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A METHODOLOGY FOR MAPPING AREAS UNDER TORRENTIAL FLOOD RISK: CASE STUDY - THE REBROVAČKI BROOK BASIN / BANJA LUKA MUNICIPALITY (B&H)

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Abstract: Torrential floods are one of the most common and destructive natural hazards that cause great material damage and numerous environmental problems. This article is focused on presentation of a new methodological approach to mapping torrential flood risk that could potentially be applied to other torrential rivers in Bosnia and Herzegovina. A hybrid digital terrain model was developed using geodetic surveys of cross-sections of river channels and river valleys and the existing digital terrain model. This was a basis for hydraulic modelling in HEC-RAS software. Hydrological modelling determined flood flows of 100 and 500-year return periods, ranging from 23m^3/s to 88m^3/s. Hydraulic modelling determined depths, velocities and extent of flooding for different return periods, values of erosion and sediment accumulation, and shear stresses along the Rebrovački Brook. Maximum velocities of 100-year flood flows range up to 11.07m/s and up to 12.41m/s for 500-year flood flow. Depth of 100-year flood flows range up to 3.96m and 4.67m for 500-year flood flow. For 100-year return period the flood extent is 34.53ha, while for 500-year return period it is 46.11ha. Shear stresses of the Rebrovački Brook for 100-year flood flows range to a maximum of 3,482N/m^2, while they are maximum 5,348N/m^2 for 500-year return period. Maximum values of erosion and sediment accumulation of 100-year flood flow for the Rebrovački Brook are 0.59m for erosion and 1.50m for sediment accumulation, while for 500-year return period they are 3.50m for erosion and 1.66m for sediment accumulation. During the preparation of the flood hazard maps, a new formula was proposed which determined the flood hazard rating of the Rebrovački Brook for 100 and 500-year floods. The resulting maximum hazard ratings of 68.90 for 100-year flood and 69.28 for 500-year flood are several times higher than the values obtained on alluvial rivers. The flood risk factors for the categories of population and economy in the Rebrovački Brook basin were determined on the basis of the obtained flood hazard rating and corrected weighted factors for the calculation of flood risk. Risk maps for floods of different return periods of the Rebrovački Brook showed that most of the floodplain is currently in a zone of negligible or low risk. However, given the current trend of city expansion and relocation of economic activities from the centre to the suburbs, this is slowly changing to high and extreme risk. The proposed methodology for developing torrential flood hazard and risk map, tested in several other basins in Bosnia and Herzegovina, gave acceptable outcomes according to the validation results, and also provides a good basis for numerous studies and projects in flood risk management, environmental protection, spatial planning, and other areas of human action.

Keywords: Natural hazard, torrential flood risk, hazard map, risk map, Rebrovački Brook, Banja Luka (B&H).

1. INTRODUCTION

In the last few decades, there has been great interest in analyzing and assessing the risk of natural hazards. The huge interest is the result of a large number of victims and the damage caused by these natural hazards around the world (Dilley et al., 2005; Gaume & Borga, 2008; Smith & Petley, 2009; Marchi et al., 2010; Gencer, 2013; Gosling & Arnell, 2013; Hirabayashi et al., 2018). Torrential floods are one of the most significant natural hazards in B&H causing serious risk to life and destruction of buildings and infrastructure. Nevertheless, this type of flood, often affecting ungauged basins, remains a poorly documented phenomenon. Despite being a serious natural hazard that affects entire B&H, torrential floods remain a poorly understood and documented natural phenomenon. Extreme events in B&H, such as those from August 2014 and May 2019, especially affected urban and suburban areas where torrential floods are one of the most common natural disasters. Therefore, there is a need to establish an appropriate methodological approach that will consider the potential risks of torrential floods for some of the basins in B&H. In previous practices, mapping flood risks in B&H was carried out only for larger alluvial rivers in accordance with the EU Floods Directive (Directive 2007/60/EC, 2007), while torrential streams were almost neglected (Blagojević et al., 2018). They were only considered in the context of the application of measures to repair the damage caused by torrential floods or in the context of the necessary construction of facilities in the channels of torrential streams or their basins. Since 2000, the City of Banja Luka has been affected by several extreme weather events that caused significant material damage and loss of life. The two most significant extreme events were 2014 and May 2019 floods. One of the main causes of this situation is climate change, which is also the reason for the increasing occurrence of rainfall over 20mm and 60mm, and five-day rainfall with over 60mm (Popov et al., 2018). Climate models indicate that the occurrence of such rainfall will be further intensified in the future, so strategies and planning for climate change adaptation should be based on possible climate changes that will take place according to the RCP 8.5 climate scenario (Đurđević et al, 2019). Intense rainfall particularly affects the urban and peri-urban areas of B&H. Non-maintenance of existing torrential streams, insufficient capacity of culverts, and overall inadequate approach to this issue only further complicate the fight against this natural disaster. The damage increases as the value of urban infrastructure and property of people constantly increases. This causes increased vulnerability in parallel with the growth of population and buildings in urban and peri-urban areas that are affected by torrential floods, and, therefore, the need for their protection. The Floods Directive 2007/60/EC indicated the need to prepare flood hazard and risk maps at river basin level. However, all activities of developing these maps related only to larger (alluvial) rivers, while torrential streams and their basins were completely omitted. Given that torrential floods in Bosnia and Herzegovina are one of the most common natural disasters, the development of a methodology for mapping torrential flood risk is of special scientific and professional interest. The development of a disaster risk management system includes the preparation of risk assessment studies as one of the preventive measures in this management. However, the methodology for torrential flood risk assessment has not been clearly defined yet. There are only recommendations with the aim of standardizing both the methodology in the broadest sense and the collection of data for certain levels of detail. In recent literature, there are a great number of useful approaches in natural hazard mapping (Teodor & Matreata, 2011; Tošić et al., 2018; Lovrić et al., 2019). However, there are only few papers that deal with the issue of torrential flood risk mapping, especially in the basins near Bosnia and Herzegovina. In that sense, the main goal of this research was to develop a methodology for mapping risks of torrential floods, which are the most common natural disasters in Bosnia and Herzegovina. The main result of this research is map of torrential flood risk of the Rebrovački Brook based on new methodological approach which could be used in other torrential streams in Bosnia and Herzegovina. The data presented in this paper are also significant to practical issues such as integrated water management projects, spatial planning, sustainable land planning, protection of soil, forest ecosystems and environmental protection, sediment management, flood risk management, agriculture and other human activities.

2. MATERIALS AND METHODS

2.1. Study Area

The study area Rebrovački brook basin is located in the northern part of Bosnia and Herzegovina and belongs to Banja Luka Municipality (Figure 1). Based on lithogenetic criteria the territory of study area contains: fluvial sediments, proluvial sediments, deluvial (slope) sediments, flysch sediments, marlstone, limestone, clay, calcarenite, breccia and other (Čičić, 2002). The dominant soils are Planosol-pseudogley, Fluvisol, dystric, eutric and mollic Gleysol (Burlica & Vukorep, 1980). The climate has the characteristics of a moderate-continental climate with an average annual temperature above 10°C and rainfall of 1,040mm. In the City of Banja Luka, the maximum daily rainfall in the observation period from 1961–2021 was 156.5mm recorded in July.

