RESEARCH PAPER

FLUVIAL PROCESSES AND LANDFORMS AS INDICATORS IN TORRENTIAL FLOOD HAZARD ASSESSMENT

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ABSTRACT. Torrential flood hazard assessment is always a challenge, especially if the aim is to do it on the level of the whole watershed. When there are no required data available, there are traces in nature, morphological indicators, that show the extent of previous floods, in period longer then instrumental period. Therefore, in this paper we deal with fluvial and slope both erosional and accumulation processes and landforms, which doubtlessly indicate torrential flood prone areas. We have selected eight indicators and grouped them into three segments: erosional process, morphometric characteristics of watershed, and accumulation processes and landforms. Selected indicators serve for fluvial processes determination and therefore could be used for proper water and flood risk management. The research was done in three middle-sized watersheds in Serbia which belong to the Velika Morava River basin, showing that integrative approach is necessary for rational watershed management, meaning for selection of measures for torrential flood hazard mitigation.

KEYWORDS: flood hazard, flood zone, fluvial landforms, alluvial plain, fan, Serbia

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INTRODUCTION

Life by the rivers, either lowland or mountainous, has always attracted people, offering a bare necessity – available water. The growth of population density and the resulting human impact (e.g. concreting the riverbanks, thus preventing natural processes; introduction of large amounts of wastewater into streams, etc.) disturbed the human–nature relation, thus in countless cases the nature made a sharp counter-strike. In these circumstances, floods become a threat that endangers the population living on the riversides and get the character of a natural disaster. Water pollution also leads to consequences (acute hydric diseases, but also other diseases with long-term consequences that can be characterized as chronic). Large number of studies dealing with natural disasters begin with devastating statistics which show that their intensity and frequency are increasing, with consequences increasing both in terms of damage and the number of victims (EM-DAT 2024). The reason for this, on one hand, lies in natural processes that have their own dynamics and trends of intensity and frequency. Although the scientists argue about the causes that lead to changes in the timing of hydrometeorological processes and phenomena, the direction in which they take place and the significance of these changes, most of them agree that changes at the global level are evident, especially in the atmosphere and hydrosphere (Arnell 2002; Shiklomanov and Rodda 2003; National Research Council 2011; Hartmann et al. 2013; Gosling and Arnell 2013). On the other hand, the studies of disasters have changed from the perspective mainly focused on a physical or natural event towards the integration to the social system (Alcántara-Ayala 2002).

In order to assess flood hazard, determination of flood zones is the first and complex task to be done. Directive of the European Parliament and of the Council establishing a framework for Community action in the field of water policy – WFD (Directive 2000), as well as the directive on the European Parliament and of the Council on the assessment and management of flood risks – Flood Directive (Directive 2007) recommend the determination of the extent of a flood zone for different scenarios (for high, common and low probability of occurrence), which are important for the preparation of hazard and risk maps, and subsequently for risk management, including spatial planning. Therefore, the basic task in this paper is to determine the indicators for defining the food zone in torrential watersheds and subsequently to assess flood hazard. Existing maps of floodplains at the global level are characterized by lower data resolution, while higher data resolution maps were made for smaller spatial units, created for river regulation in certain sections (hydro-engineering approach and method), while in mountainous areas there are no data on flood zones. In this sense, the aim of this paper is to use geographical method and an aspect that connects hydrological and geomorphological processes.

In accordance with the characteristics of torrential floods as two-phase fluid (maximum flow and high sediment concentration) as described by Coussot and Meunier (1996), the terms "debris flows", "torrent flows", "mudflows", "debris floods", "torrent floods", "flash floods", "lave torrentielle" are used in the literature and it is very difficult to precisely distinguish these phenomena. Therefore, in this paper we will deal primarily with torrential floods, as a natural process of increased intensity, which is the outflow of water with a high concentration of sediments in the riverbed. Torrential floods are associated with small streams that drain basins up to 100 km^2 (Wang et al. 1996). They refer to occasional, periodic and permanent watercourses whose watersheds are affected by erosion processes. They appear suddenly after intense rains and sudden melting of snow, have a high speed of the flood wave and last relatively short. Torrential floods often occur with other natural disasters, most often hurricanes, typhoons and their combinations with earthquakes and volcanic eruptions, and in these cases they occur as secondary disasters (Jakob and Hungr 2005), i.e. they are a consequence of multihazard (Zhou et al. 2015; Varazanashvili et al. 2012). They can also occur together with other slope processes, most often with landslides, and Jakob and Hungr (2005) state that torrential floods occur as triggers of large landslides. Kovačević-Majkić et al (2013) selected indicators for torrential risk assessment and for hazard component they selected discharge regime and erosion as segments of hazard, which is in accordance with the fact that there are two key factors that determine torrential floods:

