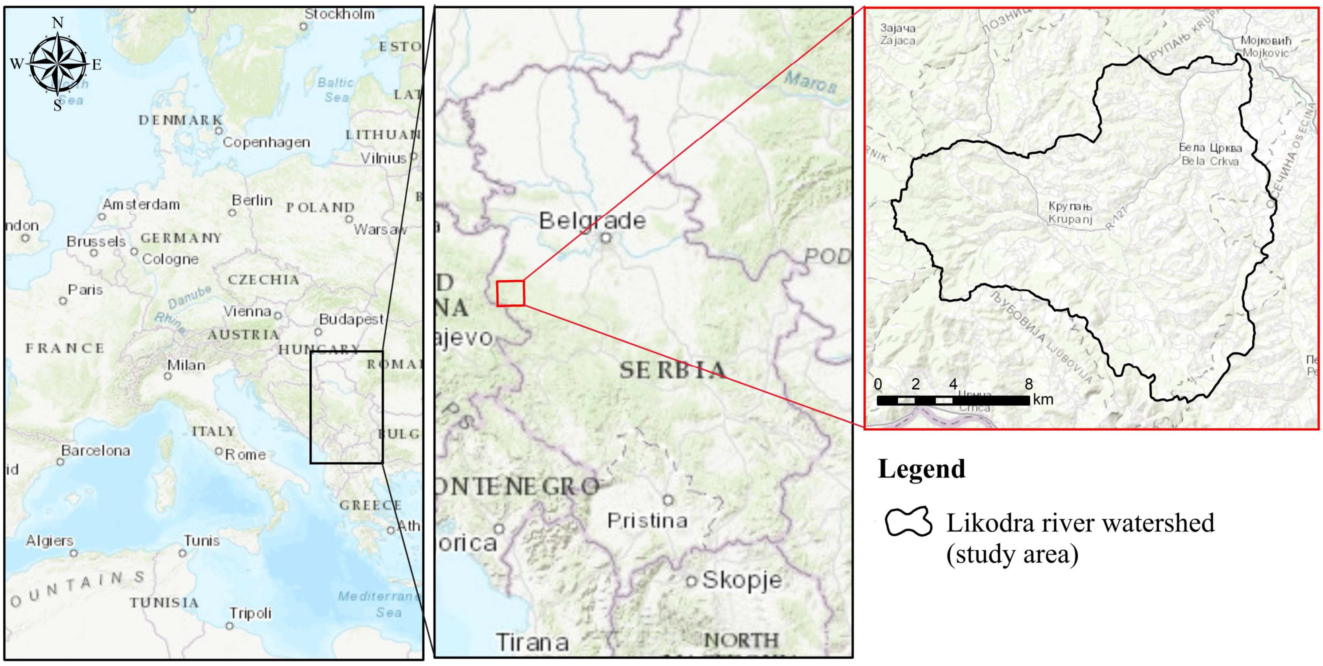


Figure 1. Geographical location of the Likodra watershed.

Table 1. Physical characteristics of the Likodra River watershed.

Parameter	Mark	Value	Unit
Watershed area	A	218.62	km^2
Perimeter	O	78.86	km
Peak point of the watershed (river basin)	H_{max}	858.64	m
Confluence point of the watershed (river basin)	H_{min}	153.86	m
River length	L	32.96	km
Shortest distance from the confluence point to the watershed central point	L_c	14.58	km
The absolute slope of the riverbed	I_a	2.14	%
The mean slope of the riverbed	I_u	1.13	%
Mean slope of the terrain	I_{sr}	21.26	%
Mean altitude	H_{sr}	446.31	m
Mean altitude difference	D	292.45	m
Total length of the waterways	$\sum L$	560.22	km
Hydrographic network density	G	2.56	km/km^2

Data used in this research were acquired from different databases and sources (Table 2). All spatial analyses were carried out using the licensed ArcGIS 10.8.2 desktop version.

The highest point in the Likodra River watershed is 960 m and the lowest is 153 m. The low areas under 200 m occupy 5.87 km^2, i.e., 2.69% of the territory, hilly mountainous area, from 200 to 500 m, occupies 146.57 km^2, i.e., 67.04% of the territory; and the mountain area higher than 500 m occupies 66.18 km^2, or about 30.27% of the territory.

In this study, steep slopes over 30% occupy 177.52 km^2 of the watershed area, while slopes up to 30% occupy 41.10 km^2. This shows a big potential for flash flood occurrence. The steeper and longer the slope, the less time for water to infiltrate the soil. Exactly 81.2% of the area is under the slopes over 30% (Figure 2).

