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Flood hazard assessment in Montenegro through the application of two-dimensional hydraulic modelling

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Abstract. Floods, induced partly by climate change and partly by the negative impact of human actions, may be regarded as the most common type of natural catastrophe in Montenegro, causing significant economic, ecological, social, and health damage yearly. Therefore, the focal point of flood risk assessment is reflected in properly determining flood hazards. However, within the Montenegrin National flood risk assessment, which is entirely scenario-based, the hazard is treated only by estimating the occurrence probability of a specific scenario. The paper provides an overview of recent efforts to overcome the potential weaknesses of scenario-based risk assessment by constructing hazard maps for all areas of potential significant flood risk in Montenegro. Hazard maps are intended to visualise different flood intensities (e.g., flood depth, velocity, etc.) for selected return periods. Such outputs are generated by two-dimensional hydraulic modelling, which requires extensive work on gathering the available field data, calculating hydrological inputs, building and calibrating the model, and defining uncertainties that may affect the results. The final production of the hazard maps is conveyed by post-processing the computation results in GIS-based software.

1. Introduction

Permanent or periodic flooding and high groundwater levels endanger over 26,000 ha of land in Montenegro [1]. Flooding in Montenegro is manifested differently depending on the features of the watercourse that causes it. Settlements, traffic infrastructure, industrial facilities, and agricultural areas are commonly located in the downstream valleys of rivers. Their upstream sections are distinguished by significant slopes, high speed of flood wave propagation, and significant quantities of suspended and dragged sediment. Although relatively modest, agricultural areas in these valleys are substantial for agricultural production because the total agricultural resources in Montenegro are pretty limited. Due to this concentration of goods in the river basins, potential damages caused by floods, even on a relatively small scale, can be significant [1].

In addition, uncontrolled urbanisation, especially in the coastal region, contributes to a higher risk of urban flash floods during high-intensity rain events. Also, there is a strong link between urbanisation and flood risk management [2]. The effect of floods in Montenegro is further amplified due to the lack of storm-water sewer systems (or their insufficient capacity), illegal construction work in the floodplains, inefficient river regulation measures, inadequate waste disposal, etc.

The community must make a concerted effort to significantly impact flood risk awareness and local community involvement [3].

Many historic floods that occurred in the past have had catastrophic consequences in terms of damages. The most severe recent events include floods from 2010, which resulted in over 18 million € of injury, as estimated in the damage assessment report composed by the appointed national commission (based on the documentation supplied by local authorities) [4].

The flood risk assessment has yet to be studied for the area of Montenegro. The contribution of this research is reflected in the application of methodology based on risk matrices. Such a methodology allows for considering all the specifics related to flood risk assessment in Montenegro.

2. Flood hazard legal framework in Montenegro – current state

Given the importance of flood-related issues for the future development of the entire water sector in Montenegro, various documents that deal with this matter (at least to a certain degree) have been implemented in the Montenegrin legislative system: National flood protection and rescue plan, National emergency strategy, Water management strategy, Disaster risk reduction strategy, etc.

As a candidate country for joining the European Union, Montenegro was obliged to assess natural and artificial risks and submit data on risk threats to the European Commission per the European Guidelines. As a result, the European Commission approved financing for the project "Disaster Risk Assessment of Montenegro" [5]. As a result of the project, which ended in December 2021, National Disaster Risk Assessment (NDRA) was constituted.

2.1. National disaster (flood) risk assessment

NDRA comprises several independent parts, each dealing with different risk types (floods being one). Flood risk, which according to the EU guidelines may be regarded as a combination of hazard probability and its consequences [6], was calculated only for the selected relevant scenarios - historic events chosen as representative examples for risk assessment purposes. Considering that the main prerequisites for scenario selection are its probability and consequence severity, two types of scenarios were considered:

- the most likely adverse event,
- the event with the worst possible consequences.