1) The key factor and at the same time the trigger for the occurrence of torrential floods is the intense short-term precipitation (usually less than 24 hours), whereby in that time the total amount can reach several tens of millimeters per hour, e.g. 42 mm/h (Radović and Todorović 1989), 80 mm/h (Shimizu et al. 2002), 35-40 mm/ 30 min (Brajković and Gavrilović 1989), up to several hundred mm (320 mm/24h; Kompare and Rismal 1989). High soil moisture, caused by previous precipitation or melting snow, is also important for the occurrence of sudden floods, due to which the soil cannot receive new amounts of water (Jakob and Hungr 2005; Ristić and Malošević 2011).

2) Another key factor for the occurrence of torrential floods is the high prevalence of erosion in the basin and high sediment transport during torrential floods, which reaches more than ten times higher values than the average sediment transport (Costa 1988; Shimizu et al. 2002).

In addition to the two mentioned basic factors, there are also the conditions for the occurrence of torrents: a) physical-geographical: climatic (which in addition to precipitation includes air temperature), geological (type of rock), pedological (type of substrate), morphometric related to the basin (slope and shape of the basin), morphometric related to the riverbed (slope of the riverbed), vegetation (type, structure, age of vegetation) and b) anthropogeographic (land use). Their influence was assessed by Jakob and Hungr (2005), as well as by Ristić and Malošević (2011). Land use changes as urgent issue are pointed out by Gradel et al (2019). The authors appeal that forests are crucial for hydrological balance and land degradation prevention. Nolos et al. (2022) also write about the importance of good forest management. Generally, the trend in research of erosional processes is to put them in the context of environment and ecology, as well as sustainability. Researches expanded in the sphere of modelling and estimation of erosion processes. By the analyses of Zhuang et al. (2015) before 2001 the soil erosion research was mainly distributed across the USA and Europe, and afterwards the research was spread in Asia (dominantly in China and India) and Australia.

Considering the spatial distribution of mentioned erosional and accumulation processes, there are usually three characteristic zones in the torrential watersheds: 1) the "collection zone" that covers the upper parts of the watershed, where the process of soil erosion takes place to a greater or lesser extent, depending on the physio-geographical and anthropogeographical conditions in the watershed, 2) the "transit zone" or "torrent throat", represented by riverbeds in which the transport of torrent material primarily takes place or, as explained by Mazzorana et al. (2013), one-dimensional (1D) flow processes are active, the valleys are often gorge-like, with pronounced vertical erosion, and 3) "flood zone" which represents the part of the basin where the sedimentation material settles and most often has the shape of a fan, the space where two-dimensional (2D) flow occurs (Mazzorana et al. 2013). This zone is important as morphological indicator or "trace" of flooding (Milošević et al. 2015) which testifies about previous cases of torrential floods. Therefore, fluvial erosional and accumulation processes and the resulting landforms, as well as morphometric characteristics of watersheds presented by selected indicators, are appropriate for torrential flood hazards assessment.

Even though torrential floods are characteristic of the relatively small and middle-sized watersheds, they manifest and have impact on large-scale river basins as well, which is also stressed by Borga et al (2014). Therefore, it is difficult and almost impossible to determine the exact boundary where one or another type of flood occurs. Thus, the question is whether it is necessary to draw the exact line between river floods in the lower parts of large river basins and torrential floods that occur at higher elevations. Furthermore, the integral approach and work are the only correct and purposeful options. The results obtained are useful for numerous users, responsible and interested stakeholders, such as decision makers, spatial planners, researchers, insurance companies etc.

MATERIALS AND METHODS

The study area

Floods are among the most common disasters in Serbia causing the greatest damage (Official Gazette 2011; Dragićević et al. 2011; Gavrilović et al. 2012). In addition, torrential floods are the most common disaster, since 86.4% of the territory of Serbia (hilly and mountainous areas mainly south of the Sava and Danube River) is exposed to erosion processes (Ristić et al. 2012). The torrential floods inventory in Serbia was made by Petrović et al. (2014), and contains register of 848 torrential floods in which 133 people lost their lives in the period 1915-2013. The largest number of torrential floods occurred in the Južna Morava River basin, most commonly in May and June. In this paper we have selected three watersheds (the Skrapež River watershed, Belica River watershed and Lužnica River watershed) that belong to the Velika Morava River basin (Fig. 1).