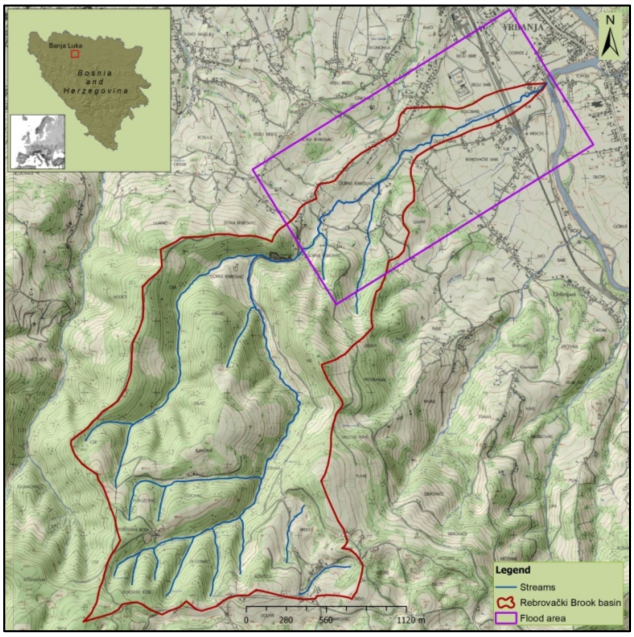

Figure 1. Study area - Rebrovački Brook - Banja Luka Municipality (B&H)

Given that at the Banja Luka weather station the maximum daily rainfall of over 30mm was recorded in almost every month in the period 1961-2021, it is clear that torrential floods can happen in any month during the year (Popov et al., 2018). Basic hydrographical features of the Banja Luka Municipality are the rivers Vrbas and Vrbanja and the smaller streams Crkvena, Široka Rijeka, Rebrovački Brook, Jelovac etc. In urban and peri-urban part of the City of Banja Luka, 49 torrential streams were registered. Taking into account the 2014 and 2019 events, this research analyses the Rebrovački Brook as a typical torrential stream. The Rebrovački Brook is formed by merging the streams Pakovac and Drenovača at an altitude of 598m. It is a left tributary of the Vrbanja and its confluence is at an altitude of 158m. Basic characteristics of the Rebrovački Brook basin: basin area 4.78km^2, basin length 6.23km, average width 0.77km, average basin altitude 421m, and average basin gradient 18.02°. Surface erosion processes in the basin are manifested in the form of sheet erosion, while linear erosion processes occur in the form of furrows, rills, gullies and ravines. Landslides are extremely common, especially those sliding into the river channel whose material is transported in one of the torrential floods. According to the results of mapping the intensity of erosion in the basin, the specific annual sediment production is 325.61m^3/km^2/year, while the specific annual sediment yield is 185.79m^3/km^2/year (Lovrić & Tošić, 2018). These values represent average annual values, while during extreme events, such as those from 2014 or 2019, the values increase several times (10 to 11 times), showing all the specificity of torrential floods and their destructive effects. According to the results of hydrological research, flood flows in the Rebrovački Brook range from 23.00m^3/s for a 20-year flood to 88.00m^3/s for a 500-year flood.

2.2. Data and Methods

Given the distribution of hilly and mountainous areas in Bosnia and Herzegovina and the hydrographic network, torrential floods occur extremely often, almost every year. These floods are mostly affected by rainfall characteristics (intensity, duration, quantity, space-time distribution), and the physical (intensity of soil erosion) and hydrological (slope, basin shape and land use) characteristics of the basin. Studies of torrential floods in Bosnia and Herzegovina define them as a rapid onset of flood flow in a river channel with a high concentration of the solid phase. Torrent watercourses are usually watercourses of hilly and mountainous areas characterized by a large longitudinal gradient of the river channel, while the length of watercourses and surface of basins vary in a wide range, from torrent large rivers, small rivers and brooks to torrent ravines and gullies. Studies of torrent floods generally treat torrent watercourses as including only those with a drainage basin of $A<100km^2$. However, from the aspect of hydrology and sediment production and transport, torrent watercourses cannot be confined only to drainage basins of $A<100km^2$ because other larger watercourses can have similar hydrological characteristics, sediment production and transport characteristics (i.e. drainage basins of $100 < A < 1000km^2$) (Kostadinov, 2008; Tošić et al., 2018). The phenomenon of torrential floods is very complex. It is a set of processes and phenomena taking place in a torrential stream and riparian area when a flood wave arrives. An erosion map, together with a cadastre of torrential streams, enables the establishment of clear indicators of the torrential flow regime and the basis for the development of a torrential flood susceptibility model. This research used the following: the Vrbas River Basin Erosion Map, detailed Cadastre of Torrential Streams in the Vrbas basin, the Torrential Floods Susceptibility Model of the Vrbas Basin. The results of mapping the intensity of erosion, the development of the cadastre of torrential basins, and the Torrential Floods Susceptibility Model of the Vrbas Basin are presented in detail in the following geomorphological papers: "Assessment of Soil Erosion and Sediment Yield using Erosion Potential Method: Case Study - Vrbas River Basin (B&H)" and "Assessment of Torrential Flood Susceptibility using GIS Matrix Method: Case study - Vrbas River Basin (B&H)" (Tošić et al., 2018; Lovrić & Tošić, 2018). These data, erosion map and torrential floods susceptibility map, along with a detailed cadastre of torrential streams/basins, are one of the most important input data or, better said an assumption, for rainfall-runoff modelling and development of torrential flood hazard and risk maps. Therefore, a quantitative study of geomorphological elements can, on one hand, contribute relevant information for calibrating hydraulic models (Fernandez-Lavado et al., 2017).

2.2.1. Geometry Data in ArcGIS and HEC RAS

The existing digital terrain model (DTM) with a resolution of 0.5m (EPSG: 3908 MGI 1901 Balkans Zone 6) was used for the drainage basin of the Rebrovački Brook. The model was additionally supplemented by geodetic surveys (GNSS) of the river channel and valley, and data on structures in the main river channel (weirs, dams, culverts, bridges, etc.). In addition to the existing DTM, cross-sections were surveyed at sites of all structures and characteristic (representative) sections along the main channel of the Rebrovački Brook. A hybrid digital terrain model (HDTM) was generated in this way. The model covers an area of 140ha, horizontal resolution of 0.5 and vertical resolution of 0.01m. It includes all relevant information on the morphometry of the main river channel and the river valley along 2.6km. The HDTM created in this way contains all the information on the spatial position and horizontal position representation of roads of different categories, railways, terraces, etc. Based on the updated hybrid digital terrain model of the Rebrovački Brook basin, a geometry file of the hydraulic model was formed in HEC-RAS 6.0.0 software. The HDTM range is wider than the extent of the largest recorded flood. If there are no reliable data on historical flooding maxima from the analyzed torrential stream, it is necessary to determine the extent of the analyzed area on the basis of available field data and hydraulic practice, so that the geometry file covers an area larger than the computed flood extent. All aspects of the terrain configuration and possible floodplains must be taken into account, as well as facilities that affect the channel flow. This research also used a digital orthophoto (DOF) from 2021 in the scale of 1:1,000 (DOF 2021 1:1,000).