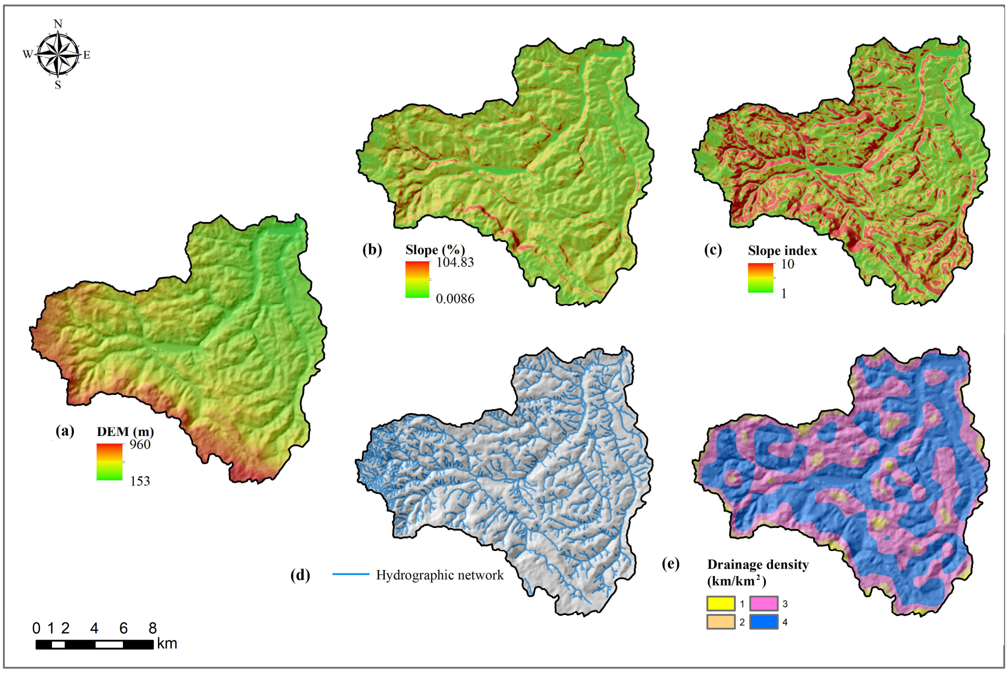


Figure 2. (**a**) Elevation; (**b**) slope; (**c**) slope index; (**d**) hydrographic network; and (**e**) drainage density (1—low; 2—medium; 3—high; 4—very high).

The drainage density of Likodra watershed has very high density. Areas covered by high-drainage density (1.0–2.0 km/km^2) occupy 89 km^2 or 40.71% and very high-drainage density areas (>2.0 km/km^2) occupy 111.7 km^2 or 51.1% (Figure 2). Flash flood potential areas are characterized by high-drainage density.

The Likodra River is partially regulated by the right defensive embankment along its course through Krupanj. After that, Likodra flows through the alluvial plain, all the way to the mouth of the Jadar River. Ristanović points out that the hydrographic conditions in this area are stipulated primarily by tectonic activity (Sava seismic area), geological composition, and climatic conditions (temperate continental climate with the characteristics of a microregion) [43].

The geologic formation of the Likodra watershed is lithologically represented by limestones, sandstones, agrilophyllites, phyllites, clays, grandiorites, pegmatites, dacite-andesites, and alluvium [22]. Regarding soil types, most of the watershed area (87.24%) is covered by fluvisols and cambisols. Those soils have moderately high infiltration rates and moderately low runoff potential. Their hydraulic conductivity is between 10 and 40 µm/s when saturated. Soils as planosols and vertisols cover 12.61% of the watershed, and they have hydraulic conductivity from 1 to 10 µm/s, a moderately low infiltration rate, and moderately high runoff potential. Nudilithic Leptosol covers 0.15% of the total watershed area and has a low infiltration rate, and high runoff potential (hydraulic conductivity less than 1 µm/s).

The average annual rainfall in the research area for the period 1992–2021 according to the Republic Hydrometeorological Service of Serbia data is 916.41 mm [44]. The least amount of precipitation occurs in the winter months (January–February), which is characteristic of this area. There are two rainfall peaks during the year, the first in the period of March–April, and the second one in the period of June–July [22,44].

Despite the abundance of streams and rivers in the Krupanj municipality, the orography and prevailing climate conditions point to major issues with frequent flash floods and intense erosion processes.

2.2. Method

Flood susceptibility areas were determined using the FFPI method and its modification with the AHP method (WFFPI). By adding another two parameters, also weighted by AHP, flood hazard areas were determined using FFHI.

2.2.1. Flash Flood Potential Index (FFPI) Method

The flash flood potential index (FFPI) method was developed by Smith in 2003, for the detection of areas potentially endangered by flash floods based on natural conditions (pre-event characteristics) [23]. Smith used a simple concept of combining raster data (in a GIS environment) of a slope, forest density, soil type, and land use to identify areas of high potential for flash floods (Equation (1)). A relative flash flood potential index ranging from 1 to 10 was assigned to each data layer based on the layer attributes corresponding to the hydrologic response. In the original method developed by Smith [23], input layers were weighed equally, apart from the slope layer, which was weighed slightly more (1.5 according to [24]), because of the significant influence that slope has in flash flood development.

$$\mathrm{FFPI} = (\mathrm{n}\cdot(\mathrm{M}) + \mathrm{L} + \mathrm{S} + \mathrm{V})/\mathrm{N} \quad (1)$$

where

FFPI is the specific value of FFPI with a theoretical range of 0–10; M—slope gradient; n—the weight of slope layer; L—land use; S—soil texture; V—vegetation cover/tree canopy density; N—a sum of weightings.

To calculate the FFPI in this study, the same parameters were used as in the approach that was initially established by Smith [23], and equal weights were assigned to them. Each parameter was further classified and the relative FFPI value between 1 and 10 was assigned to each class, depending on the features and hydrologic response, which is described in the upcoming text.