The Skrapež River watershed (647 km^2) belongs to the upper part of the Zapadna Morava River basin. It is located in a mountainous region where the average elevation of the basin is 600.76 m. About 65% of the watershed lies between 400 and 700 m asl, less than 2% above 1000 m asl. (the

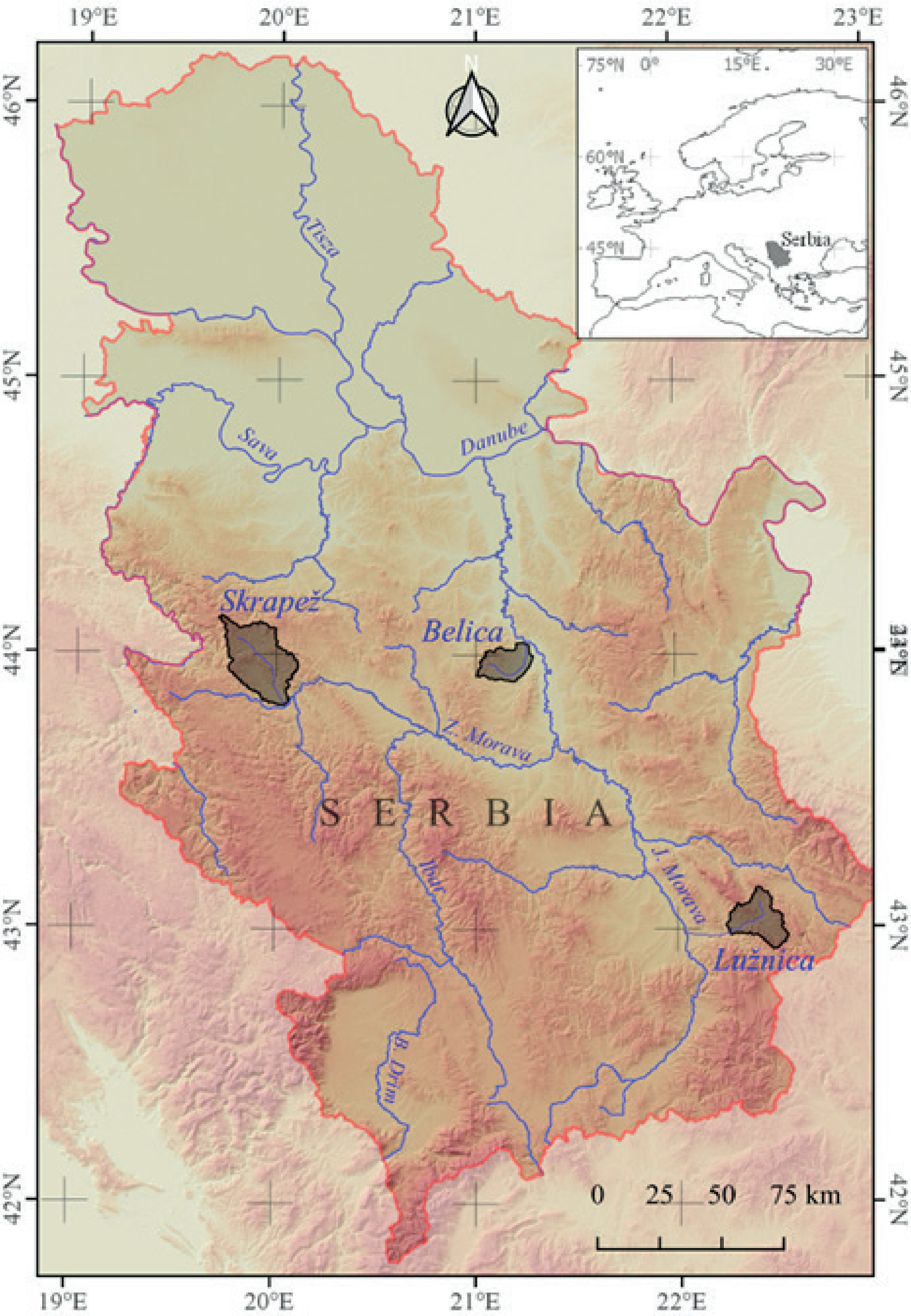

Fig. 1. Location of the Skrapež, Belica and Lužnica watersheds in Serbia

slopes of Povlen Mt. and Maljen Mt.), and about 10% below 400 m asl. (alluvial plains of the Skrapež River watershed and its largest tributary Lužnica River) (Kovačević-Majkić, 2009). Since most of the basin is built of metamorphites prone to decomposition and Miocene clastic rocks and sediments, this has resulted in increased erosion.