2.2.2. Hydrological Modelling

Determining flood flows in hydrologically ungauged basins is a major challenge in hydrological practice. Given the needs and application of flood hydrographs, which in flood hazard and risk maps are always linked to the return period, the method of determining flood flows based on design rain depth is the most logical choice. The key element in this method is the choice of a rainfall-runoff model. For extremely small homogeneous urban areas, it makes sense to use a simpler model, such as the rational method or the SCS method in small rural basins. However, these methods do not allow an input of time-varying rainfall, which can significantly underestimate the relevant flood flow. For this reason, more sophisticated models for the calculation of flood hydrographs are generally found in literature (i.e., Norbiato et al., 2008; Jain et al., 2018; Kong et al., 2019). The procedure of determining a flood hydrograph in this paper can be divided into three steps: a) defining design rain depths; b) transformation of gross rainfall into net rainfall (determining effective rainfall); and c) transformation of rainfall into runoff. The last two steps depend on the choice of hydrological model. The Banja Luka Weather Station is the relevant station for the area of the torrential basin, which has rainfall observations and IDF curves (intensity-duration-frequency) based on sub-hourly rainfall observations from 1961 to 2013. The curves were determined with an assumption that rain intensities of all durations followed the same probability distribution (Koutsoyiannis, et al., 1998). This method can overcome problems that arise when determining these relationships in practical engineering tasks. The procedure and description of determining this relationship is presented in the paper Plavšić, et al., 2015, where the following relationship was obtained using the data from the Banja Luka WS:

$$i(t_k, T) = \frac{8.06 - 12.1[1 - (-\ln(1 - 1/T))^{-0.26}]}{(t_k + 9)^{0.77}} \quad (1)$$

where: T – return period in years and t_k – rainfall duration in minutes.

Intensities are obtained in units (mm/min). Of many available models, HEC HMS (US Army Corps of Engineers) was selected for its easy availability, more options in terms of spatial and temporal modelling resolution, model validation in many projects and research showing better performance than other models (Xin et al., 2019). Given that georeferenced maps with corresponding curve numbers (CN) were available for the research area, the SCS method (Feldman, 2000) was selected to determine the effective rainfall, while a simple delay method with a delay time determined according to the SCS method was selected to transform rainfall into runoff. Design rain depths were formed in a form of block rain - a constant intensity over the duration of the rainfall that was used to determine the design rainfall duration for which the design runoff was obtained. After determining the design rainfall duration, hyetograph of alternative blocks were constructed (Chow et al., 1988) with maximum intensity in the first 25% and 33%, then at 50% of the rainfall duration, and in the last 66% and 75% of the rainfall duration. Applying these design rainfall depths leads to the design form of rainfall (in terms of temporal rainfall variability), which produces design flood hydrographs of a certain frequency. This method was used to calculate quantiles and unit discharge of certain return periods, which were presented through flood hydrographs. This method introduces a basic assumption that the rainfall return period determines the flood return period, although it is known that this relationship is not linear but is close to that in the domain of flood flows (McIntyre, et al., 2007). Therefore, the analysis and management of torrential flood risk are clearly conditioned by the availability of existing hydro-meteorological data. This research determined 20, 100 and 500-year floods but the paper presents the results only for 100 and 500-year return periods.

2.2.3. Hydraulic Modelling

Torrential streams are characterized by large variations in water levels and discharge, permanent processes of morphological changes, while the flow regime is extremely turbulent with spatially uneven flow. Specific hydraulic characteristics are conditioned by great longitudinal gradient of the channel and characteristic dynamics of the torrential phenomenon that arises from two-phase character of the flow, with a significant share of solid phase. Considering previous research on sediment transport in torrential streams of Bosnia and Herzegovina, analysis of sediment transport can be treated as a hydraulic phenomenon (not as a rheological phenomenon), respecting certain universal laws that apply to all natural streams, as well as specific hydraulic characteristics of torrential streams. During extreme hydrological events, when water spills over the main river channel, the character of the flow along the river valleys changes. Due to the complex interaction between the flow in the main river channel and in the flood areas, it is necessary to use multidimensional 2D flow models (planar or spatial model) in hydraulic analyses of torrential streams. Significantly higher number of computational operations compared to 1D modelling is justified when taking into account that flooding processes in torrential floods are not usually in the direction of the flood strongest current but there are lateral overflows and frequent changes in flow direction due to obstacles on the ground (insufficient capacity of culverts, traffic infrastructure, breaching embankments, flood defenses of insufficient height, etc.). In numerical simulations of 2D flow, two orthogonal components are determined by the depth of averaged velocities and the depth of flow at the computational mesh points that are formed on the surface that represents the flow area. By applying 2D flow models, the exchange of fluid between different parts of a complex flow is obtained directly as a result of numerical simulations. From the above, it can be concluded that the simulation of unsteady flow is a more adequate approach to calculations due to spatial transformation, i.e., the retention capacity of the river valley during the passage of a flood wave. Upstream boundary condition is the computed hydrograph of 20, 100 and 500-year return period, while at the downstream end of the section, the computed levels in the recipient are assigned or the corresponding water elevation at the downstream end of the analysis. Hydraulic losses in the mathematical flow model of a torrential stream depend on the values of the model parameters, the Manning coefficient and the turbulent viscosity coefficient. Given that in a two-dimensional flow model, unlike one-dimensional flow model, there is a member with turbulent stresses, it is necessary to select adequate values of the Manning coefficient in relation to the values that would be selected in cases of using a one-dimensional flow model (Batinić, 1994). The value of the turbulent viscosity coefficient (v_t) is determined by the following formula (Jovanović, 2008):

$$v_t = D \cdot h \cdot u_* \tag{2}$$

where: D – dimensionless coefficient (‘mixing coefficient’) whose values are selected according to the recommendations from literature, taking into account the degree of irregularity of the flow geometry, h – average depth and u_* – shear velocity. Shear velocity (u_*) is calculated on the basis of hydraulic radius (R), velocity (V), gravitation (g) and Manning coefficient (n) (Jovanović, 2008):

$$u_* = \frac{n\sqrt{g}}{R^{1/6}}|V| \tag{3}$$

Sediment transport capacity is indirectly assessed based on the comparison of the ratio of computed (modelled) shear stresses (τ) (at the bottom of the main river channel and floodplains) for the characteristic size of the bed load at the analyzed section of a torrential stream (previous grain size distribution analysis of bed load was carried out in torrential stream). As the shear stress increases, the conditions for the movement of bed load particles at the stream bed improve, as well as the conditions for the movement of smaller particles of suspended load. Thus, by comparing the values of shear stresses, certain conclusions can be drawn regarding the transport of both bed and suspended loads. The aim is to establish the ratio between the shear stress at the bottom (τ) and the critical shear stress (τ_{cr}), which leads to an assessment in the absolute sense and defines the zones of possible movement and deposition of sediment. If this ratio $\tau/\tau_{cr} = 1$, it is the boundary value at which the sediment starts to move at the stream bed. If the ratio is < 1, then it can be expected that there is no movement of sediment particles. If the ratio is > 1, it is expected that sediment particles are moving in that section of the river channel. The shear stress (τ) is calculated using shear velocity (u_*) in the following formula (Jovanović, 2008):

$$\tau = \rho u_*^2 \tag{4}$$

While the critical shear stress (τ_{cr}) is calculated on the basis of the selected value of the dimensionless critical shear stress, i.e., the sediment particles mobility parameters ($\theta_{cr} = 0.047$) (Jovanović, 2008):

$$\tau_{cr} = 0.047(\rho_s - \rho)gd \tag{5}$$

where: ρ_s – sediment density, ρ – water density and d – sediment size.

The calculation of sediment transport was modelled by the Meyer-Peter & Müller method (Jovanović, 2008), with a preliminary definition of the area and the unit of the grain size distribution of the torrential stream. The end result is a map of maximum shear stresses and an erosion map of the river channel and sediment accumulation. Two-dimensional flow during a flood in the Rebrovački Brook torrential basin was simulated using a numerical model implemented in HEC-RAS 6.0 software. The same software was used for other hydraulic analyses. The calibration phase of the model is necessary for fine adjustment of Manning coefficients of flow resistance, hydraulic resistance in the area of bridges, culverts and other structures after obtaining the above initial hydraulic modelling results. Special attention was given to the calibration of the hydraulic model using geomorphological evidence of previous torrential events, flood traces from these events, and areas that were flooded by torrential floods in 2014 and 2019.

