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Development of flood hazard and risk maps in Bosnia and Herzegovina, key study of the Zujevina River

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Abstract. Floods represent extreme hydrological phenomena that affect populations, environment, social, political, and ecological systems. After the catastrophic floods that have hit Europe and the World in recent decades, the flood problem has become more current. At the EU level, a legal framework has been put in place with the entry into force of Directive 2007/60/EC on Flood Risk Assessment and Management (Flood Directive). Two years after the entry into force of the Floods Directive, Bosnia and Herzegovina (B&H), has adopted a Regulation on the types and content of water protection plans, which takes key steps and activities under the Floods Directive. The "Methodology for developing flood hazard and risk maps" (Methodology) was developed for the territory of Bosnia and Herzegovina, following the methodology used in the majority of EU member states, but with certain modifications to the country's characteristics. Accordingly, activities for the preparation of the Preliminary Flood Risk Assessment for each river basin district were completed in 2015 for the territory of Bosnia and Herzegovina. Activities on the production of hazard maps and flood risk maps are in progress. The results of probable climate change impact model forecasts should be included in the preparation of the Flood Risk Management Plans, which is the subsequent phase of implementing the Flood Directive. By the foregoing, the paper will give an example of the development of the hydrodynamic model of the Zujevina River, as well as the development of hazard and risk maps. Hazard and risk maps have been prepared for medium probability floods of 1/100 as well as for high probability floods of 1/20. The results of LiDAR (Light Detection and Ranging) recording were used to create a digital terrain model (DMR). It was noticed that there are big differences between the flood maps obtained by recording LiDAR techniques in relation to the previous flood maps obtained using georeferenced topographic maps. Particular attention is given to explaining the Methodology applied in Bosnia and Herzegovina.

Keywords: flood hazard maps; flood risk maps; GIS; HEC-RAS; hydraulic modeling

1. Introduction

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Flooding of river systems is the most frequent and costly natural hazard, affecting the majority of the world's countries regularly (UNISDR 2011, IPCC 2012). Floods are happening, they have happened in the past and they will happen in the future. Regardless of the level of protection established, there is always the possibility of a major flood that can cause harm to people, property, and the environment. Even if the adverse impact of human activities on the occurrence and development of floods is neglected, full flood protection is not possible. There is always a risk that the built flood defense system, which provides a certain level of safety, will be overtaken. To increase the level of protection, it may be necessary to significantly increase financial investment. Therefore, it is necessary to choose the optimum level of flood protection, to align the investments in the construction and maintenance of the system with the potential damage (Prohaska and Ilic 2010). In the last decade of the twentieth century, flood costs were unrecoverable in terms of property damage and loss of lives (Brody *et al.* 2009, Haraguchi and Lall 2015). Flooding in Europe is worsening, with increasing damages and rising pressure on disaster risk financing (Jongman *et al.* 2014). Floods are among the most destructive natural disasters that strike people and infrastructures, and it is not surprising that modeling and forecasting such events have increasingly become a high priority in many countries in Europe (Kundzewicz *et al.* 2013).

Extreme hydrological situations are perhaps the most dangerous causes of natural floods when heavy rains and/or melting snow cause flows that watercourses cannot evacuate (Kuspilić *et al.* 2014). Globally, about 65% of floods are caused by heavy and/or prolonged rains, short-term storms 15%, tropical cyclones 10%, monsoon rains 5%, rains and snowmelt 3%, while 1% of global floods are caused by dam fractures and hydraulic structures, or for some other reason (Alphen *et al.* 2005). Despite controversy over the cause, it is undeniable that scientists agree with the existence of marked climate variability, and the occurrence of extreme rainfall that has a major impact on floods. Also, prognostic climate models indicate an increasing possible occurrence of extreme weather events, both globally and locally. The increasing frequency of extreme hydrological events increases the risk of flooding.

The impact of climate change on flood risk is not yet fully investigated, both qualitatively and quantitatively for Bosnia and Herzegovina. Within several European projects such as ESPON6[a] and ClimWatAdapt7[b], regions in Europe have been identified where significant changes can be expected. The region of Southeast Europe is characterized as vulnerable, given its low capacity to adapt to change. Also, within the ClimWatAdapt[7] project, which covers the entire Danube river basin, it was estimated that the greatest potential damage to health and economy can be expected in Bosnia and Herzegovina. However, according to a study by the Geneva-based Intergovernmental Panel on Climate Change (UNDP 2016), in the Sava River Basin in B&H between 2000 and 2050, no significant climate change is expected.

In response to the floods that hit Europe in the late 20th and early 21st centuries, the EU has adopted the Directive on Flood Risk Assessment and Management 2007/60/EC, which defines the necessary steps for a more objective and unified approach to flood risk management. The purpose of this Directive is to establish a framework for the assessment and management of flood risks to reduce the harmful effects of floods on human health, the environment, cultural heritage, and economic activity (Jabučar and Lukovac 2014). A reliable instrument in achieving these goals is

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[a] https://www.espon.eu/applied-research
[b] https://climate-adapt.eea.europa.eu/metadata/tools/climwatadapt-integrated-assesment-framework

the preparation of maps of flood hazards and risk areas together with flood risk management plans. It is clear that not all flood risks can be avoided, and flood risk management (FRM) and its effectiveness between countries is highly variable (Alexander *et al.* 2016, Ek *et al.* 2016, Kaufmann *et al.* 2016, Larrue *et al.* 2016). Since the occurrence and nature of floods depend on a variety of factors, there may be significant differences between countries in the approach used to identify flood hazards and risk maps.

The Flood Directive defines measures and activities that abandon the flood control approach and move to a flood risk management approach. The directive also strengthens public participation by strengthening the right of access to information and participation in the planning and decision-making process. Taking into account the requirements of the Water Framework Directive 2000/60/EU (WFD), whose main aim is to establish a "good ecological status of water", all activities implementing the FD should be consistent with the WFD, especially through flood risk management plans and water management plans. Flood management generally comprises four distinct stages: predictions, preparations based on the predictions, preventative measures, and the assessment of damage (Konadu and Fosu 2009). Flood risk management in a restricted sense is the procedure of managing an existing flood risk situation (Plate 2002), and in a broader sense, it includes the planning of a system, which will reduce the flood risk.

To define flood water levels, great importance should be given to the quality of hydrological data, geodetic data, geomorphological, and other important data, to make the results of hydraulic modeling as curate as possible. Sufficiently reliable geodetic maps, as well as data on hydrological characteristics, are a prerequisite primarily for the calibration and verification of the hydraulic model, but also for the development of flood forecast models. Data on river bed morphology and inundation are also among the data that can greatly influence the results obtained by hydraulic models. High-quality topographic data, along with the appropriate application of hydraulic modeling, are likely the most important factors required for accurate inundation maps. But one should also take into account the fact that flood mapping is a somewhat subjective process and that the results are influenced by the experience of engineers in selecting input data (flow design and topographic information), model type (1D/2D) and river geometry description in the model (Merwade 2009). In not so long-ago practice, it was common to use topographic maps of different scales, but in recent times there is increasing use of different remote sensing techniques, such as LiDAR or some other techniques, to obtain the most accurate 3D terrain (Fewtrell *et al.* 2011, Milišić *et al.* 2021).