The Belica River watershed (233 km^2) is located in central Serbia and is one of the watersheds on the left side of the Velika Morava basin. The average elevation of the basin is 229.5 m. The basin of the Belica River consists of three morphological units: plains (with slopes up to 3°), hilly areas (with slopes up to 10°) and mountainous parts (with slopes up to 40°). The plains are the most represented, followed by hilly landscapes, and areas above 500 m asl. - the slopes of Crni vrh (708 m asl). Lithologically, the basin consists of clastic sediments of considerable thickness (sands, siltstones, sandy clays, clayey sands, clays) and regoliths composed of compact rocks, most often metamorphites (gneisses, mica-schists, dolomite marbles and amphibole shales) (Vujisić et al. 1981). Considering the mentioned lithological composition, which is subject to decay, and the slopes, areas with intensive erosion are poorly represented, and processes with medium and weak erosion dominate, while the lower part of the watershed is characterised by accumulation process.

The Lužnica River watershed (325 km^2) is located in southeastern Serbia. It belongs to the watershed of the Vlasina River, which is a right tributary of the Južna Morava River. Among the morphological units, the most represented are hilly (51%) and mountainous areas (46%) with the highest peak of 1385 m asl, while the plains cover the smallest area of the basin (3%). The lithological composition of the watershed consists of (1) limestones and dolomites of Suva Planina Mt, whose slopes represent the right valley side; (2) flysch, conglomerates and sandstones that form the left valley side, while (3) the Lužnica Miocene basin, located in the middle part of the basin, consists of conglomerates, gravel, sand and clay (Vujisić et al. 1980). Considering the spatial distribution of lithological units, the left valley side is more characterized by erosion than the right side.

Defining indicators for the flood hazard assessment

Floods about which there are no written sources happened in watersheds where there are potentials or conditions that lead to the occurrence of torrential floods. In accordance with character of torrential floods, we have selected the indicators that describe them. The challenge of proper indicators selection (thematically adequate, spatially and temporally available, and approved by scientific community) was elaborated by Kovačević-Majkić et al. (2013) and Kovačević-Majkić (2018). After meeting all of the mentioned criteria, we have grouped the indicators to: (1) segment on erosional fluvial processes, (2) watersheds morphometry segment; as well as traces in nature that testify that torrential floods occurred (morphological indicators), evidenced by (3) segment of landforms of fluvial and slope accumulation (floodplains, alluvial plains, fans). Selected indicators are presented in Table 1.

Data on erosional fluvial processes testify on erosion intensity and are described through four indicators: Areas affected by erosion processes of I, II and III category (H1a and H1b), Erosional coefficient Z (H1c) and Watercourses' density (H1d). Required data were collected from topographical maps 1:25000, Shuttle Radar Topography Mission (SRTM), pedological maps 1:50000, pedlogical map of Serbia (Mrvić et al, 2013), and Corine Land Cover (2018). Erosion was calculated by the method of Gavrilović (1972) in which the first class means the most intensive erosion. The method is widely used in the region and in countries of former Yugoslavia.

For selected morphometric characteristics of watersheds data, sources were the topographical maps 1:25000, SRTM, and Google Earth Service (2019). *Module of watershed divide line development* explains the role of the shape of the watershed in the formation of a torrential flood wave, meaning more rounded watershed means smaller *Module of watershed divide line development*, and subsequently higher probability of rapid water concentration. Whereas we need the indicator that is directly proportional to flood hazard, we have used the variation of the mentioned module, *Reciprocal module of watershed divide line development*, as indicator, whereby more rounded watershed means higher *Reciprocal module of watershed divide line development*.

Data on the landforms of fluvial and slope accumulation originate from the process of flooding and thus represent data on past floods, i.e. the area they covered. These landforms are alluvial plains and fans (Fig. 2), and based on their identification and spreading, the extent of the flood zone is determined. To determine the flood zone as a source of data on traces of torrential floods from the past, it is possible to use geomorphological maps 1:100,000 archived by the Geological Survey of Serbia. Selected torrent watersheds are presented on the maps by Menković and Košćal (1981), Menković and Košćal (1982), Menković, Košćal and Mijatović (1988). An example of a map is presented in Fig. 2. For a flood zone determined in that way, we use the term "geomorphological flood zone" (Geomorphological flood zone as indicators H3a and H3b in Table 1).