Slope: For slope analysis, and other physical–geographical characteristics of the watershed, the European Digital Elevation Model (EU-DEM), version 1.1 coordinated by the European Environment Agency (EEA) in the frame of the EU Copernicus program at 25 m resolution (raster), was used [45]. The slope map was prepared directly from the DEM using the ArcGIS spatial analyst tool, a method commonly used in generating slope maps using GIS. First, the slope of the terrain was expressed in percent, and then Equation (2), created by Zogg and Deitsch, was applied to reclassify the percentage slope into an FFPI slope index value (1 to 10), setting any slope of 30% or higher to an FFPI value of 10 (Table 2) [46]. Using a basic equal interval classification method, slopes ranging from 0 to 30% were given FFPI scores between 1 and 9 [23].

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

(n—slope in %).

Land use/land cover: The CORINE Land Cover database was used to create a land use map (ESRI FGDB 2018 version, funded by Copernicus). It consists of an inventory of land cover in 44 classes and has a spatial resolution of 100 m [47]. FFPI values were assigned to each land use class (Figure 3, Table 2), based on land use impact on flood occurrence [28,31,34]. The highest values of FFPI (7, 8, 10) are assigned to urbanized areas and areas used for massive agricultural production, i.e., areas where surface runoff forms the fastest. As a result of their role in surface runoff reduction owing to infiltration, areas such as forests and pastures are assigned with lower values (2, 3, 5).

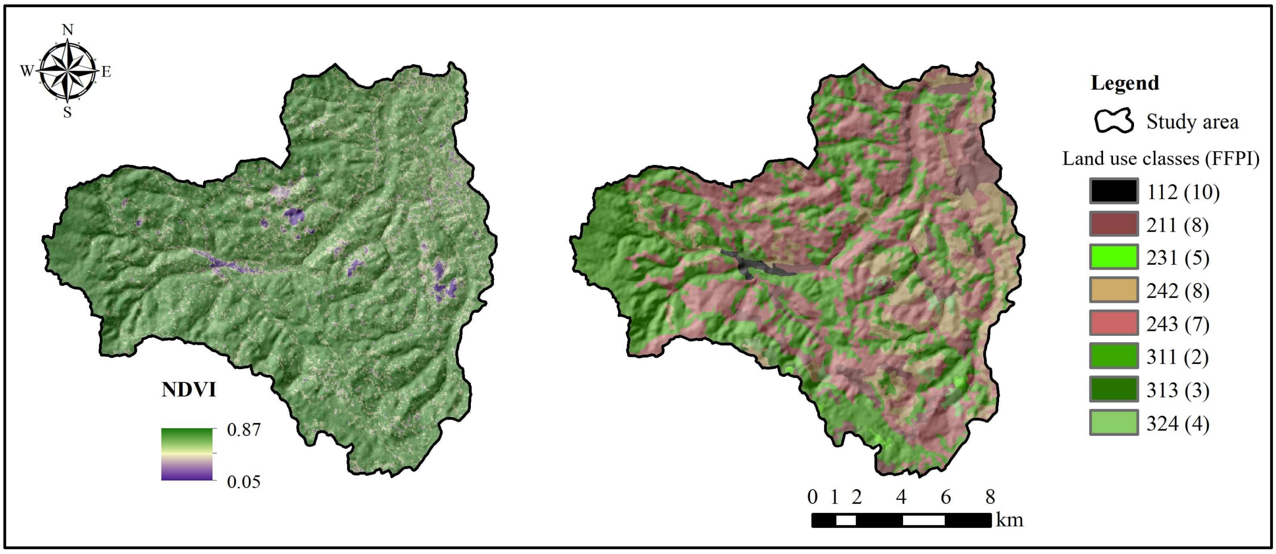


Figure 3. NDVI and land use map.

Vegetation index: Using the Google Earth Engine platform, vegetation cover was detected for the vegetation period (1 May–30 September) using the normalized difference vegetation index (NDVI). NDVI was calculated using Landsat 8 satellite images (LC08/C02/T1_TOA), with a spatial resolution of 30 m [48], as a ratio between the red (R) and near-infrared (NIR) values (Equation (3)). The NDVI values in the Likodra watershed vary from 0.049 to 0.87 (Figure 3). Values closer to zero represent urbanized/populated areas, indicated by the lower presence of vegetation (0–0.2). Moderate NDVI values (0.2–0.5) indicate the presence of sparse vegetation (pastures, shrubs, etc.). High NDVI values (over 0.5) indicate the presence of forests and other dense vegetation. Later, vegetation density was classified into FFPI values (Table 2). The lower the vegetation density, the higher the corresponding FFPI value.

$$\text{NDVI} = (\text{NIR–Red})/(\text{NIR} + \text{Red}) = (\text{Band 5–Band 4})/(\text{Band 5} + \text{Band 4}), \quad (3)$$

Hydrologic soil group: The research area's soil types were defined using the Soil Map of SR Serbia from 1966 (an edition of the Institute of Soil Science in Belgrade, scale 1:50,000), and the hydrologic soil group (HSG) was determined based on its ability to store water from rainfall and reduce runoff. The HSG represents the runoff potential and infiltration rates. Soils are classified into four categories: A, B, C, and D (A—high infiltration rate, low runoff potential; B—moderately high infiltration rate, moderately low runoff potential; C—moderately low infiltration rate, moderately high runoff potential; D—low infiltration rate, high runoff potential) [49,50]. The HSG was used to assign FFPI value (Table 2). The FFPI value for soils categorized in HSG group B was set at 4, considering both the characteristics of this soil group and the consulted literature [35,36], while the FFPI values of 6 and 8 were assigned to soils of HSG C and HSG D, respectively (Figure 4).