Recently, detailed LiDAR data have been increasingly used to produce accurate flood maps. Although LiDAR data provide more accurate topographic information compared to old contour maps or digital elevation in public domain models, the entire flood map production process needs a more thorough assessment to investigate the impact of other factors such as modeling approach and geometric representation (Cook and Merwade 2009).

2. Flood risk management in Bosnia and Herzegovina

Bosnia and Herzegovina is at great risk of flooding. The floods, which have occurred in the last 20 years, have damaged society, infrastructure, the environment, and human health, including the loss of human lives. Often causing secondary problems, in the form of diseases and potential infectious epidemics. In addition, they have a negative long-term effect on agricultural activity, and thus on the state's economy. The development of flood forecast models is necessary in order to reduce the harmful consequences. The creation of exact terrain models is a requirement for the hydraulic model's accuracy. Data collection, flood analysis, and risk mapping are becoming considerably faster and more accurate because of developments in geospatial technologies.

2.1 Flood directive and its implementation in Bosnia and Herzegovina

As a signatory to the Stabilization and Association Agreement with the EU, although not mandatory, Bosnia and Herzegovina has adopted the implementation of the FD with a two-year delay. The legal act "Decree on the types and content of protection plans against adverse effects of water of the Federation of Bosnia and Herzegovina" has been used to implement the Floods Directive's criteria, (Hadžić *et al.* 2020). Three essential actions are involved in process of flood risk management: (1) To prepare preliminary flood risk assessment (PFRA) within river basins and associated coastal waters to identify areas for further assessment (AFAs), referred to in EU Flood Directive as Areas of Significant Potential Flood Risk (ASPFRs); 2) Preparation of hazard maps (FHM) and flood risk maps (FRM) for such areas; (3) Creation of a flood risk management plan (FRMP) that outlines steps to reduce risks and potential consequences based on prevention, protection, and preparedness.

2.2 Methodology for developing flood hazard and risk maps in B&H

In December 2013, a "Methodology for developing Flood Hazard and Risk Maps in B&H" was prepared (HEIS 2013).

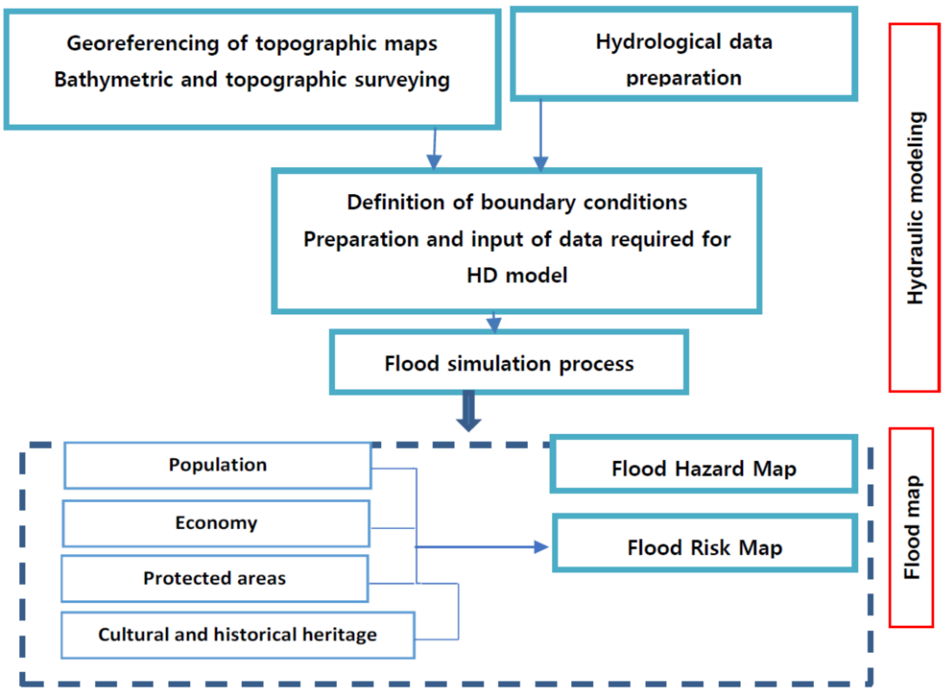

Fig. 1 Steps in creating hazard and risk maps

Table 1 Flood hazard (O) as a function of water depth and water velocity

		Depth (m)									
		0.25	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**	**2.5**
Velocity (m/s)	**0**	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25
	0.25	0.19	0.38	0.56	0.75	0.94	1.13	1.31	1.50	1.69	1.88
	0.5	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
	0.75	0.31	0.63	0.94	1.25	1.56	1.88	2.19	2.50	2.81	3.13
	1	0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75
	1.25	0.44	0.88	1.31	1.75	2.19	2.63	3.06	3.50	3.94	4.38
	1.5	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
	1.75	0.56	1.13	1.69	2.25	2.81	3.38	3.94	4.50	5.06	5.63
	2	0.63	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63	6.25
	2.25	0.69	1.38	2.06	2.75	3.44	4.13	4.81	5.50	6.19	6.88
	2.5	0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
	2.75	0.81	1.63	2.44	3.25	4.06	4.88	5.69	6.50	7.31	8.13
	3	0.88	1.75	2.63	3.50	4.38	5.25	6.13	7.00	7.88	8.75
	3.25	0.94	1.88	2.81	3.75	4.69	5.63	6.56	7.50	8.44	9.38
	3.5	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
	3.75	1.06	2.13	3.19	4.25	5.31	6.38	7.44	8.50	9.56	10.63
	4	1.13	2.25	3.38	4.50	5.63	6.75	7.88	9.00	10.13	11.25
	4.25	1.19	2.38	3.56	4.75	5.94	7.13	8.31	9.50	10.69	11.88
	4.5	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
	4.75	1.31	2.63	3.94	5.25	6.56	7.88	9.19	10.50	11.81	13.13
	5	1.38	2.75	4.13	5.50	6.88	8.25	9.63	11.00	12.38	13.75

The Methodology is largely in line with the methodologies used in most EU Member States, with certain modifications by B&H's specifics. Each member state of the EU, including those on the way to membership, is free to modify how the Directive's requirements are implemented with their national laws, the nature of local floods, and the characteristics of the area for which flood management plans must be created. Flood hazard scenarios were defined as follows in the B&H Methodology: (i) Extreme floods with a low probability (1/500); (ii) Floods with a medium probability (1/100); (iii) Floods with a high probability (1/20). Flood hazard and risk maps are based on the results of hydraulic modeling. The development of flood risk and hazard maps needs to show some important elements of flood scenarios, such as the flood extent, the water surface elevation, water depth, water velocities, and discharge at different critical cross-sections. Figure 1. illustrates the steps involved in designing flood hazard and risk maps in accordance with the Methodology.

The flood hazard was expressed by the following formula, which combined modeled depth and velocity, displayed in Table 1

$$O = h \cdot (v + 0{,}5) \qquad (1)$$

Where are: O-Flood hazard; h-Flood depth (m); v-Flood velocity (m/s); 0,5 -Velocity correction constant.

Table 2 Flood hazard categories

Category	O ≥	O ≤	Description
Category 0	0.00	0.75	Insignificant hazard
Category 1	0.75	1.50	Hazard to vulnerable minorities (children, elderly, sick, non-swimmer)
Category 2	1.50	2.50	Hazard to the majority
Category 3	2.50	25.0	Hazard to all

Table 3 Classes of flood risk severity

Class (RF)	Risk category
0	Insignificant risk
0 < R < 0,25	Low risk
0,25 < R< 0,50	Moderate risk
0,50 < R < 0,75	High risk
0,75 < R < 1,0	Extreme risk

As illustrated in Table 2 there are four categories for the severity of flood hazards.