In purpose of obtaining the results, the following software packages were used: *Microstation, Global Mapper, QGIS,* and *Microsoft Excel.*

Table 1. Torrential flood hazard indicators

Indicators		Segment
Area affected by erosion of I, II and III category (km^2)	H1a	Erosional fluvial processes
Area affected by erosion of I, II and III category (%)	H1b	
Erosion coefficient Z	H1c	
Watercourses density (km/km^2)	H1d	
Main course slope (‰)	H2a	Watersheds morphometry
Reciprocal module of watershed divide line development	H2b	
Geomorphological flood zone (km^2)	H3a	Accumulation fluvial and slope landforms
Geomorphological flood zone (%)	H3b	

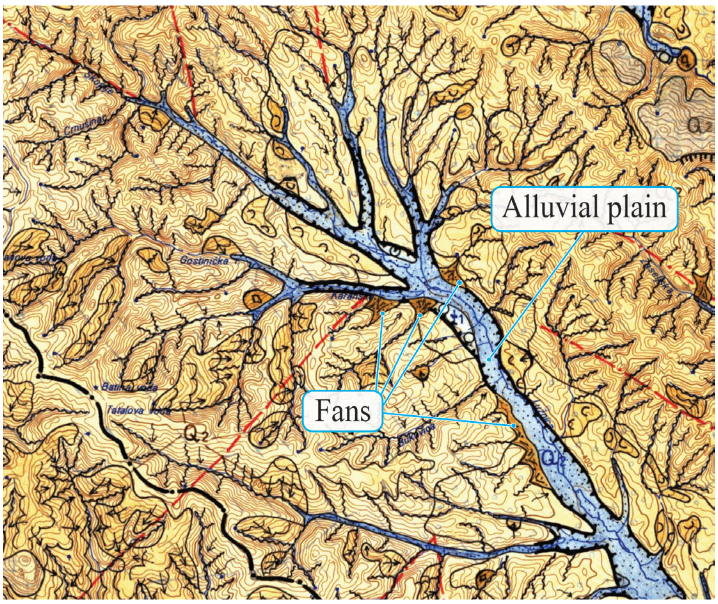

Fig. 2. Segment of the geomorphological map with marked flood-derived landforms, sheet Užice (Menković and Košćal, 1982)

RESULTS

The results used are obtained for three watersheds in Serbia. They were selected following several criteria.

First criterion was presence of erosion of I, II and III categories. According to the results of the calculation of erosion and sediment production by the method of S. Gavrilović (1972), which refers to the period 2012-2016, in all three watersheds there was a decrease in erosion processes, the most significant in the Lužnica watershed, which moved from the category of strong (II) erosion to the category of very weak (V) erosion (Kovačević-Majkić 2018). The erosion processes are presented in Fig. 3. In the selected basins, the characteristics of erosion and river regime are such that they represent the conditions for the formation and occurrence of torrential floods. Moreover, with a large amount of sediment they endanger the accumulations in the higher order basins to which they belong, and according to Gavrilović et al. (2009) they belong to the I and III category of areas affected by extreme torrential floods. Second criterion was detected floods. According to the torrential floods inventory in Serbia made by Petrović et al. (2014) in all three watersheds the torrential floods have happened and been registered. Larger floods in the Skrapež River basin occurred in 1910, 1926, 1938, 1965, 1975, 2001, 2006 and 2014; in the Belica River basin in 1929, 1964, 1965, 1976, 1999, 2002, 2010 and 2014; and in the Lužnica River basin in 1976, 1988, 2003 and 2007. (Gavrilović, 1981; Petrović et al, 2014; UN, EU & World Bank, 2014). Third criterion was morphometric characteristics of watershed which are described above in the Study area. All selected watersheds are positive to these criteria. Additionally, onomastic indicators (hydronyms) in selected watersheds and described cases of torrential floods (literature sources, case studies containing data on victims and other consequences of torrential floods, torrent inventory, newspaper articles) were criteria for torrential watershed selection and at the same time verification that selected indicators are the proper ones.

Based on geomorphological maps of 1:100,000 scale, 50 floodplains were identified in the Skrapež River watershed, 10 in the Belica River watershed, and 8 in the Lužnica River watershed. Milić (1984) dealt with a more detailed analysis of fans in the Lužnica River watershed and identified 60 fans. They differ in type and age, but also in size. Those less than 100 m in range were also identified. Regardless of the characteristics, they undoubtedly testify that torrential floods occurred. The Skrapež River watershed has the largest geomorphological flood zone, while the percentage share of the geomorphological flood zone is the largest in the Belica River watershed (Fig. 4).