2.2.4. Hazard Maps

Hazard maps are a graphical representation of a flood area affected by a certain probability of flood where there is a real hazard to population, their material goods and the environment. They are based on hydrological and hydrodynamic calculations and the results of rainfall-runoff and hydraulic modelling, which define the basic flooding indicators. The methodology of creating hazard maps on alluvial rivers of Bosnia and Herzegovina was the basis for creating a new methodological approach to creating torrential flood hazard and risks maps (Blagojević et al., 2018). Taking into account the nature and diversity of flood events, a new formula was created to calculate flood hazard rating (HR_t) for torrential floods:

$$HR_t = h \cdot (v + 0.5) \cdot (3 + |e(a)|) \tag{6}$$

where: h – flood depth (m), v – flood velocity (m/s), 0.5 – correction constant of the velocity, e – erosion (m), a – accumulation (m) and 3 – correction constant of erosion and accumulation impact in the formula for calculating torrential flood hazard rating.

The physical parameters that must be represented are the height of the water sheet, the flow velocity, height of sediments in accumulation zones and the depth in erosion zones (Ballesteros-Cánovas & Álvarez-Troncoso, 2020). The values of the maximum shear stresses are analyzed and shown separately, as well as other information about the processes triggered by a torrential event. This approach defines flood hazard maps for torrential streams. As for alluvial rivers, hazard is presented in four classes: low, moderate, significant and extreme hazard (Table 1). The resolution of flood hazard maps of a torrential basin has many limitations and is a dynamic category. However, it should not be forgotten that torrential flood risk mapping usually focuses on mapping in the scale of 1:5,000 to 1:10,000, so the processor is left to choose the scale depending on the purpose and the required level of detail (Blagojević et al., 2018). This research used horizontal DTM resolution of 1m in the river valley and from 0.25m to 0.5m in the main river channel, with a maximum 0.01m vertical accuracy.

Special attention was given to the validation of resulting hazard maps, which were developed using the proposed formula for calculating the torrential flood

Table 1. Flood hazard classes

Class	Hazard rating	Description	Class name
0	0 – 0.75	Negligible hazard	Low hazard
1	0.75 – 1.5	Hazard for some categories (children, elderly, etc.)	Moderate hazard
2	1.5 – 2.5	Hazard for most population	Significant hazard
3	>2.5	Hazard for all population	Extreme hazard

hazard rating. The validation used representative traces of river channel and bank erosion and traces of sediment accumulation inside and outside the river channel, that were created during previous torrential events in 2014 and 2019, which can be clearly seen in the field and on historical satellite images. The significance of the resulting torrential flood hazard map/model, which is an integral part of potential erosion and accumulation of sediments (obtained by hydraulic modelling), was tested using the Degree of Fit method. This method considered a degree of matching locations (surfaces) with clear traces of erosion or accumulation of sediments with certain classes of hazard rating (HR_t) for different flood return periods (100 and 500-year). After mapping torrential flood hazards of several torrential streams in Bosnia and Herzegovina within the Project "Mapping Flash Flood Risks of Urban Areas in Bosnia and Herzegovina with Preliminary Assessments of Applying Protective Measures of Nature-Based Solutions in the Cites of Banja Luka and Tuzla", the correction constant of the impact of erosion and accumulation was defined in the formula for calculating the torrential flood hazard rating. The introduction of this constant increases the torrential flood hazard rating which is proportional to its real impact on vulnerable categories (population and economy).

2.2.5. Risk Maps

The procedure for defining the content of risk maps is determined by the EU Directive (Directive 2007/60/EC), Article 8, specifying that flood risk maps must show the following: the indicative number of inhabitants potentially affected by flood, land use, types of economic activity of the area potentially affected, facilities and installations which might cause accidents and environmental pollution, and other important information (key infrastructure, cultural heritage, etc.) (Directive 2007/60/EC). Pursuant to the EU Directive on the Assessment and Management of Flood Risks, the following vulnerable categories are defined: population, economy, protected areas, cultural and historical monuments, and IPPC installations. Depending on the need, it is possible to divide these further into subcategories (Directive 2007/60/EC). Weighted coefficients for calculating flood risk for torrential streams were adjusted compared to the weighted factors for alluvial rivers, in order to reduce the calculated risk to realistic range, taking into account the resolution and extent. In general, it is concluded that in order to adequately assess and define the risk of torrential floods in a specific area of analysis, it is necessary to assess the real value of material assets in the flood area and the vulnerability of the population and infrastructure. Subsequently, depending on potential losses, weighted factors are adjusted. The weighted factors recommended in the EU directive were changed and harmonized in this research to suit torrential streams. The aim was to reduce the weighted risk factors to realistic range, taking into account the surface area and categories present in the potentially flooded area (Table 2 and 3). Therefore, in order to adequately assess and define the risk of torrential floods, it is necessary to first assess the real value of material assets in the flood area and the vulnerability of infrastructure, and subsequently adjust the weighted factors depending on potential material losses. After a detailed analysis of potential vulnerable categories in the flood area, this research proposed to use adjusted/modified weighted factors for the population and economy categories, while other categories were not considered (protected areas, cultural and historical monuments, and IPPC installations), given that they are not present in the flood area of the Rebrovački Brook.

All collected data are archived in a GIS database, which is classified into three types according to the type of data: point (representing population (number of households), facilities, installations, plants, etc.); line (representing roads, embankments, etc.); and polygon (representing agricultural land, forests, etc.). After defining the weighted factors for certain categories of vulnerability/hazard, the risk factor (RF) is calculated with limit values of risk factor thresholds (Table 4 and 5). The risk factor (RF) is determined according to the following formula:

$$RF = \sum n \cdot WF \cdot HR_t \quad (7)$$

where: RF – risk factor, n – number of points, length of lines (km) or surface of polygons (km^2), WF – weighted factor and HR_t – hazard rating.

The values of risk factors (RF) are normalized to flood risk classes in the range from 0 to 1.0, which describe the nature of the risk by separate categories for the population and the economy (Blagojević et al., 2018).

Table 2. Weighted factors for calculating flood risk – population

Population	CODE/EU NACE Rev.2	Division, group, class, category	GIS data	Weighted factor (WF)
Households	1010	House	Point	95
	1020	Building	Point	200 – 500
	1040	Outbuilding	Point	30

Table 3. Weighted factors for calculating flood risk – economy

Economy	**CODE/ EU NACE Rev.2**	**Section**	**Division, group, class, category**	**GIS data**	**Weighted factor (WF)**
ECONOMY AND AGRICULTURE	1.1	A – Agriculture, forestry and fishing	Growing of annual crops	Polygon	0.7 – 6.5
	1.2		Growing of perennial crops	Polygon	8.5
	45.2	G – Trade	Maintenance and repair of motor vehicles	Point	200
	47.3		Retail sale of automotive fuel in specialised stores	Point	1200
	47.1		Retail sale in non-specialised stores	Point	30
	52.1	H – Storage	Warehouse/Storage	Point	35
	56.1	I – Accommodation and catering	Restaurants and mobile food service activities	Point	400
	71.2	Other independent shops		Point	300
	2010	Local road		Line	10 – 15/m
	2020	Regional road		Line	20/m
	2030	Trunk road		Line	25/m
	2040	Uncategorized road		Line	10/m
	2050	Railway		Line	40/m