Within flood risk area (Area for Further Assessment-AFA), vulnerable assets need to be identified for each flood hazard probability (20, 100, and 500-year return period), categorized, and presented on category map layers (containing GIS elements-points, lines, polygons) with their georeferenced attributes stored in a GIS database. The asset categories specified in the FD include population, houses, public buildings, commercial units, roads, railways, communication infrastructure, electric power lines, water supply, and sanitation facilities, water quality, cultural and historical heritage sites, agriculture, and forestry. For areas where asset survey data do not exist, the CORINE Land Cover Map (EEA, 2017) can be used (the map covers mainly agricultural land and forest areas).

Each category is divided into a hierarchy of divisions, groups, and classes according to the Statistical classification of economic activities in the European Community (EU NACE Rev. 2, 2008). Each group and class is given a numerical code and a weighting factor (WF) according to the EU NACE Revision 2 Categories implemented in the Code of B&H 2010 (HEIS, 2015). According to Methodology, flood risk factors by category, which are predetermined (population, economy, protected areas, cultural and historical heritage, and IPPC), are obtained for each category by multiplying the number of facilities (e.g., residential houses (number), road length (km), protected land area (km^2)) by an appropriate weighting factor and flood hazard (O) shown on the flood hazard map

$$FR = \sum N \cdot WF \cdot O \qquad (2)$$

Where: *FR*=flood risk factor; *N*=number of objects, feature length (km) or feature area (km^2); *WF*=weight factor; *O*=flood hazard ($h \bullet (v + 0.5)$)

For convenient representation on flood risk maps, values of FR for each category are rescaled, ranging from 0 to 1.0 (0% to 100%), where 1.0 (100%) represents the maximum value of FR in the category. The rescaled values of FR, the relative risk factors (R), are then divided into severity classes as shown for various categories in Table 3. Whereas individual WFs are used for each class to prepare flood risk maps for each category, average WFs for each category are used to prepare summary flood risk maps. This practically means for example for “population”: The risk is extreme (=1.0) if there are potentially 10 or more people in the extreme risk area (or 50+ people in the moderate risk area).

The relative risk factors obtained in this way, expressed through numerical "classes" for different categories, are reduced to a summary risk map by summing the values by rasters with the correction of the relative risk factor for a certain category, with the corresponding weighting factor of that category. The average WFs adopted in the Methodology are as follows: (i) Inhabitants=0.40 (40%); (ii) Economy=0.35 (35%); (iii) Cultural and Historical Heritage=0.10 (10%); (iv) Protected Areas=0.15 (15%); (v) IPPC Installations=out of category. Flood risk factors (FR) are rescaled into relative risk factors (R) which are then divided into up to five risk severity classes values ranging from 0 to 1.0 i.e., from 0% to 100%, as shown in Table 4. A mathematical model was developed in the 'Model Builder' function of the ArcGIS software to produce the flood risk maps.

Table 4 Risk (R) Classes of flood risk for various categories

FR	Class	Risk category	FR	Class	Risk category
0-49	0	Insignificant risk	0-499	0	Insignificant risk
50-499	0 < R < 0,25	Low risk	500-3.499	0 < R < 0,25	Low risk
500-999	0,25 < R< 0,50	Moderate risk	3.500-6.999	0,25 < R< 0,50	Moderate risk
1.000-1.499	0,50 < R< 0,75	High risk	7.000-9.999	0,50 < R< 0,75	High risk
≥1.500	0,75 < R < 1,0	Extreme risk	≥10.000	0,75 < R < 1,0	Extreme risk

(a) Population (b) Economy

FR	Class	Risk category	FR	Class	Risk category
0-49	0	Insignificant risk	0-499	0	Insignificant risk
50-249	0 < R < 0,33	Low risk	500-1.499	0 < R < 0,33	Low risk
250-499	0,33 < R< 0,67	High risk	1.500-2.499	0,33 < R< 0,67	High risk
≥500	0,67 < R < 1,0	Extreme risk	≥1.500	0,67 < R < 1,0	Extreme risk

(c) Cultural and historical heritage (d) Protected areas

(e) IPPC installations:

FR	Class	Risk category
0-149	0	Insignificant risk
150-299	0 < R <0,50	High risk
≥300	0,50 < R < 1,0	Extreme risk

2.3 Hydraulic modeling of natural rivers

Hydraulic modeling of natural rivers could be successfully analyzed with four equations: continuity, energy, momentum, and Manning (Saadi 2008, Hadžić *et al.* 2018). The Manning equation is considered to be empirical and is used to estimate friction loss while the energy equation is considered semi-empirical. In an open channel or overland flow of shallow depth, flood wave propagation is the concept that requires governing equations for its solution. The computation of governing equations (both momentum equation and continuity equations) to be solved are generally called the Saint-Venant equations. These equations are highly nonlinear partial differential equations, solve these equations and proper discretization with proper selection of grid size and time step provides the results more effectively and accurately.

The Saint-Venant equations (both continuity equation and momentum equations) for one dimensional steady and unsteady flow of the river are given by (Ferreira *et al.* 2017)

The continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q_L = 0 \tag{3}$$

The dynamic, or momentum, equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g \cdot A \cdot \frac{\partial Z}{\partial x} + g \cdot A \cdot S_f = 0 \tag{4}$$

where: Q=Discharge (L^3/T); A=Cross sectional area (L^2); x=The distance along the longitudinal axes of the channel or floodplain (L); t=Time (T); q_L=Lateral inflow per unit length ((L^3/T)/L); S_f=Friction slope; Z=Stage Elevation of water levels (L); g=Acceleration due to gravity (L/T^2).

Although Manning and Chézy's equations were developed for uniform and steady flow, it is accepted that they are well suited for resistance estimations in open channels in the unsteady regime (Chow 1959). Therefore, the Manning equation can be used to calculate friction slope (Ferreira *et al.* 2017)

$$S_f = \left(\frac{nQ}{AR_h^{2/3}}\right)^2 = 0 \tag{5}$$

where n represents the Manning roughness coefficient and R_h the hydraulic radius (m).

Unsteady-flow equations are complex and generally are not amenable to closed-form analytical solutions. Thus, numerical methods such as finite difference and finite element methods must be used to solve these equations. Finite difference methods, explicit or implicit, are the most common procedures for one-dimensional problems (Akbari and Firoozi 2010). Such schemes are based on the principle of transforming differential equations into algebraic expressions, in which derivatives are converted into finite differences. In general, they have first or second-order accuracy, are simple for computational implementation, and generate results quickly (Ferreira *et al.* 2017).

One-dimensional (1D) approaches to flow modeling are based on the Saint -Venant equations or variations, which form the majority of traditional numerical hydraulic models used in practical river engineering. The equations of Saint-Venant cannot be solved explicitly, except by making very large assumptions that are unrealistic in most situations. Therefore, numerical techniques have to be used. Wide use in practice can be explained not only by the fact that 1D models (compared to multi-dimensional hydraulic models) are easier to use for rivers (when the length of the river is dominant in relation to its width and depth), but also require a minimum amount of input data and computer power. Also, their use for more than a few decades shows us that their application is justified.