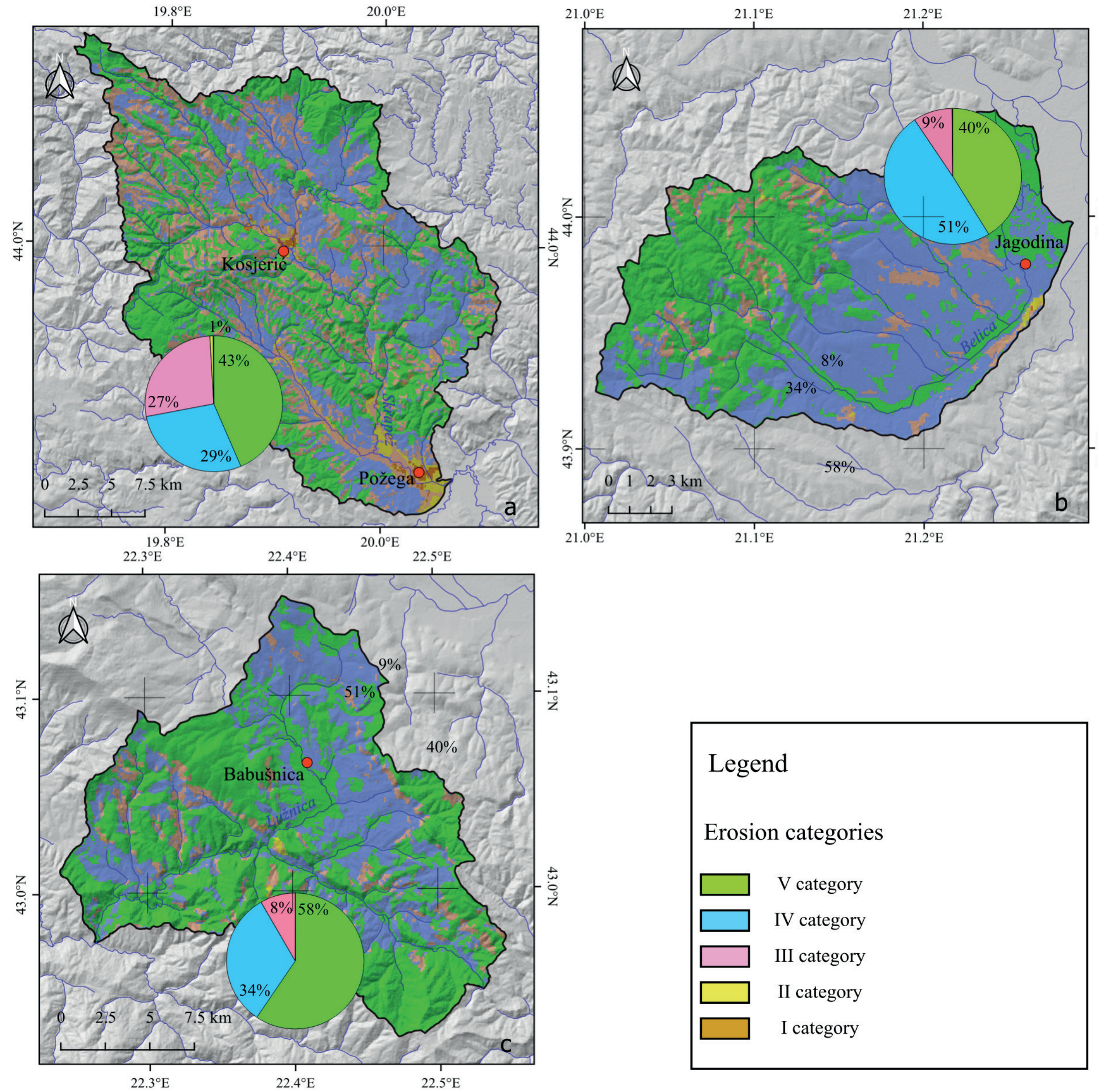

Fig. 3. Spatial distribution of erosional processes in Skrapež River watershed (a), Belica River watershed (b) and Lužnica River watershed (c)