Table 4. Risk factors and classes for population

RF	**Class**	**Description**
0 – 49	0	Negligible risk
50 – 499	$0<R\leq0.25$	Low risk
500 – 999	$0.25<R\leq0.50$	Moderate risk
1,000 – 1,499	$0.50<R\leq0.75$	Significant risk
≥1,500	$0.75<R\leq1.0$	Extreme risk

Table 5. Risk factors and classes for economy

RF	**Class**	**Description**
0 – 499	0	Negligible risk
500 – 3,499	$0<R\leq0.25$	Low risk
3,500 – 6,999	$0.25<R\leq0.50$	Moderate risk
7,000 – 9,999	$0.50<R\leq0.75$	Significant risk
≥10,000	$0.75<R\leq1.0$	Extreme risk

Following all previous activities, torrential flood risk maps are produced by multiplying spatial coefficients of flood hazard rating (*HR*) in a grid form (obtained from torrential flood hazard maps for different flood return periods ($Q_{1/100}$ and $Q_{1/500}$) with values of torrential flood risk susceptibility classes for defined vulnerability categories (also in a grid form). An assessment of the risk of natural disasters uses four components: Hazard (H), Exposure (E), Vulnerability (V) and Resilience (R). These risk components are divided into segments and an indicator is defined for each of them. The resilience of a community to fight and reduce the risk of torrential floods to an acceptable level is achieved through different actions and behaviours in a potential floodplain. For torrential floods, this resilience is reflected in implemented erosion control measures (in terms of soil erosion and sediment transport), monitoring measures, measures of adequate construction of facilities in the floodplain, bioengineering measures, sediment retention ponds and barriers, river channel management (stream bed and slope stabilisation), etc. Therefore, the analysis of implemented measures in a torrential basin is crucial for the assessment the resilience index (erosion and sediment transport), as well as the assumption that all measures are functional and implemented to a full capacity (regular maintenance). This research, which, in addition to the analysis of potential hazards and categories exposed to risk, included torrential flood risk mapping, did not consider any elements of vulnerability and resilience. Therefore, risk or information on spatial distribution of risk was determined by hazard and exposure indicators. Vulnerability, as a reduced ability to absorb the impact of a torrential flood and recover from it, was considered through the categories of vulnerability, while resilience was not included because no measures were taken in the basin to reduce the overall risk of torrential floods.

3. RESULTS

The presented methodology for determining flood flows also determined modelled flood hydrographs of different return periods of the Rebrovački Brook. According to hydrological analyses, flood flows in the Rebrovački Brook basin range from 44.10m^3/s for a 100-year flood to 88.00m^3/s for a 500-year flood (Figure 2). The hydraulic analysis covered an area of 1.40km^2 and a stream length of 2.62km. Hydraulic flow resistances, determined in accordance with methodological guidelines, ranged from 0.016m$^{-1/3}$s (in the regulated concrete channel section) to 0.045$^{1/3}$s (in densely vegetated channel sections of irregular stream bed at the upstream end). Boundary conditions at the downstream end were design modelled levels of the Vrbanja and at the upstream end modelled hydrographs of the same return period as in the section of the Vrbanja.

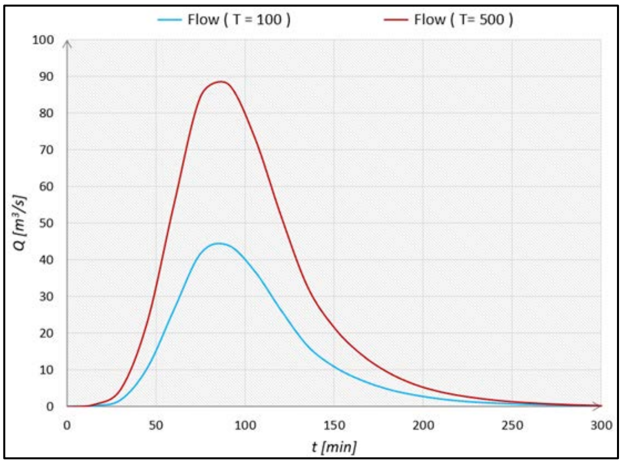

Figure 2. Modelled hydrographs for 100 and 500-year floods of the Rebrovački Brook

The results of hydraulic modelling are presented graphically (Figure 3) and also through a spatial distribution of flood depths and velocities (Figure 4). Significantly increased intensity of flood velocities in torrential streams is caused by the presence of a solid phase in the fluid (considering a non-Newtonian (two-phase) fluid). In the process of occurrence and development of torrential flood events, there is an increase of suspended and bed load particles, which increases the fluid/water density of 1,000kg/m^3 by up to three times depending on the morphology of the river channel. Therefore, velocities range up to 11.07m/s for 100-year flood and up to a maximum of 13.55m/s for 500-year flood. This shows how the dynamics of torrential streams is different from that one of alluvial rivers where maximum velocities are several times lower. Grain size distribution curves were defined as input data for the calculation of shear stresses. The curves are a result of 5 samples of natural river material taken from the stream bed and tested according to BAS EN standards. The map of shear stresses of the Rebrovački Brook for a 100-year flood shows that they range up to a maximum of 3,482N/m^2, while for a 500-year flood up to 5,348N/m^2 (Figures 5).

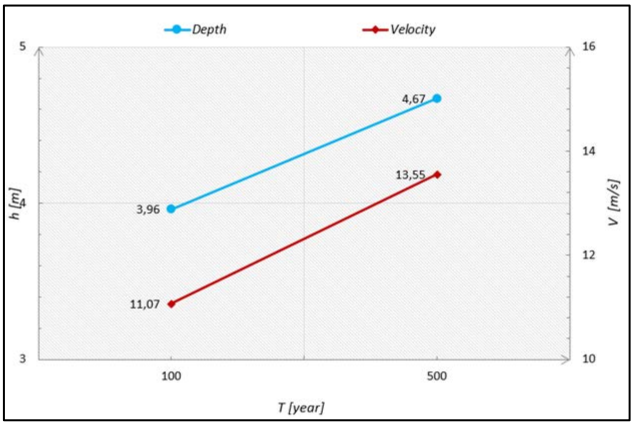

Figure 3. Hydraulic modelling result for 100 and 500-year flood

Significantly increased flood velocities and occurrence of extremely high shear stresses in torrential streams (up to 10 times higher than those in large rivers) are reflected in the two-phase fluid (presence of solid phase in the fluid). Erosion maps of the river channel and sediment accumulation sites in the Rebrovački Brook for 100 and 500-year floods were developed on the basis of set boundary conditions for the calculation of erosion and sediment transport, sediment calculation method, type of stream bed material and grain size distribution for each sediment transport zone (Figures 6). Erosion values expressed with "-" represent loss (downcutting erosion), while those expressed with "+" represent sites of sediment accumulation. Table 6 provides the maximum values of erosion and sediment accumulation for the Rebrovački Brook for floods of different return periods. These maximum values of erosion refer to the sections of the river channel where there are also maximum shear stresses. The maximum values of sediment accumulation refer to the locations of culverts or areas of backwater which reduce velocities and shear stresses intensifying the sediment accumulation process.