The Hydrologic Engineering Centre-River Analysis System (HEC-RAS), developed by the US Army Corps of Engineers, is one of the most known, analyzed, and used models for flood mapping both in the scientific literature and in practice (US Army Corps of Engineers 2016). It performs 1D or 2D steady and unsteady flow calculations on a network of natural or man-made open channels. (Horritt and Bates 2002). In the recently released version (release 5.0.7), the HEC-RAS model has been enriched with novel modules, performing fully 2-D computations based on the 2-D fully dynamic equations as well as the 2-D diffusion wave equations; moreover, the application of rainfall to each cell of the two-dimensional domain is now possible (Costabile *et al.* 2020, Dhungel *et al.* 2019).

Basic input data required by the model include the channel network connectivity, cross-section geometry, reach lengths, energy loss coefficients, stream junction information, and hydraulic structures data. Cross-sections are required at all important locations throughout a stream reach and at locations where changes either in discharge, slope, shap,e or roughness occur. Boundary conditions are necessary to define the starting water depth at the stream system endpoints, i.e., upstream and downstream. Water surface profile computations begin downstream for supercritical flow or upstream for subcritical flow.

The HEC-RAS model solves the Saint-Venant Equations, (Eqs. (3)-(4)) formulated for natural channels. The computation engine for the HEC RAS 1-D unsteady flow simulator is based on the USACE's UNET model (US Army Corps of Enginers, 2016). These equations can be solved by the River Analysis System (HEC-RAS) software which uses the Preissman implicit scheme. This numerical scheme is completely non-dissipative but marginally stable when run in a semi-implicit form, which corresponds to a θ weighting factor of 0.5 for the unsteady solution (Patel *et al.* 2017), which represents a half weighting explicit to the previous time step's known solution, and a half weighting implicit to the current time step's unknown solution.

However, practically speaking, due to its marginal stability for the semi-implicit formulation, a θ weighting factor of 0.6 or more is necessary, since the scheme is diffusive only at values of θ greater than 0.5. This increases solution stability but at the expense of solution accuracy (Patel *et al.* 2017).

3. Key study of the Zujevina River

The general methodology for flood modeling and mapping used in this paper included primarily: (i) site touring and reconnaissance, in order to understand the processes in the catchment area, socio-economic situation in the analyzed area, and critical infrastructure; (ii) analysis and collection of data necessary for the development of the hydraulic model of the river Zujevina, primarily hydrological, geological and geomorphological and geodetic data, both riverbeds and inundations; (iii) Hydraulic modeling to obtain water level data; (iv) Flood mapping: the results of hydraulic modeling was combined with topographic information to produce flood area maps; (v) Comparison and analysis of flood maps produced in this paper (which used LiDAR terrain surveys as topographic bases) with the results obtained through PFRA phase. During this phase hydraulic models were mostly obtained with the use of georeferenced topographic maps at a scale of 1: 5000 or 1: 2500.

3.1 Basic characteristics of the Zujevina river

Zujevina is a river that is a left tributary of the Bosna, with a total length of 21.1 km. The catchment area of the Zujevina river basin is 198.49 km^2. Zujevina river has a torrential character. The average flow of the Zujevina River at HS Blažuj is Q_{sr}=3.10 m^3/s, with the associated orographic catchment area F_{sl}=172 km^2. A characteristic river discharges on HS Blažuj are: $Q_{1/100}$=168 m^3/s, $Q_{1/50}$=133 m^3/s and $Q_{1/20}$=79.9 m^3/s. Most of the water is from February to May due to the melting of snow on the slopes of Bjelasnica mountain.

Upstream from the confluence, almost every year, the river Zujevina floods the territory of the

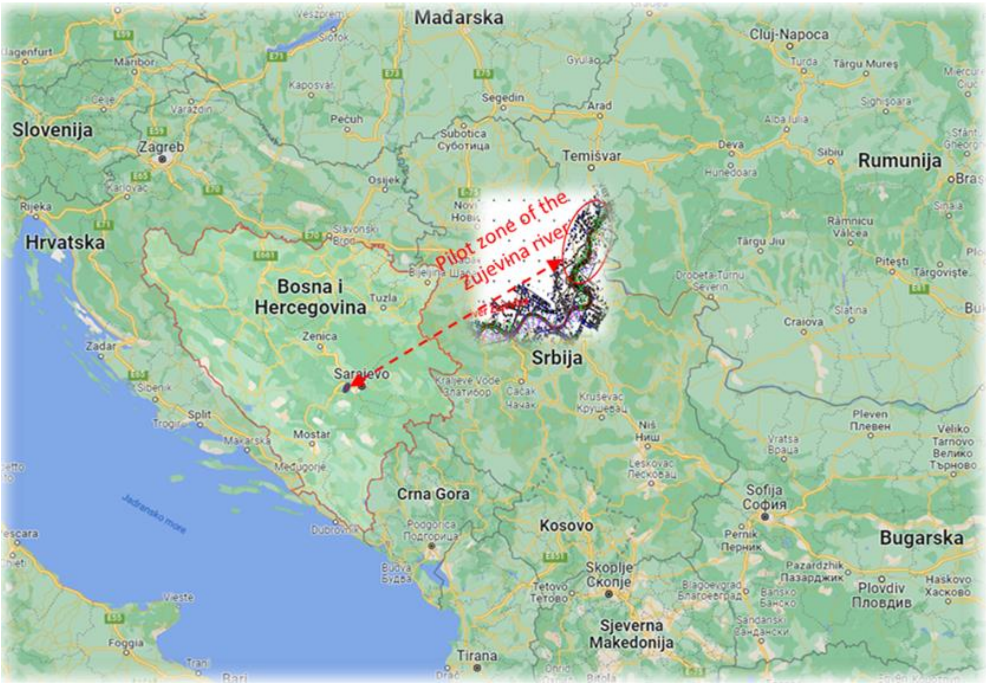

Fig. 2 The location of the considered zone of the Zujevina river in B&H

municipality of Ilidža. These floods cause significant damage to residential, industrial, agricultural, and other facilities. Damage also occurs due to the instability of the existing banks, which directly endangers residential and other buildings along the watercourse, as well as agricultural lands. The territory of the settlement of Blažuj, with a length of about 3600 m, is particularly threatened by frequent floods with a probability of 1/20. The average slope of the natural riverbed in this section is 0.5%. Fig. 2 shows the location of the analyzed zone of the Zujevina River considered through this study, in B&H.

3.2 Preliminary flood risk assessment for analyzed zone of the Zujevina river

Three fundamental approaches were used in the development of the PFRA to identify AFAs in Bosnia and Herzegovina: (i) analysis of historical floods (use of information on floods that occurred in the past -data obtained from municipalities); (ii) analysis of probable floods (areas that could be subject to floods); (iii) based on the data of the Federal Operational Plan for Flood Defense and consultations with Water Management Agencies. The first step in making a Preliminary Flood Risk Assessment is to collect available historical records and data on significant floods that endanger material goods, humans, or the environment. To form the criteria for selecting areas significantly threatened by floods were used data on the number of flooded buildings, the endangered population, the length of the flooded roads, etc.