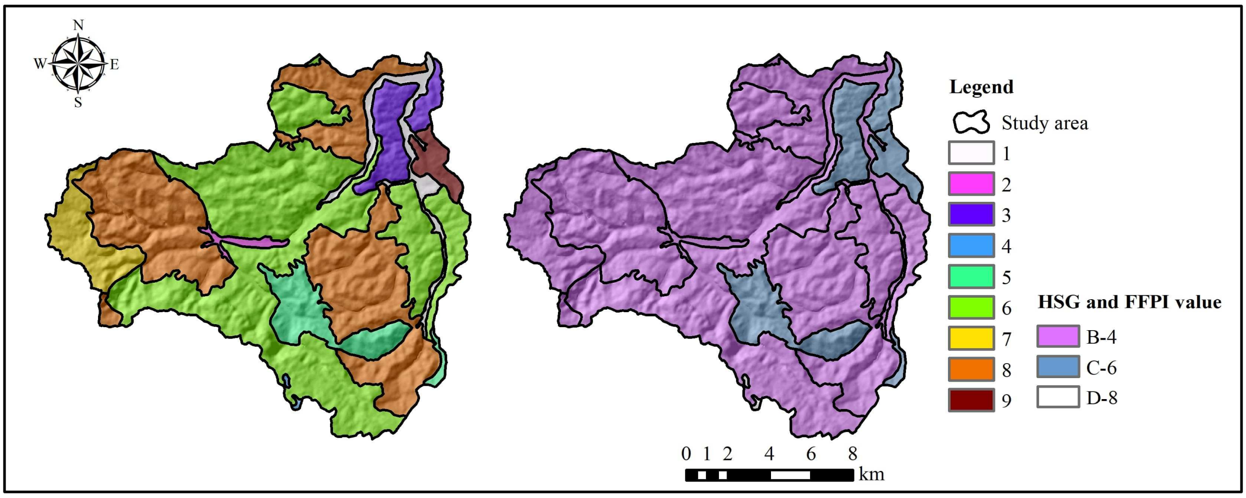


Figure 4. Soil map and HSG index (Soil type legend: 1—Haplic Fluvisol Coluvic Regosol; 2—Haplic Cambisol (Dystric, Skeletic on Granite); 3—Haplic Fluvisol (Eutric, Arenic); 4—Planosol; 5—Haplic Cambisol (Dystric, Skeletic on Shale); 6—Vertisol; 7—Haplic Cambisol (Eutric, Leptic); 8—Haplic Cambisol (Dystric, Siltic); 9—Nudilithic Leptosol).

Table 2. Parameters and its classes values assigned to calculate FFPI and WFFPI.

Parameters (Source and Resolution)	Classes		Area		FFPI Values	References
			km²	%		
Slope	<30%		41.10	18.80	1–9	[23,46]
European Digital Elevation Model (EU-DEM), version 1.1 (25 m)	>30%		177.52	81.20	10	
Land use/land cover	112_Discontinuous urban fabric		1.28	0.58	10	[28,31,34]
CORINE Land Cover database (ESRI FGDB 2018 version) (100 m)	211_Non-irrigated arable land		16.51	7.55	8	
	231_Pastures		1.00	0.46	5	
	242_Complex cultivation patterns		27.89	12.76	8	
	243_Land principally occupied by agriculture, with significant areas of natural vegetation		74.24	33.96	7	
	311_Broad-leaved forest		92.76	42.43	2	
	312_Coniferous forests		0.06	0.03	2	
	313_Mixed forest		1.28	0.58	3	
Vegetation index	Low	0.04–0.1	0	0	10	*
Landsat 8 satellite images (LC08/C02/T1_TOA) (30 m)		0.1–0.2	0.26	0.12	9	
	Moderate	0.2–0.3	0.68	0.31	8	
		0.3–0.4	1.12	0.51	7	
		0.4–0.5	4.04	1.85	6	
	High	0.5–0.6	10.03	4.59	5	
		0.6–0.7	24.84	11.36	4	
		0.7–0.8	146.76	67.13	3	
		0.8–0.87	30.89	14.13	2	
Hydrologic Soil Group	A	Sandy, sandy loam	0	0	2	[35,36]
Soil map of SR Serbia from 1966 (an edition of the Institute of Soil Science in Belgrade, scale 1:50,000)	B	Loamy, silty	190.72	87.24	4	
	C	Loamy, loamy clay	27.57	12.61	6	
	D	Clay, clay loamy	0.33	0.15	8	

Note(s): * Classification according to the equal interval method.

2.2.2. Weighted Flash Flood Potential Index (WFFPI) method and The Analytic Hierarchy Process (AHP) Method

For the calculation of WFFPI, the same parameters were used as in the FFPI method (Table 2), with the difference in assigning weights to each of the parameters based on the impact they have on flash flood occurrence.

The AHP method was developed by Tomas Saaty [51]. This method is a descriptive approach to decision making and is being used as the decision support in situations where there are more criteria (quantitative and/or qualitative) of different importance. AHP generates a weight for each evaluation criterion according to the pairwise comparison of the criteria by the decision maker. The higher the weight, the more important the corresponding criterion. The weight calculation obtained by the AHP method was combined with FFPI to obtain much more realistic results. Weights calculation starts with the generation of pairwise comparison matrix $A = [a_{ij}]$, $i, j = 1, 2, \ldots, n$. The coefficient a_{ij} are judgments provided by decision makers using Saaty's 1–9 scale, (where: 1—equal importance, 3—moderate importance, 5—strong importance, 7—very strong importance, and 9—extreme importance; 2, 4, 6, and 8 are values in between). Here in this paper, pairwise comparison was carried out by an expert's opinion (Table 3). To measure the consistency of judgment, there is a consistency ratio CR, in which value should be less than 0.1. The priorities of criteria (weights) could be derived using the Eigenvector prioritization method by Saaty [52].