Hazard maps for the Rebrovački Brook for 100 and 500-year floods include all data on hazard rating (Figure 7). Table 7 provides the maximum hazard ratings and flood extents for the specified return periods, where it is evident that the hazard ratings are significantly higher than the limit value of extreme hazard which is higher than 2.50 according to the classification (Table 1). In addition to the maximum hazard rating, the spatial distribution of other hazard

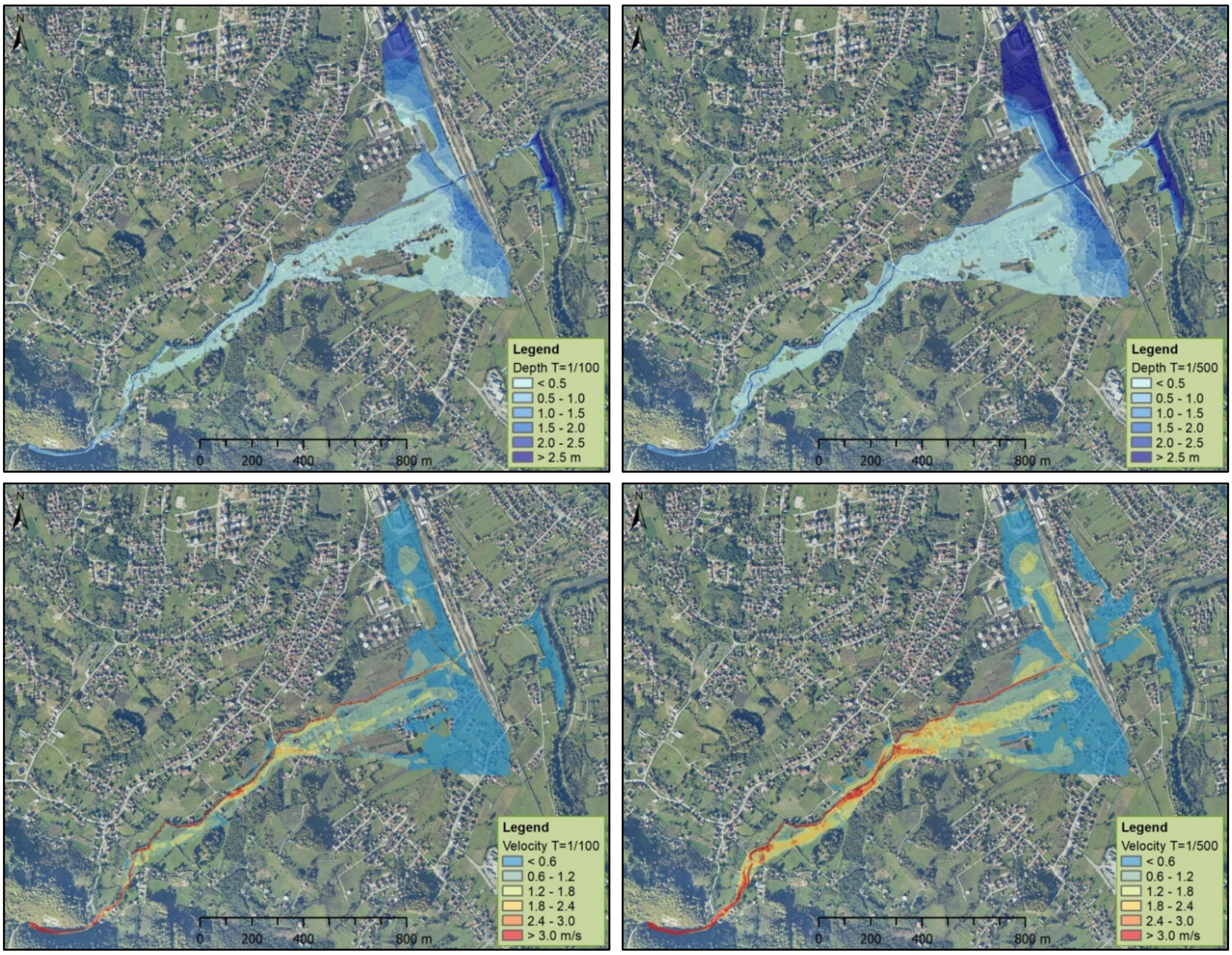

Figure 4. Hydraulic simulation results of design scenarios in the area of the Rebrovački Brook for 100 and 500-year floods

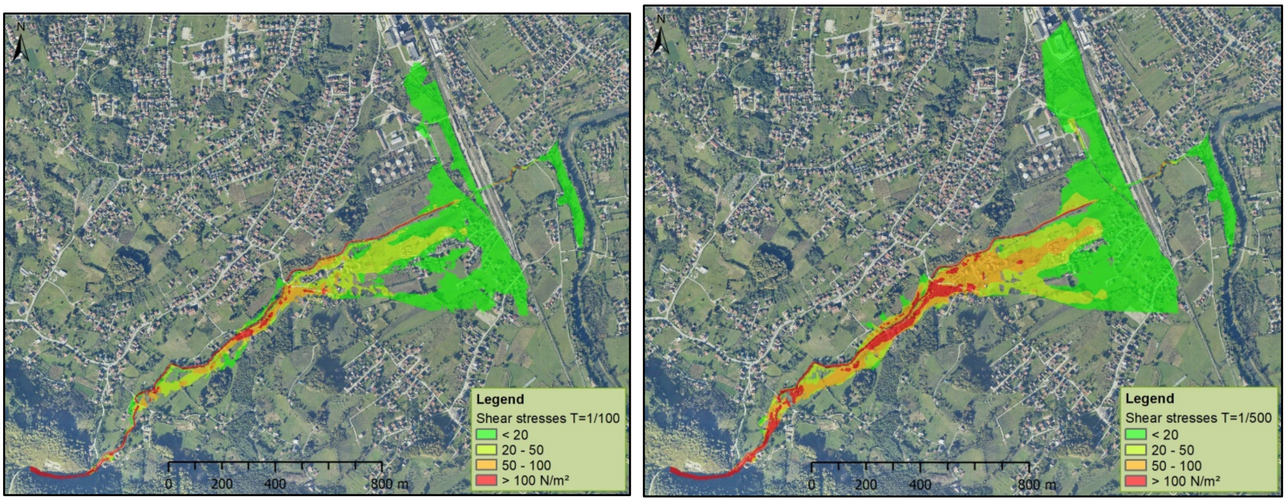

Figure 5. Shear stresses for the Rebrovački Brook for 100 and 500-year flood

Table 6. Maximum values of erosion and sediment accumulation in sections of the Rebrovački Brook for 100 and 500-year floods

Return period	**1/100**	**1/500**
Erosion (m)	-0.59	-3.50
Accumulation (m)	1.50	1.66

Figure 6. Erosion and sediment accumulation map of the Rebrovački Brook for 100 and 500-year flood

Table 7. Maximum hazard rating and flood extent of the Rebrovački Brook for 100 and 500-year floods

Return period	**1/100**	**1/500**
Flow area (ha)	34.53	46.11
Hazard	68.90	69.28

ratings for the entire analyzed area is provided for different return periods. Although there is a small difference in the maxima of floods of different return periods, there is a great difference in spatial distribution and share of individual hazard classes in flood flows of both return periods.

The development of flood risk maps required data collection for a detailed inventory of material assets exposed to torrential flood risk. Data include individual houses, residential buildings, industrial plants, infrastructure, agricultural land and facilities, roads, etc. Input data for flood risk mapping are integrated into a GIS database as layers of different types of data (points, lines and polygons). Sections of torrential river channel are identified from the polygons with risk values where the risk of floods is not considered. In the torrential basin of the Rebrovački Brook, data were collected on households and material assets that are at risk from 100 and 500-year floods (Table 8 and 9).