Corine Land Cover codes were used to determine the value of land depending on the type and manner of land use. Although the water depth (h), velocity (v), and duration of the flood (t) are important parameters that influence its significance, they did not exist at the stage of the preliminary flood risk assessment. The parameters that define the importance of floods were

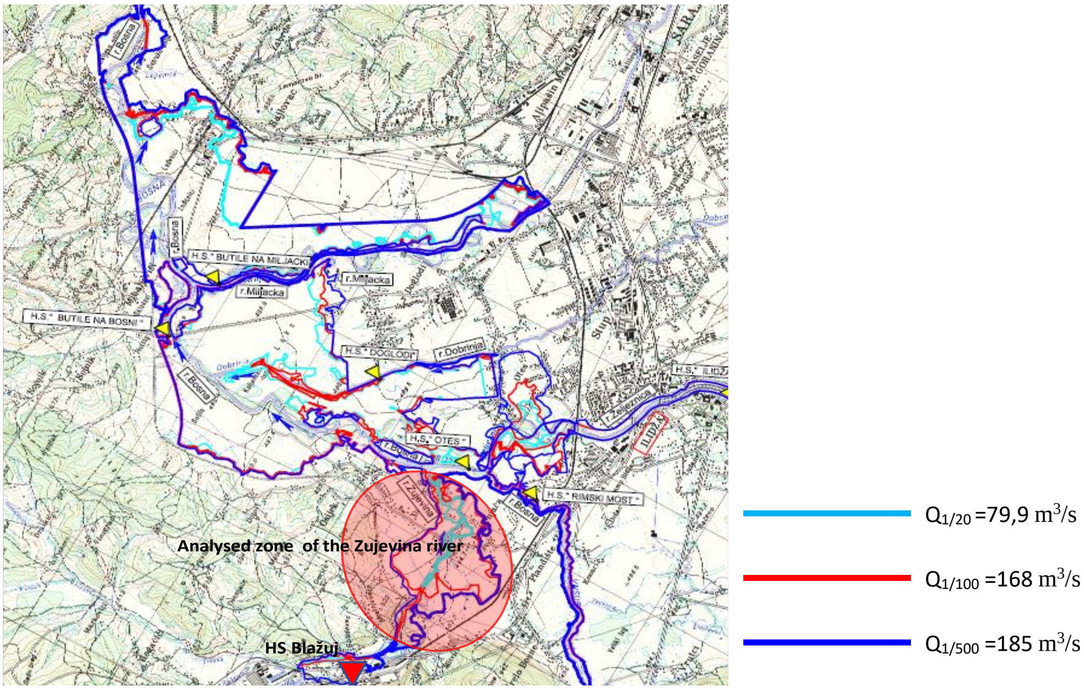

Fig. 3 Results of PFRA for Canton Sarajevo-floods with a probability of occurrence 1/500, 1/100, and 1/20, (FOP 2015 and HEIS 2013)

calculated assuming a flood depth of 1 m, a water velocity of 1 m/s, and a flood duration of 5 days, (these data were estimated based on historical flood data, and the duration of the flood is the average duration of typical floods in the region).

During the preparation of the PFRA, flood forecast models were based on topographic maps of different scales, mostly between 1:2500 and 1:5000, and usually presented at georeferenced topographic maps with a scale of 1:25000. In this phase, for the analyzed zone of the Zujevina river, data for hydraulic modeling were used from georeferenced topographic maps of scales 1: 1000 and/or 1:2500. The size of the area affected by floods (for this zone) with a probability of occurrence of 1/20 was 0.1505 km^2 (marked with turquoise color in Fig. 3). Also, it is noticeable that there is a very small difference in the sizes of the area affected by floods with probabilities of occurrence of 1/00, as well as 1/500.

4. Developing new hazards and risks maps using LiDAR terrain surveys

The effect of topography on a flood inundation map varies depending on the size of the river, bathymetric description and modeling approach (Cook and Merwade 2009). For the preparation of hazard and risk maps for the considered zone of the river Zujevina, appropriate geodetic surveys were performed using the total station Trimble S5 3 ″ Autolock, DR Plus. A detailed recording of the situation around the riverbed in the width of about 40 m-60 m from the water surface, in the scale of 1: 500, transverse profiles of the bed in the scale of 1: 100/100 at a distance of 50 m or thicker, depending on the need. A wider inundation zone on both banks was also recorded with

LiDAR technology. Too small a resolution of the Digital Terrain Model (DMT) requires more computing time and memory needed to simulate flood events and does not contribute to flooding accuracy. According to the Handbook of Good Experience for Flood Mapping in Europe (EXCIMAP 2007), a resolution of 10 m×10 m (possibly 5 m×5 m) in horizontal projection and a minimum of 0.5 m for vertical representation is recommended. In this study, it is proposed to adopt a horizontal DMT resolution of 5 m×5 m with a vertical accuracy of up to 10 cm.

The cross-sections recorded for the hydraulic analysis included the main riverbed, which, after connecting with the LiDAR geometry of floodplain surveys, enabled the formation of a reliable geometric terrain model of the Zujevina River flow profile. Using the updated geodetic data of inundation and river bed was developed a new hydrodynamic model. Velocity and depth maps for flooded areas were also obtained using this model. For the analyzed zone of the Zijevina River, more detailed hazard and risk maps were carried out with the use of new geodetic data obtained by the LiDAR technique.

4.1 Hydraulic model of the Zujevina River

A very important segment for the production of flood hazard maps and later the flood risk map is an adequate hydraulic flow model. In this study we used HEC-RAS. The river segment that was studied is 3600 meters long. A total of 80 cross-sections at various important locations on the river have been used. The effect of meandering has been neglected as there is no reasonable curvature seen in the study reached by providing expansion and contraction coefficients as 0.3 and 0.1 respectively. Numerical modeling of the Zujevina River flow (establishment, development, calibration, and verification of the model) was done for one-dimensional steady flow. The calibration parameter involved in the development of the hydraulic model is Manning's roughness coefficient (n). The flooded areas along the Zujevina River have been mapped based on the flow rates for a 20-year return period using the HEC-RAS model, GIS for spatial data processing, and HEC-GeoRAS for interfacing between HEC-RAS and GIS.

Calibration and verification of the hydraulic model of the river Zujevina were performed for data taken from the existing water metering stations HS Blažuj. It should be noted that among the various hydraulic parameters, channel roughness plays a very important role in the study of open channel flow, especially in hydraulic modeling. The unevenness of the canal is not a constant parameter and varies along the river depending on the variation of the characteristics of the canal along the course, but also depending on the period of the year. Therefore, it is very important to take into account this parameter, which is directly proportional to the velocity of water, i.e. water flow, through the Manning equation.

The channel roughness elements in terms of '*n*' were estimated based on material, irregularities, cross-sectional variations, barrier effect, vegetation, and meander. Horizontal and vertical variations in "*n*" were compiled for each cross-section and iterations were performed to fine-tune the calibration of the flow-to-river ratio. The downstream boundary conditions are given by the flow curves and the normal depth is defined by the Chezy-Manning equation. The control point at which the calibration was performed is located in HS Blažuj and the known flow curve (Fig. 4). The Blažuj hydrological station belongs to the Zujevina river basin and is located on the eponymous watercourse at a distance of about 2.5 km m from the mouth of the Bosnia.