Table 3. WFFPI pairwise comparison matrix.

Matrix 1	NDVI [1]	LULC [2]	M [3]	HSG [4]
NDVI	1	2	3	4
LULC	1/2	1	2	3
M	1/3	1/2	1	1
HSG	1/4	1/3	1	1

Note(s): [1] NDVI—normalized difference vegetation index; [2] LULC—land use/land cover; [3] M—slope index; [4] HSG—hydrologic soil group.

2.2.3. Flash Flood Hazard Index (FFHI) Method

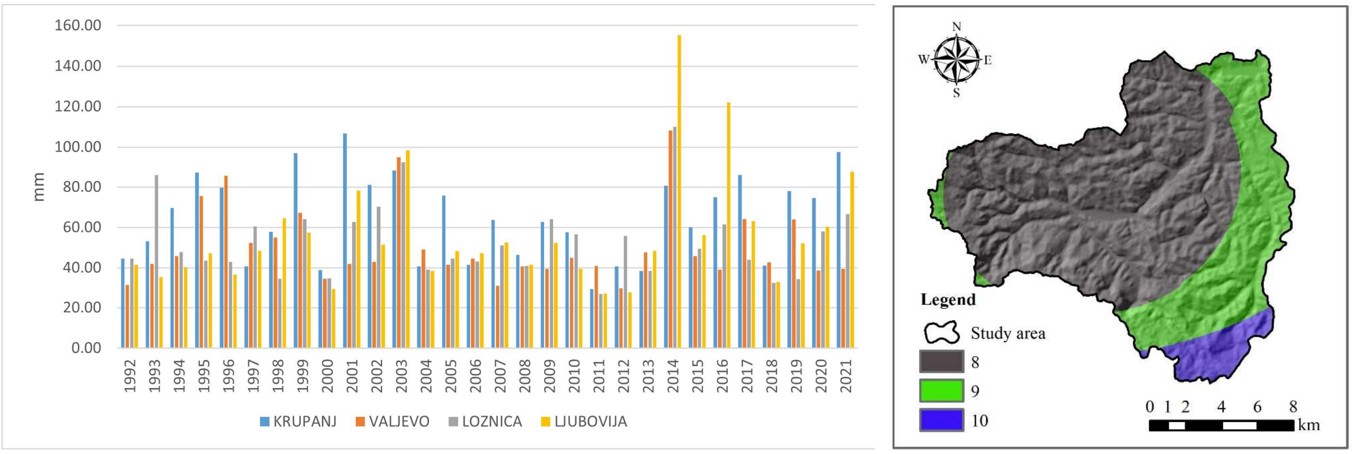
For the calculation of FFHI, in addition to parameters for the calculation of the FFPI (WFFPI) method, max daily rainfall and drainage density were used. Pairwise comparison matrix and weights for additional parameters were also determined by the AHP method based on an expert's opinion (Table 4).

Table 4. FFHI pairwise comparison matrix.

Matrix 1	MDR [1]	NDVI [2]	LULC [3]	M [4]	HSG [5]	DD [6]
MDR	1	2	2	3	4	4
NDVI	1/2	1	2	3	4	4
LULC	1/2	1/2	1	2	3	3
M	1/3	1/3	1/2	1	1	2
HSG	1/4	1/4	1/3	1	1	1
DD	1/4	1/4	1/3	1/2	1	1

Note(s): [1] MDR—max daily rainfall; [2] NDVI—normalized difference vegetation index; [3] LULC—land use/land cover; [4] M—slope index; [5] HSG—hydrologic soil group; [6] DD—drainage density.

Rainfall: The analysis included maximum 24 h rainfall for the flood season (May to September) for the 30-year period (1992–2021). The max daily rainfall recorded in this study area occurred in May 2014. Data were acquired from the official website of the Republic Hydrometeorological Service of Serbia from four different climate stations (Krupanj, Loznica, Ljubovija, Valjevo) [44]. These data were integrated into the ArcGIS environment and interpolated from points to meteorological stations to a raster format, using inverse distance weighted (IDW) interpolation. For the determination of FFHI values, a simple equal interval classification scheme was used. FFHI values that were assigned to rainfall data are shown in Figure 5b and Table 5. Maximum 24 h rainfall data from year 2014 was used, because it deviates the most from the average values. The average daily amount of precipitation in the Likodra basin is around 6 mm, in the flood season. Analysis shows that the maximum 24 h rainfall in this study area values are in a range from 80.6 mm (recorded on Krupanj station) to 155.2 mm (recorded on Ljubovija station). Precipitation between 80.6 and 91.9 mm was given an FFHI value of 8, between 91.9 and 103.2 mm was given a value of 9, and above 103.2 mm was given a value of 10 (Table 5). Maximum 24 h rainfall data for the period from 1992 to 2021 are shown in Figure 5a, as well as the spatial distribution of maximum 24 h rainfall for the 2014 year (Figure 5b).



(**a**) (**b**)

Figure 5. (**a**) Maximum 24 h rainfall (1992–2021); (**b**) maximum 24 h rainfall (2014) distribution map and corresponding FFHI values.