Risks for the population and economy categories were defined in the Rebrovački Brook basin for two design flood events, while no potential risk was identified for other categories defined by the EU Floods Directive (Figure 8).

4. DISCUSSION

The Rebrovački Brook is characterized by a specific torrential flow regime which is reflected in sudden flood waves after high-intensity rainfall and high concentration of eroded sediments. Before its confluence with the Vrbanja, this stream flows through a densely populated local community of

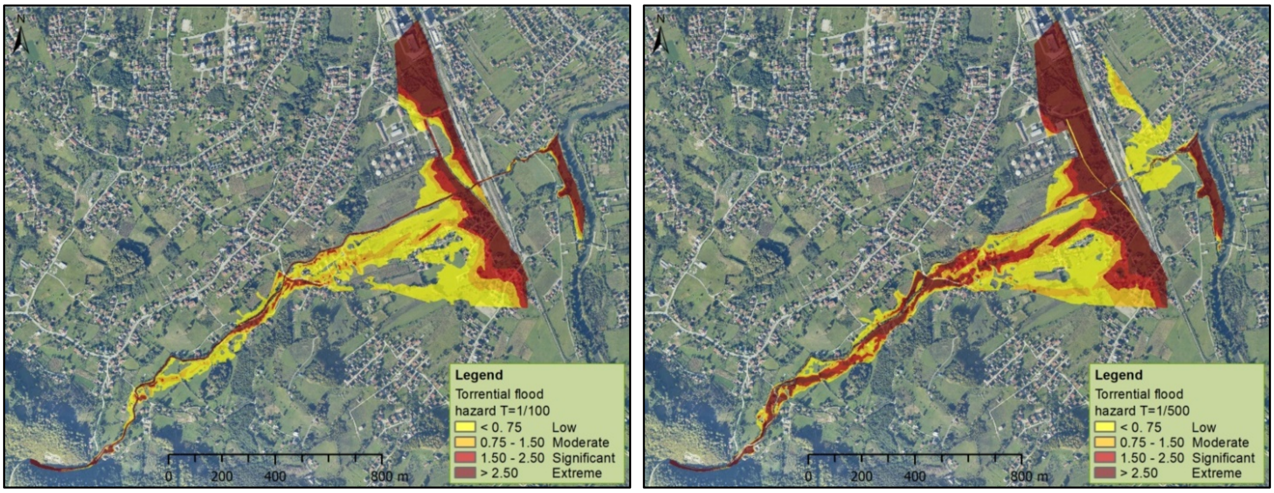

Figure 7. Torrential flood hazard map of the Rebrovački Brook for 100 and 500-year flood

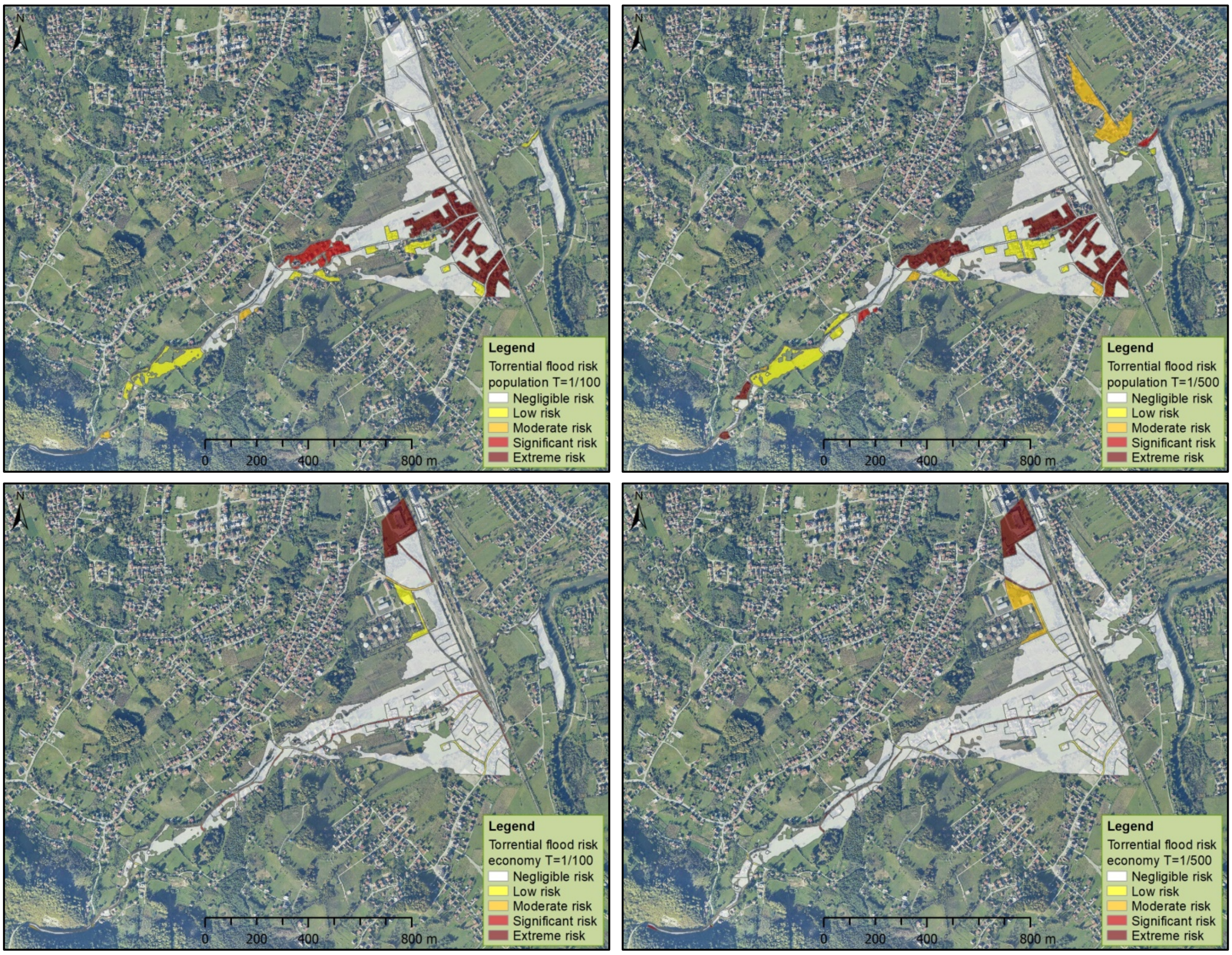

Figure 8. Torrential flood risk map of the Rebrovački Brook for 100 and 500-year flood

Table 8. Data on population number and identified households and public institutions in the floodplain of the Rebrovački Brook basin

Return period (T)	Population	Facilities (number)			
		Houses	Residential buildings	Outbuildings	Public institutions
1/100 – Q $_{1/100}$	535	194	-	465	-
1/500 – Q $_{1/500}$	682	247	-	592	-

Table 9. Data on identified economy facilities, road infrastructure and agriculture in the floodplain of the Rebrovački Brook basin

Return period (T)	Facilities – total (number)	Roads (km)	Agricultural land (ha)
1/100 – Q 1/100	2	4.18	24.01
1/500 – Q $_{1/500}$	2	4.97	35.59

Rebrovac, where the river channel is extremely narrow due to construction and urbanization. The flow routes are intersected by various obstacles causing frequent spill over banks and torrential floods. Given intensive erosion processes in the upper part of the basin, large amount of sediment at the stream bed, flood flows that appear within few hours, urban restrictions and inadequate culverts along roads, almost every flood wave has an extremely destructive power causing great damage and sometimes human casualties. The development of a torrential flood risk map required prior consideration of the characteristics of erosion processes through mapping erosion intensity and producing an erosion map (Tošić et al., 2018, Lovrić & Tošić, 2018). The erosion map of the Rebrovacki Brook basin and site investigations allowed the determination of clear indicators of the torrential flow regime and preconditions for rainfall-runoff modelling and the production of torrential flood hazard and risk maps.