The HEC-RAS model for the Zujevina River was used to simulate the flow for different individual roughness coefficients (Manning's "*n*"). After entering all the necessary data, the analysis of the steady flow was performed. Calibration of the model was performed by adjusting

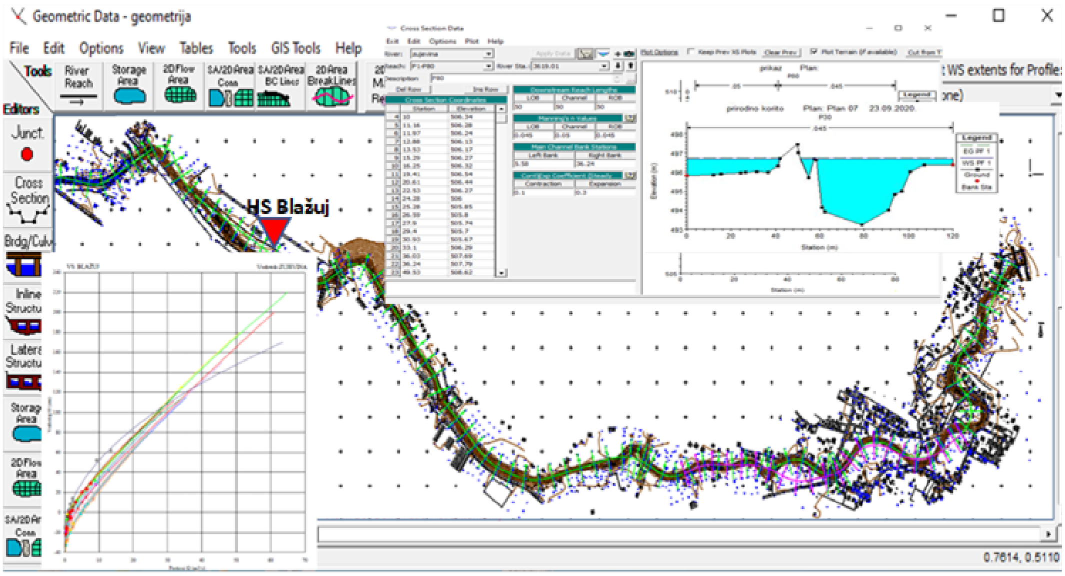

Fig. 4 Considered area of the Zujevina River in the Hec-RaS interface, with Q-h curve and cross-section

the Manning n value and simulated and observed data from the water meter station were compared.

The Manning coefficient values obtained for the river bed ranged from 0.35 to 0.50. Model validation was performed with the same parameters used in the calibrations. After validation, the model results were used to create flood mapping.

4.2 HEC RAS with HEC-GeoRas

Results obtained with the HEC-RAS model were used in combination with ArcGIS to prepare floodplain maps for 20-years return periods. Version 10.3 of ArcGIS was used, together with the extension HEC-GeoRAS, to prepare geometric data for hydraulic modeling and display the results on maps. This tool connects GIS and hydraulic models of steady and unsteady flow. HEC GeoRas also enables other characteristics of floodplains (e.g., roughness due to vegetation) to be obtained from DMT and digital ortho-photo (Fig. 5). In this way, much better information on topography is available, which enables more accurate hydraulic analysis and higher resolution when determining the calculated flood lines.

HEC-GeoRAS proved to be an extremely useful software tool for the development of flood maps of the Zujevina River. This software uses the Triangular Irregular Networks (TIN) network to create DMTs. TIN has several obvious advantages over raster DMT (Patel *et al.* 2017). In this study, recorded transverse profiles and LiDAR images of the considered zone were used for DMT production, by means of which a TIN model of the riverbed was obtained. When the DMT is made and the TIN model is prepared, using HEC-GeoRAS in the ArcGIS program, files with more accurate geometric data of a wider space are prepared.

Hydraulic calculation and preliminary analyzes are done in HEC-RAS and later transfer to HEC-GeoRAS. This allows to map floodplains and display floods in 3D, but it also allows to draw a network of isobaths (lines connecting places of equal water depth) and isothaches (lines of equal

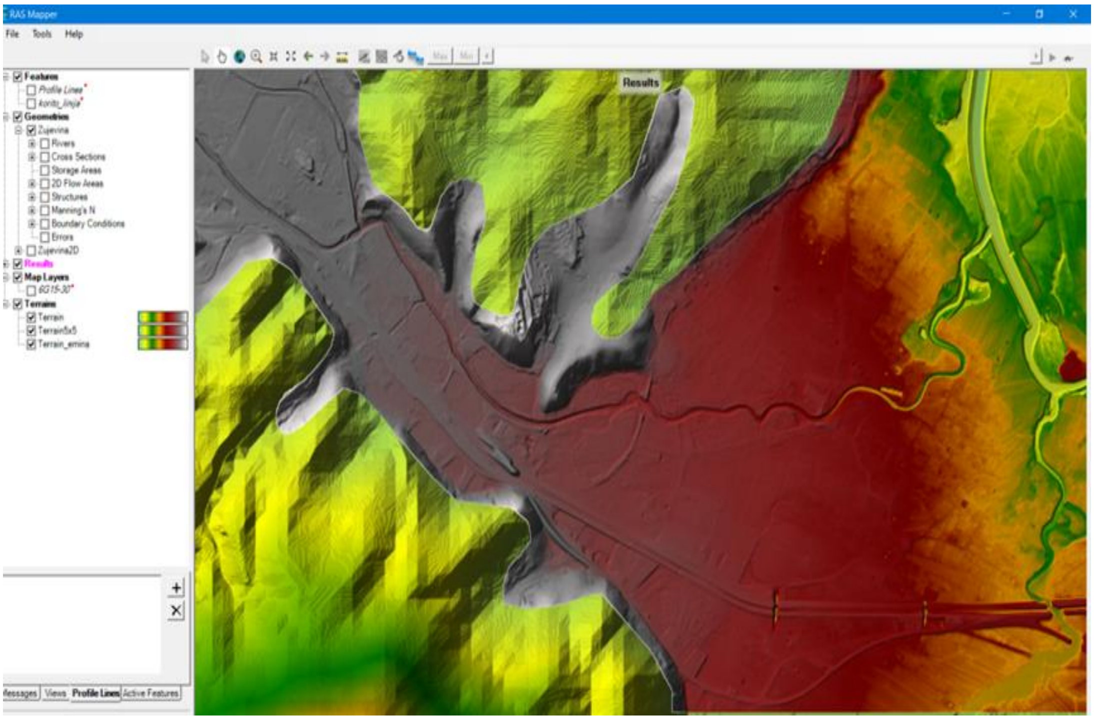

Fig. 5 Zujevina riverbed and inundation zones shown in RAS Mapper

velocities). The developed hydraulic model of the river Zujevina was made as a one-dimensional model (1D) and calibrated to a steady flow, and in such a model, simulations of steady flow for high waters of certain return periods were performed. Water level lines and water velocity data calculated in HEC-RAS are displayed in HEC-GeoRAS, which gives the ability to produce flood hazard maps (Patel *et al.* 2017). This transfer to HEC-GeoRAS is done by generating the RAS GIS output file RASExport.sdf, and importing it into ArcGIS, and in this way, the flood volume for a specific flood event i.e., flows of different return periods, is mapped.