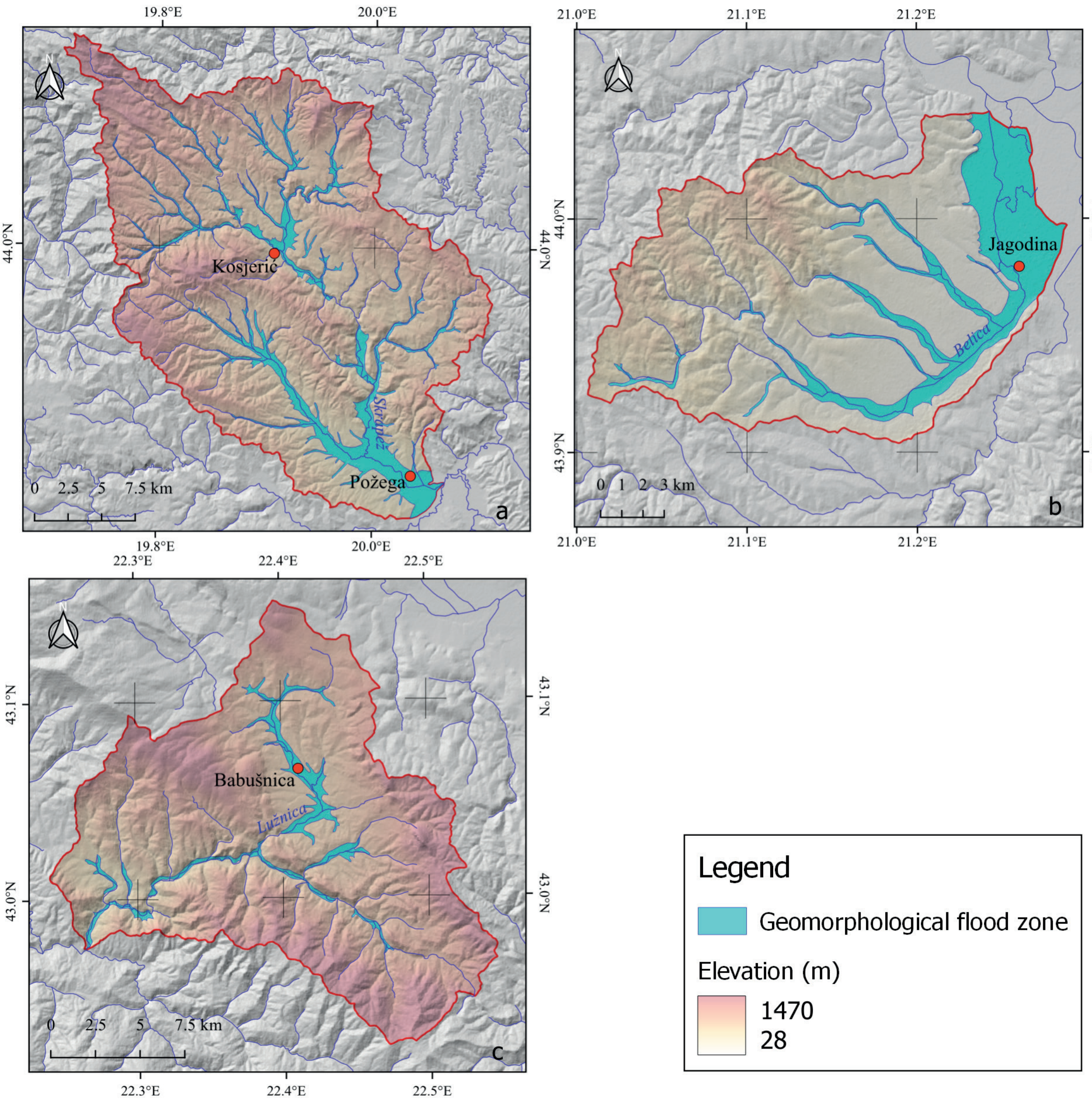

Fig. 4. Geomorphological flood zone in watersheds of the Skrapež River (a), Belica River (b) and Lužnica River (c)

The values of all selected indicators are shown in Table 2. Six of eight indicators are the highest in the Skrapež River watershed. Areas under erosion of I, II and III categories are the largest in the Skrapež River watershed, while they are almost equally represented in the Belica and Lužnica watersheds in absolute measure units and in relation to the size of watershed. The erosion coefficient is slightly higher in the Skrapež River watershed than in the other two basins. The Skrapež River has the most developed river network, as well as the largest watercourse slope, and the Belica River has the smallest. The development of the watershed divide line is unique, but the greatest for the Belica River watershed.

DISCUSSION

The motivation for starting the research process on torrential flood assessment was based on difficulty in determining the flood zone at the level of the entire watershed. Despite the fact that flood hazard could be assessed using hydrological data and geomorphological data, hydrological data have the relatively short series related to instrumental data collection. They are usually analysed using probability in order to obtain data on discharge and water levels for certain return periods. Also, there is a problem that generally there are no hydrological stations on small watercourses. Many hydrological and hydraulic models are developed in order to obtain the extent and depths of floods. Assessing flood hazard also includes other characteristics such as water velocity and for torrential floods erosion processes and deposits (except water, second important phase) are necessary to obtain and have in flood hazard assessment. Therefore the geomorphological data – landforms resulting from the processes of fluvial accumulation (alluvial plains and fans) – are distributed over the whole watershed and testify about floods that happened long time before the instrumental period. The solution to the problem of torrential flood hazard assessment was in detection of traces that point to large and as many floods in history as possible. Such data and their sources may be geomorphological maps that present the flooding-derived landforms, originating within the process of fluvial and slope accumulation. Arnaud-Fassetta et al (2009) point out that fluvial geomorphology can make a significant contribution to understanding the spatio-temporal distribution of flood hazard and flood risk management. Since the only correct water management is at the level of the entire watershed, then for determination of the flood zone, in addition to the landforms of the fluvial accumulation of the main river (alluvial plains), the landforms of fluvial accumulation of tributaries, must be observed. If tributaries have torrential character, then fans are the landforms we must determine as well.