Drainage density: The stream network was extracted from the digital elevation model (DEM), and then drainage density was determined as the ratio between the river segment length and the drained area (in km/km^2). In Serbia, there are four basic groups according to drainage density (km/km^2): low (<0.5), medium (0.5 to 1.0), high (1.0 to 2.0), and very high (>2.0) [53]. Drainage density classes were used to assign FFHI value (Table 5). The lowest FFHI values (2) were assigned to low-drainage density areas. The FFHI values rose along with an increase in drainage density (medium—4, high—6, very high—8) [28].

Table 5. Additional parameters and its classes values assigned to calculate FFHI.

Parameters (Source and Resolution)	**Classes**		**Area**		**FFHI Values**	**References**
			km^2	**%**		
Max daily rainfall	80.6–91.9 mm		148.21	67.79	8	*
Republic Hydrometeorological Service of Serbia	91.9–103.2 mm		58.17	26.61	9	
	>103.2 mm		12.24	5.60	10	
Drainage density	low	<0.5 km/km^2	2.76	1.26	2	[28]
	medium	0.5–1.0 km/km^2	15.16	6.93	4	
European Digital Elevation Model (EU-DEM), version 1.1 (25 m)	high	1.0–2.0 km/km^2	89.00	40.71	6	
	very high	>2.0 km/km^2	111.7	51.1	8	

Note(s): * Classification according to the equal interval method.

3. Results and Discussion

3.1. AHP Method Analysis

Methods for the determination of the weights used in many studies are different. Some researchers used AHP [28,31,37], while some used an integrated approach of the AHP and the information entropy theory as a weighting method [25]. In other cases, the weighting of factors was made simply (linear regression), in order of contribution regarding flood production [34,54].

Criteria weights for WFFPI and FFHI were calculated based on the opinion of an expert (Tables 6 and 7). For the calculation of criteria for WFFPI (Table 6), vegetation cover was determined as the most important factor and weighted at 0.47. Land use was determined as second in importance (weighted at 0.28) and slope with a weight of 0.14 as third. The hydrologic soil group was determined as the least important and weighted at 0.11 (Table 6).

Table 6. WFFPI criteria weights.

Parameters	Weights
NDVI [1]	0.470
LULC [2]	0.280
M [3]	0.140
HSG [4]	0.110

Note(s): [1] NDVI—normalized difference vegetation index; [2] LULC—land use/land cover; [3] M—slope index; [4] HSG—hydrologic soil group.

Table 7. FFHI criteria weights.

Parameters	Weights
MDR [1]	0.333
NDVI [2]	0.262
LULC [3]	0.175
M [4]	0.095
HSG [5]	0.071
DD [6]	0.064

Note(s): [1] MDR—max daily rainfall; [2] NDVI—normalized difference vegetation index; [3] LULC—land use/land cover; [4] M—slope index; [5] HSG—hydrologic soil group; [6] DD—drainage density.

In the calculation of FFHI, additional criteria (maximum daily rainfall and drainage density) were considered for determining hazard areas (FFHI). Maximum daily rainfall was determined to be the most important index, weighted at 0.333 (Table 7). Drainage density is the least important index weighted at 0.262. Vegetation cover, land use, slope, and hydrologic soil group were weighted at 0.262, 0.175, 0.071, and 0.064, respectively (Table 7).

After the computation of weights using Saaty's pairwise comparison method, the consistency ratio (CR) for WFFPI (Table 6) was 0.011, and for FFHI (Table 7) was 0.018. The obtained CR is lower than the threshold value of 0.1 and indicates a high level of consistency in the pairwise judgments.

Vegetation cover was considered as one of the most important factors in forming a direct runoff by reducing the amount of precipitation potentially reaching the soil surface [3]. Areas under broad-leaved forests coincide with a high NDVI class. Land mainly occupied by agriculture, with significant areas of natural vegetation, also corresponds to a high NDVI class, because the satellite images were obtained for the vegetation period (1 May–30 September) when crops were at their peak. This is important for flash flood occurrence because the vegetation is one of the most important factors in forming a direct runoff [3,55]. Moreover, anthropogenic activities such as inadequate use of agricultural land, illegal and excessive deforestation, or illegal and unplanned house constructions in the riverbed are contributing to the accelerated development of these natural disasters in the municipality of Krupanj (flash floods and landslides). Compared to other studies [28,35,36] that included vegetation index in their calculation, Zeng et al., observe it as the factor which contributes the most to flash floods [25]. The important influence that impervious surfaces (urban areas, traffic infrastructure) have on flash flood occurrence is slightly less significant than vegetation cover. Soil sealing is directly connected with runoff. In addition, agricultural areas contribute to runoff with different cultivation practices (tilling down the slope) and plant varieties (corn, wheat, orchards). Researchers find that land use is a vital parameter of the FFPI method [28,31,32,35,36].