4.3 Flood hazard and risk maps of the Zujevina River

Flood inundation models require four types of data: (1) topographic data for the hydraulic model computational grid and the inundation maps; (2) boundary conditions at the upstream and downstream ends of the model domain; (3) effective friction values (Manning's n) for each computational segment (1D model) or cell (2D model); and (4) bathymetric and topographic data used to develop the model validation data (Bates *et al.* 2004). In this paper, a steady-state flow analysis is performed to determine the water level for floods over a 20-year return period. The main output variables of this analysis are the height of the water surface on the cross-sections of the river, the flow velocity, and the extent of the flood. Flood inundation maps have been generated by exporting GIS data to the HEC-RAS for different return intervals. These maps show flooded area in plan/topo maps for floodplain and water depth for the 20-year return period and distribution of water velocities for the 20-year return period (Figs. 6-8). In accordance with the Methodology, hazard maps and risk maps were created for the analyzed area of the Zujevina River.

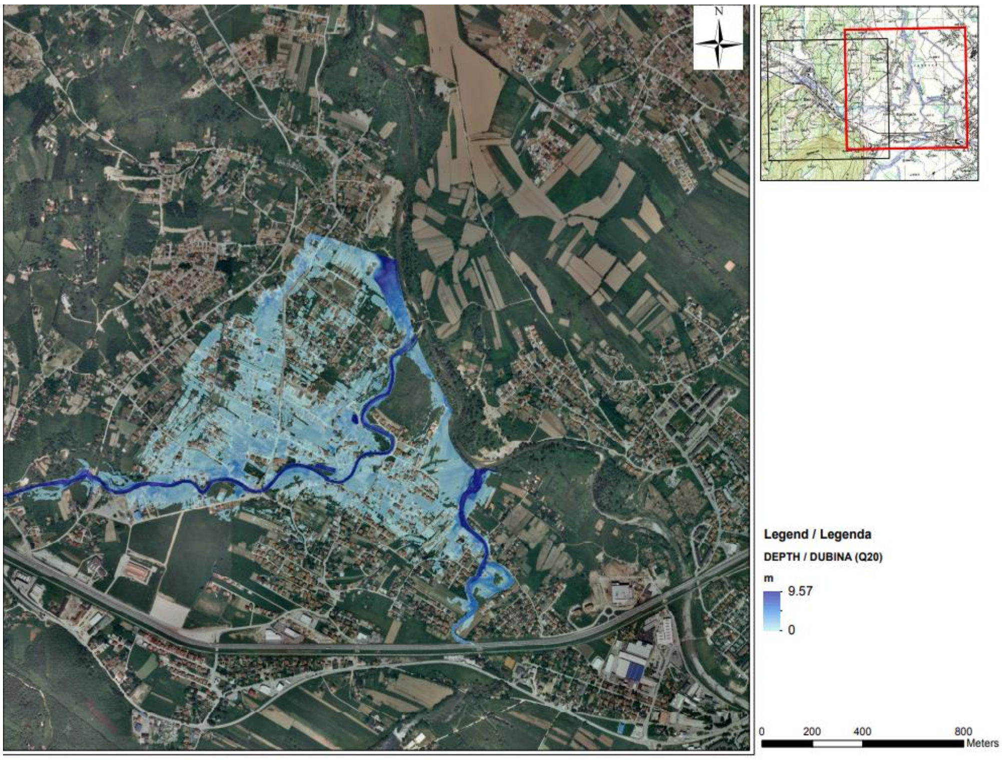

Fig. 6 Floodplain and water depth on the Zujevina River for the 20-years return period

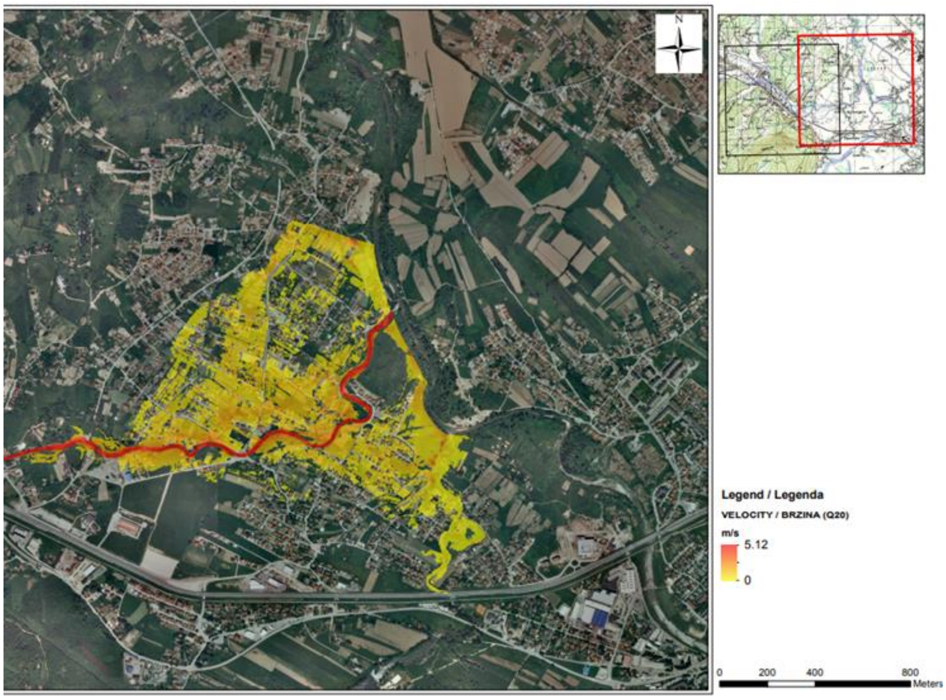

Fig. 7 Floodplain and distribution of water velocities on the Zujevina river for the 20-years return period