Table 2. Flood hazard indicators in the Skrapež, Belica and Lužnica Rivers watersheds

Indicators	Skrapež River	Belica River	Lužnica River
Area affected by erosion of I, II and III category (km^2)	181.06	21.87	27.02
Area affected by erosion of I, II and III category (%)	27.95	9.37	8.32
Erosion coefficient Z	0.269	0.215	0.176
Watercourses' density (km/km^2)	2.04	1.52	1.63
Main course slope (‰)	15.01	8.99	12.40
Reciprocal module of watershed divide line development	0.63	0.74	0.68
Geomorphological flood zone (km^2)	65.20	45.53	15.16
Geomorphological flood zone (%)	10.06	19.50	4.67

The choice of methods for determining the flood zone also depends on the level of detail, i.e. the size of the area for which the flood zone is determined. The nature of torrential floods, i.e. the area they cover and the consequences they have, implies that it is best to work on risk assessment studies at the regional and local level (UNDP 2004). This is supported by the statement of Stojkov et al. (1998) that the causes of natural hazards such as landslides and torrents are developing at the regional level, and that they should be considered in this way. However, their participation in the total risk of disasters is also significant at the macro (national) level because it is accumulated at the local level and increases the risk at both the national and global level (UNDP, 2004).

Limitations of geomorphological method are the problem of intrazonality and the fact that this method determines the horizontal extent of the flood zone, while the vertical extent or depth of flooding is not detected. Geomorphological flood zone is not registered in areas where fluvial erosion processes dominate, and fluvial accumulation processes are absent. These are narrowed river valleys (canyons, gorges, epigenetic valleys) on whose steep valley sides there are elements exposed to floods (most often they are infrastructural objects - roads, railways). Such areas, depending on the water level, can be directly endangered by floods (with consequences such as casualties and material damage), or indirectly endangered by floods when they become isolated and have difficulty functioning because the flood affected the surrounding areas (Kovačević-Majkić 2018; Kovačević-Majkić et al. 2020). In that sense, it is necessary to upgrade this method, i.e. to solve the problem when there is only a vertical extent of the flood.

Presence of selected indicators could serve for fluvial and slope processes determination. In Table 3 we determined the fluvial and slope processes considering the presence of erosional, accumulation and morphometric indicators. If there are both erosional and accumulation processes, torrential floods are possible and certain, even if do not have data on flood events (registered floods). In watersheds without erosional processes and river network and flood zone are detected, floods are possible, but their character is not torrential (Table 3).

Therefore, type of present fluvial processes is an eliminatory factor for flood type determination. This fluvial process determination is important for water and flood management, meaning for the selection of measures that should be used for flood hazard mitigation.

CONCLUSIONS

Almost everyday cases of torrential floods with significant consequences around the world indicate that permanent water and flood management is necessary. This implies constant data collection and research of all risk components, including hazard, more precisely determining the extent of flood prone areas. The assumption in this research is that fluvial and slope processes and landforms in the watershed are relevant indicators for torrential flood hazard assessment. Eight selected indicators were grouped

Table 3. Possible fluvial and slope processes

Fluvial erosion	Fluvial accumulation	Watershed morphometry	Fluvial and slope process
+	+	+	Torrential flood
+	+	-	There is no such process[1]
-	+	+	Flood
-	+	-	There is no such process[2]
+	-	+	Proluvial and/or colluvial slope processes[3]
+	-	-	There is no such process[4]
-	-	+	Potential flood

1 – It is not possible that there are erosion and accumulation indicators and that there are no selected morphometric indicators of watershed
2 – This means that the erosion process is finished and that we have plain without slope
3 – These processes are present in upper parts of the watershed, i.e. in collection and/or transport zone of the watershed
4 – It is not possible that there are erosion indicators and that there are no selected morphometric indicators of watershed

into three segments: erosional process, morphometric characteristics of watershed, and accumulation processes and landforms. In three middle-sized watersheds in Serbia (Skrapež River, Belica River and Lužnica River watersheds), which belong to the Velika Morava River basin, selected indicators were detected, proving that rivers and their tributaries have torrential character. They indicate that torrential floods happened, and that there is probability that floods will happen again. Flood prone areas determined in this way are wider than those determined by hydrological-hydraulic methods, but it is on the side of safety and in accordance with holistic approach to watershed management. Presence of selected indicators also can help in flood and slope processes determination, and subsequently can be used for selection of measures for torrential flood hazard mitigation.

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