The slope of a watershed affects the amount and the timing of runoff. The steeper and longer the slope, the less time for water to infiltrate the soil. Forming surface runoff, water-carrying eroded soil particles can have negative (catastrophic) environmental consequences (flooding, property damage, landscape destruction). The slope index is one of the most used factors in the application of Smith's method [23] throughout the world [26,31,32,34,37] and often, the most important. Slope can influence direct runoff by affecting the speed and direction of water flow. Steeper slopes can increase the speed of water flow and reduce the amount of time available for infiltration into the ground. However, the impact of slope on direct runoff can also be influenced by other factors such as soil type, vegetation cover, and land use. Land use can have a significant impact on the formation of direct runoff and flash flood potential. The type of land cover, such as vegetation, pavement, or buildings, can affect the amount of rainfall that is absorbed into the ground or runs off the surface. In some cases, land use may be considered more important than slope in forming direct runoff because it can have a more direct and immediate impact on the amount of water that is absorbed or runs off the surface. However, the relative importance of these factors can vary depending on the specific conditions that prevail on the chosen study area. That is why an individual approach to every watershed is important. Here, in our study, the expert conducted the comparisons.

Soil texture index was not as widely used as the other parameters, but it has a major impact on the infiltration and runoff process [25,28,32,34]. Soil has a huge impact on runoff and infiltration. The soil analysis showed that over 80% of the soil in this watershed is in Group B. Even though these soils have moderately high infiltration rates and moderately low runoff potential when it comes to direct runoff and flash flooding, other factors need to be considered [54]. First and foremost, previous soil saturation needs to be considered.

3.2. FFPI, WFFPI, and FFHI Analysis

Results of the FFPI method show the presence of all four susceptibility classes: low, medium, high, and very high [23]. Analysis shows that, when equal weights are assigned to all criteria, the class of low susceptibility is barely present at 0.01% of the watershed area; the medium class covers 22.62%; the high class of flash flood susceptibility is present on the watershed at 76.20%; and areas with high susceptibility occupy 1.17% of the total watershed area (Table 8). In the Likodra watershed, medium and high classes were found throughout, while very high class is mostly present in the south and south-west parts of the watershed. This shows that the Likodra watershed is very susceptible to flash floods.

Table 8. Likodra watershed flash flood susceptibility classes.

Susceptibility Classes		FFPI		WFFPI		FFHI	
		km^2	**%**	**km^2**	**%**	**km^2**	**%**
1	Low (0–2.5)	0.01	0.01	0.05	0.02	0	0
2	Medium (2.5–5)	49.45	22.62	10.16	4.65	0.45	0.21
3	High (5–7.5)	166.60	76.20	191.91	87.78	200.53	91.73
4	Very high (7.5–10)	2.56	1.17	16.50	7.55	17.64	8.07
	Total	218.62	100.00	218.62	100.00	218.62	100.00

By adding different weights to FFPI criteria (WFFPI), results are somewhat similar. Still, there are four susceptibility classes present, but results vary in favor of more susceptible ones (Table 8). According to the WFFPI analysis, low class is hardly evident covering 0.02% of the watershed area. Medium and high classes were found throughout, mainly in upper parts of the Likodra watershed. Medium class covers 4.65% of the watershed and high class 87.78%. Very high class, covering 7.55%, is present in the lower parts of the Čadjavica, Brštica, Bogoštica and Kržava watersheds, gravitating towards the town of Krupanj.

Considering additional criteria (FFHI), such as drainage density and maximum daily rainfall, analysis demonstrates that the class of low susceptibility is no more present; medium class covers 0.21%; high class of flash flood susceptibility is present on the watershed with 91.73%; and areas with very high susceptibility are occupying 8.07% of the total watershed area (Table 8). Analysis by FFHI indicates the absence of low class compared to FFPI and WFFPI. Medium class is weakly present in the central part of Likodra watershed, in the vicinity of Krupanj. High and very high classes are most prevalent in the southern part of the Likodra watershed, but it also extends along the hydrographic network and gravitates towards Krupanj.

Spatial technologies enable effective disaster risk management to assess and map the extent of natural events such as floods. These disaster products derived from space-based inputs generated in near/real time are extremely useful for planning and decision making. Figure 6 shows the spatial distribution of FFPI (Figure 6a), WFFPI (Figure 6b), and FFHI (Figure 6c).

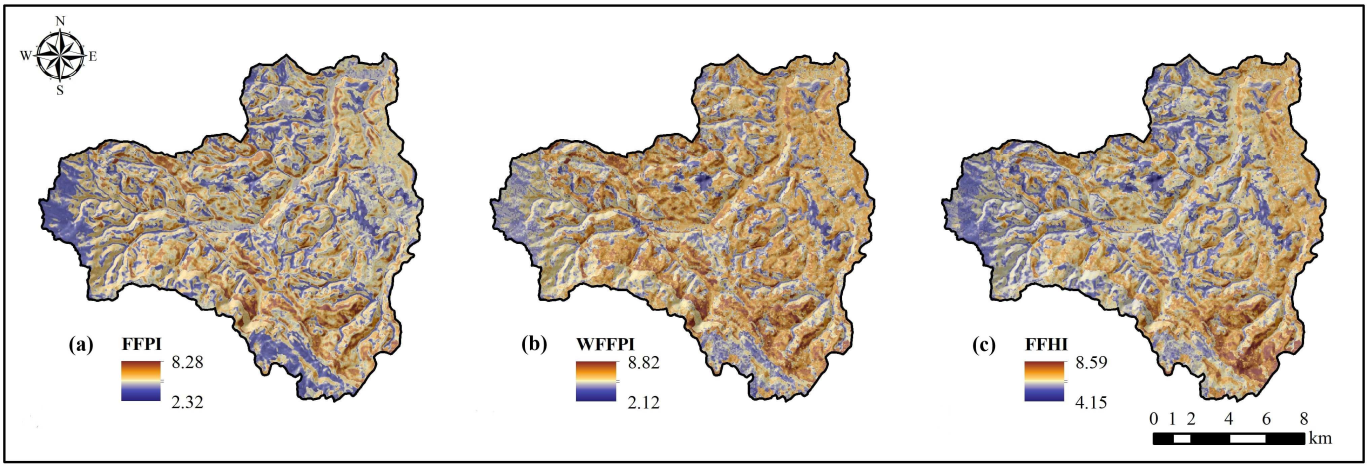


Figure 6. Spatial distribution of (**a**) FFPI; (**b**) WFFPI; and (**c**) FFHI.