Hydrological analyses carried out for this ungauged basin, where there are no observations of water levels and runoff, showed high discharges for the analyzed return periods (1/100 and 1/500) and a short period in which a flood wave is formed. Therefore, the basic characteristic of the Rebrovački Brook is rapid formation of a torrential flood wave, together with a large amount of eroded material from the basin and river channel. The results of hydraulic modelling presented by the spatial distribution of the flood extent and depth indicate areas identified in this hydraulic modelling that are flooded during a torrential flood, where the most significant damage occurs to population and economy. Compared to alluvial rivers, the flooded areas are much smaller but flood depths and particularly velocities are much greater. This, together with high erosion and sediment accumulation, and shear stresses, is one of the most important characteristics of the torrent flow regime of the Rebrovački Brook. Hydraulic analysis confirmed that the river channel of the Rebrovački Brook does not have a sufficient capacity to convey even 20-year flood waves. The hazard rating results show a considerable extent of significant and extreme hazard for 100 and 500-year floods (up to 10 times higher hazard than on alluvial rivers). The torrential flood hazard ratings resulting from the proposed formula were validated using the Degree of Fit method. In this procedure we analyzed whether locations with the most pronounced traces of erosion and sediment accumulation recorded during the previous torrential events in 2014 and 2019 match with the significant and extreme hazard (Figure 12). The validation results showed that 69.25% were in the category of significant and extreme flood hazard. Therefore, the conclusion is that this torrential flood hazard map has a relatively high degree of reliability. The map of river channel erosion and sediment accumulation sites for 100 and 500-year floods, whose values are included in the hazard calculation, shows sections dominated by river channel erosion or sediment accumulation.

The resulting significant and extreme hazard required additional confirmation. Therefore, in this methodological approach, a map of shear stresses was developed for flood flows of different return periods. High shear stresses in some sections of the Rebrovački Brook match entirely to the grain size distribution of sediments in the river channel, the state of the river channel, and also traces of bed load deposited on river banks during previous torrential flood waves with accumulated layers of over 50cm (Figure 9). Given that shear stresses change along the channel of the Rebrovački Brook, sections with higher shear stresses coincide with sections of river channel erosion, while lower shear stresses coincide with sites of accumulated bed load. This methodological approach, which differs from that for alluvial rivers, clearly identifies sections that require regular maintenance in terms of removing bed load and stabilizing the river channel bed and slopes. It also identifies sections that require special attention during torrential flood waves when vulnerable categories are most at risk.

Torrential flood risk maps of the Rebrovački Brook for 100 and 500-year floods for the category of population showed that with the increase of the return period the areas at significant and extreme risk increase. There is still a large share of areas with negligible and low risk for population but due to the expansion of the City of Banja Luka, some parts of these floodplains are increasingly populated, which changes this relationship in favour of significant and extreme risk categories. Flood risk maps for 100 and 500-year floods for the category of economy showed dominant negligible and moderate risk. However,

Figure 9. Rebrovački Brook – sites of erosion and sediment accumulation after the 2014 torrential flood (Photo by R. Tošić, August, 2014)

pressure on torrential basins increases with the trend of relocating small and medium companies to peri-urban areas of the city due to high office space costs and difficulty of transporting people and goods in urban areas. Torrential basins are often misinterpreted in terms of potential risk of flooding due to poor public perception (lack of professional support). In general, the applied methodological approach to torrential flood risk mapping could be described in several steps: development of erosion map; development of cadastre of torrential streams; development of torrential flood susceptibility models; development of digital terrain model with additional geodetic surveys of river channel centreline, river banks and cross-sections; development of shear stresses maps; development of river channel erosion and sediment accumulation maps; development of hazard maps; and development of flood risk maps. In addition to the Rebrovački Brook, risk maps were developed for two more torrential streams (Jelovac and Mali Ularac). The results of these analyses are used in the preparation of spatial planning documents of the City of Banja Luka. The same methodological approach was used in the north-eastern part of Bosnia and Herzegovina, in the area of the City of Tuzla, where torrential flood hazard and risk maps were prepared for three torrential basins (Osojački Brook, Tušanjski Brook and Kovačica). Therefore, the defined methodological approach proved to be extremely effective in another region of Bosnia and Herzegovina in the basins with different physical and geographical characteristics. Given the fact that torrential floods in Bosnia and Herzegovina are almost the most common natural disaster, this methodological approach to flood risk mapping is a step to a better understanding of the phenomenon, a good basis for selecting adequate torrential flood defence solutions and erosion control protection measures, and a path to more successful adaptation to climate change. In addition, the competent institutions should carry out an analysis of all torrential events to document them together with all related impacts. Currently, such analyses have taken on more importance, given that they can contribute highly relevant information to understanding the trigger mechanisms and the evolution of the events, which can be instrumental in improving the space-time prediction of future events.

5. CONCLUSIONS

Analysing all development stages of the methodology of torrential flood hazard and risk mapping (starting from previous works on erosion map, cadastre of torrential streams, and torrential flood susceptibility models, followed by the development of hydrological-morphological and hydraulic analyses, and flood hazard and risk mapping results), the following clear conclusions can be drawn:

- The development of erosion maps, cadastre of torrential streams and torrential flood susceptibility model is one of the most important input data for the development of torrential flood hazard and risk maps in a basin or an area;
- Hazard and risk maps are developed according to the proposed formula (HR_t) and methodological procedure, taking into account all morphological and hydraulic features of flood flow regime for torrential streams. In order to additionally validate and verify shear stress map, a parameter of torrential river channel erosion and sites of sediment accumulation is introduced during the stage of developing hazard map;
- The map of shear stresses is important from the aspect of load stress and sediment transport capacity of torrential stream (defining the sites of potential erosion and accumulation of sediment formations). This map, in addition to the map of maximum velocities, points to locations where river channel erosion is expected, i.e. a process of collapsing river banks, which is a significant factor during flood flows. The material from collapsed banks is a significant component in any torrential event;
- Grain size distribution of the river channel during hydraulic analyses produces realistic indicators of shear stresses in the torrential stream. They are often characterized by high values, which identify critical points and gain knowledge about possible destructive power of the torrential stream during floods;
- Erosion maps of torrential river channels and sites of sediment accumulation are also key data. They indicate sections of torrential channel prone to erosion of the stream bed and banks during flood events. This leads to soil loss causing instability to residential properties, industries and infrastructure with a possibility of total collapse. Sediment accumulation sites define zones where, in addition to the damage caused by flooding, it is possible to multiply the damage due to the deposition of solid matter (sediment);
- Adequate assessment and definition of torrential flood risk in a specific area of analysis, such as the floodplain of a torrential stream, requires an assessment of the actual value of material assets in the flood area and the vulnerability of infrastructure. Depending on potential material

losses, it is possible to adjust weighted factors. Weighted factors for infrastructure must be scaled from floods by larger rivers due to the nature of torrential floods and the degree of infrastructure destruction.

The presented methodology is the basis for selecting adequate solutions for torrential flood defence and erosion control measures to protect the basin and also the basis for defining a catalogue of adaptation measures for adverse effects of these natural disasters through planning nature-based solutions.

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