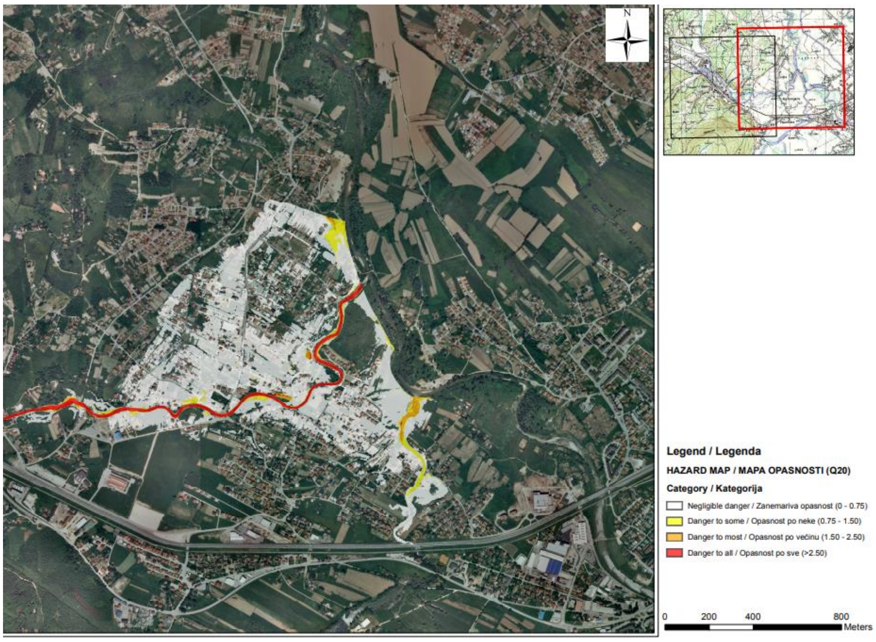

Fig. 8 Hazard map of Zujevina river river for the 20-years return period

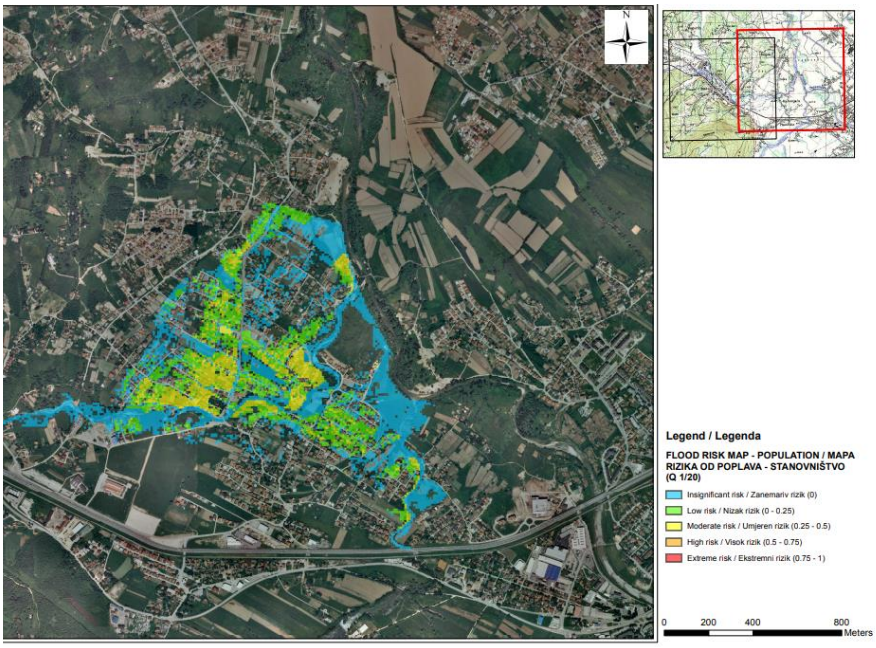

Fig. 9 Flood risk map for population, Zujevina river

The risk is determined in accordance with the classes of flood risk for various categories given in Tables 1-4 and shown in Figs. 7 and 8. Figs. 9 and 10 are shown a flood risk map for population and a combined flood risk map for population and economy for Zujevina river, respectively.

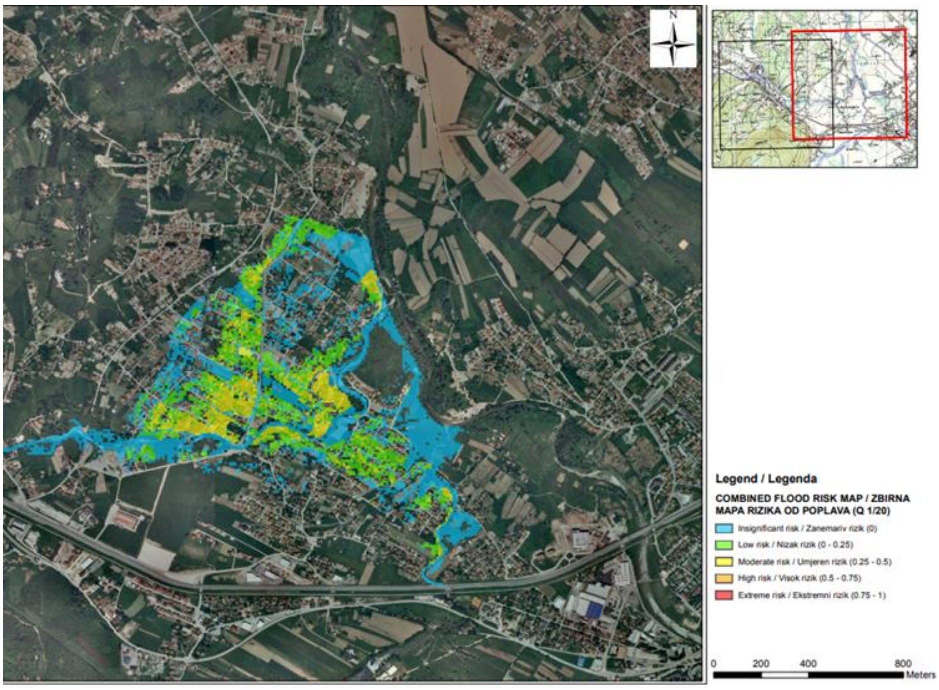

Fig. 10 Combined flood risk map for population and economy, Zujevina river

5. Conclusions

Floods are becoming more frequent, more intense, and more dangerous everywhere in the world, including in Bosnia and Herzegovina. They cannot be prevented, but by taking effective preventive and operational measures, their harmful consequences can be significantly mitigated. Flood prevention is of strategic importance for each country, and the damage caused by floods gives a special dimension to the seriousness of the approach in the implementation of preventive measures in flood protection. Flood risk reduction planning is a very complex process that requires the synergy of all factors involved in water management, protection, and rescue regardless of the level of government. However, even though the legislation regulating the field of flood protection is comprehensive, floods cause huge losses every year in material goods and human lives. Information on the extent of floods is extremely important for risk assessment in flood-prone areas, as well as for planning measures and preventive action and the protection and rescue of vulnerable categories.

Through the BH methodology and the creation of the PFRA, AFAs were defined mainly as areas threatened by floods with a 100-year return period. For these areas, additional field surveys were carried out, and hazard and risk maps were created, to create flood management plans. However, very significant damage can also occur as a result of frequent floods, such as floods with a probability of occurrence of 1/20, which is shown in this paper.It pointed out the importance of good geodetic bases that are used to create hazard maps and risk maps. High-quality topographic data (using LiDAR), with the appropriate application of hydraulic modeling, is probably the most important factor needed for accurate inundation maps, which are shown and considered in the area of the Zujevina River. By comparing and analyzing the hazard maps that were obtained during the creation of the PFRA phase, with the hazard maps that were obtained in this work, for the considered part of the Zujevina River, significant differences in the extent of flooding were observed. The extent of the flood area, obtained for the waters of the 20-year return period, for the considered area using LIDAR data, is about 2.5 times larger compared to the area obtained using topographic maps of scale 1:25000. The resulting area of the flood area was 0.38 km^2 (Fig. 6), while during the PFRA phase the area was estimated at 0.1505 km^2 (Fig. 3). Fig. 5 shows the water depth map for this probability flood, while Fig. 6 shows the water velocity map. On the flood risk maps Fig. 7, and the flood risk maps Fig. 8 and Fig. 9. it is evident that the calculated risk (according to the described Methodology-chapter 2.2) is characterized as moderate, between 0.25 and 0.5. The conducted analysis showed that for the considered flood event, the predicted area of the floodplain increases with higher spatial resolution and vertical accuracy of the topographic data. This once again emphasizes the importance of additional modeling, on more detailed topographical bases and areas that during the PFRA phase were considered insignificant from a high water perspective. The importance of such studies lies in the fact that these floods also carry a significant risk for the population, the economy, and the environment. The special segment of frequent floods in the study of the cascading effect of floods has been rather neglected through the Methodology of risk assessment of raids in Bosnia and Herzegovina. This study also showed that the appropriate application of hydraulic modeling in HEC-RAS models and high-quality topographic data such as LiDAR DEMs is extremely important in defining flood hazards and risk maps. Since accurate geodetic maps are crucial for creating reliable hydraulic models, this study creates new hydraulic flow models for the Zujevina River area using LiDAR geodetic data. The analysis revealed that there is a significant difference between the outcomes of this study and those of the PFRA phase of FD implementation.

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