Several natural factors contribute to the extremely high susceptibility of the terrain to flash floods: the terrain's high slope of over 30% [28,32], areas with scarce vegetation or land mainly occupied by agriculture, high-drainage density [37,54], low-infiltration soils or over-saturated ones [35,36], and heavy torrential rains [25,31,56]. The terrain becomes extremely vulnerable to flash floods because of the combination of these factors, due to the rapid concentration of flood runoff [57].

Each study was performed for a particular watershed, and it is unique. Consequently, to be able to take such particularities into account, the analysis at the watershed level is crucial. The geomorphometric characteristics of the Likodra watershed favor the formation of flash floods. Analysis of four FFPI parameters (slope, land use, vegetation, soil) shows that over 76.20% of Likodra River watershed areas are highly susceptible to flash floods. Adding different weights to FFPI criteria (WFFPI), over 87.78% indicates high susceptibility to flash floods. Introducing another two parameters (drainage density and rainfall) into the equation, the results prove that this area is highly susceptible to flash flood hazards. The results of this study demonstrate that this methodology is more accurate and reliable for this type of area.

In the territory of the Republic of Serbia, using the FFPI method, the basins of the Ljig, Kolubara, Jošanica, Ibar, South Morava, and Danube torrents in Serbia (from Požarevac to Negotin), Mlava, and Timok rivers were analyzed [27,29,30,58–62]. Figure 7 illustrates the percentage representation of FFPI susceptibility classes. The Likodra River watershed is the most susceptible to flash floods occurrence, with 76.20% of high class (FFPI) i.e., 87.78% (WFFPI). Following Likodra, the most susceptible watersheds are Kolubara with 53.54% of area under high FFPI class and Jošanica with 48%, while the least susceptible is the Ibar watershed with 9.43% of high class. Those analyses showed that in the Republic of Serbia, there is a lot of flash flood susceptible areas that need serious treatment.

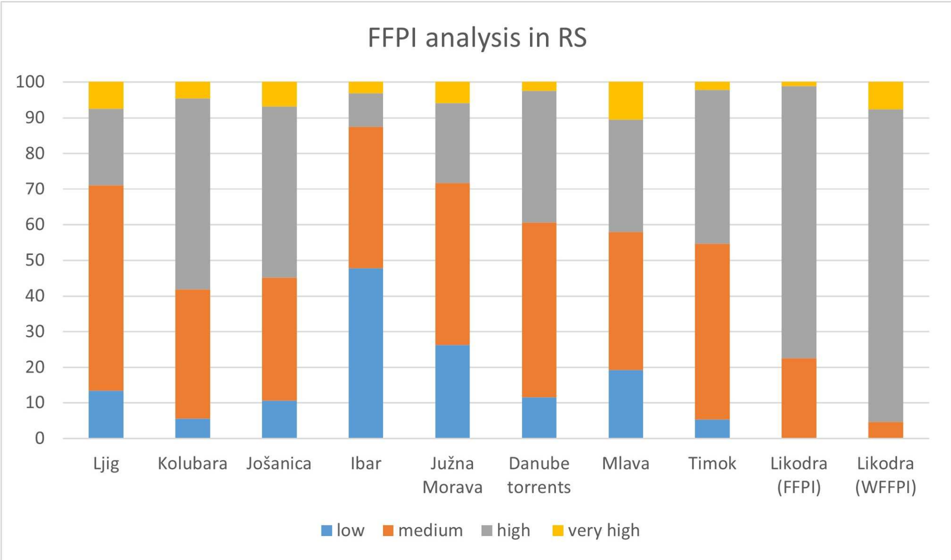


Figure 7. Results of FFPI analysis on watersheds in Serbia.

4. Conclusions

Flash floods are one of the most devastating natural disasters. Their impact on the environment, society, and economy is severe. This study used a weighting method based on the AHP to derive weights for different data types in the assessment of flash flood potential and flash flood hazard areas. Areas with a potential for flash flood occurrence usually are characterized by high-drainage density, low-infiltration capacity, steep slopes, and low vegetative cover. Analysis at the watershed level is crucial. The Likodra watershed is very susceptible to flash floods. The spatial distribution of FFHI provides important information on the extent of hazard zones which is useful in decision making and sustainable risk management. The used method can be applied on different watersheds or with increased accuracy of data at a larger scale. It also underlines the importance of geomorphometric parameters in the development and occurrence of floods. Based on this information, local and republic governments can make priorities of the necessary investments in flood mitigation. To talk about flash flood risk management, in addition to the analysis of natural factors, other more "anthropogenic" factors must be analyzed: population, infrastructure, roads, torrential stream beds maintenance, flood mitigation measures, and many more. The first step is to identify hazard and risk zones then establish real-time monitoring and properly manage the risk. The next step would be to establish an integrated river basin management system for flash flood mitigation and control, combining biological and technical works.

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