Since the entire Montenegrin hydrographic network is almost equally divided between two basins (the Danube basin covering 52.5% and the Adriatic basin covering 47.5% of the territory [4]), each of the two basins is featured through analyses of both scenario types, yielding the total of four flood risk scenarios for the whole country.

The event probability and consequences (on public health, economy/ecology and social stability) were evaluated and combined in a risk matrix (figure 1) for each scenario.

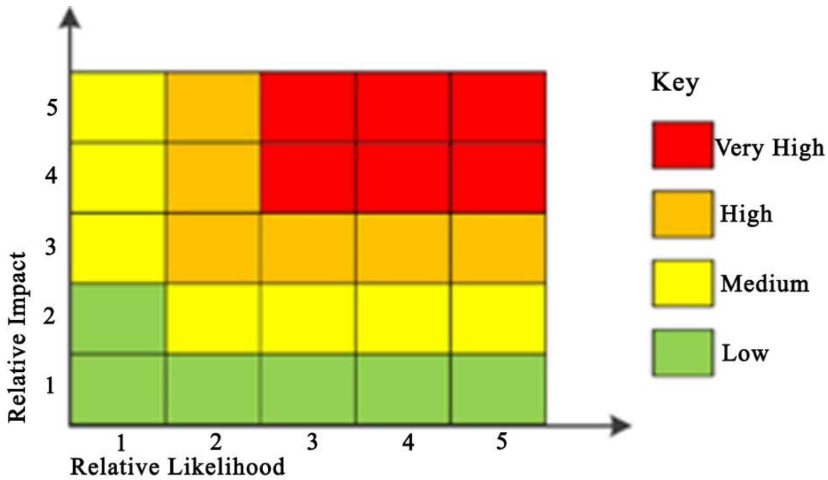

Figure 1. Definition of a Risk matrix for NDRA [6].

For example, floods that occurred in 2016. In the river basin, Lim was chosen as the most likely adverse event scenario for the Danube basin. The hazard return period (15 years in this particular case, which corresponds to a medium probability level) was estimated based on the available historical data by determining the frequency of registered similar events in this basin that occurred in the past. It is worth mentioning that the need for precise, systematic data on past flood events, their causes, and damages makes a historical review of them difficult. Taking the consequences and damages into account requires using not only all available formal data (government reports, local municipality records, etc.) but also the information from the media (papers, television, websites, etc.). When combined in a matrix, the medium likelihood (level 3) and the low consequence level (level 2) generated a moderate risk level.

For NDRA, no hazard maps were made since the hazard intensities were not computed. The only way the obtained results (risk levels) were visualised was by showing the estimated flood extent on a map, uniformly coloured according to the calculated risk level. The boundaries of the floodplain are an approximation based on the field data – locations of damaged households and evacuated people; and not the results of any hydraulic computation.

2.2. Support for implementation and monitoring of water management in Montenegro

Most recently, the Montenegrin government has procured funding from the EU (Instrument for Pre-Accession Assistance) to realise the project "Support to Implementation and Monitoring of Water Management in Montenegro." This project aims to support the national and local institutions in aligning with and implementing the EU legislation on environmental protection and climate change [7]. The critical activity in this project includes the preparation of flood hazard and flood risk maps, as well as flood risk management plans to reduce the risk of flood damage.

During the first stage of the project, a Preliminary flood risk assessment (PFRA) was prepared. Historical flood information, geographic data, urban planning information, population statistics, economic activities, digital terrain models (DTM), hydrological and meteorological information, civil protection information, and other national data was used to identify the Areas of Potential Significant Flood Risk (APSFR), which are the priority areas for subsequent further analyses [8]. The second step in the project includes the development of flood hazard and risk maps for all identified APSFRs (25 APSFRs in total were delineated throughout the country), which would later be followed by the third (and final) step – flood risk management planning [9].

The hazard of flooding is distinguished by the probability of its occurrence and the flood intensity (flood depth and velocity). Content of flood hazard maps follows the EU floods directive, covering the geographical areas of all APSFRs and showing the flood extent, water depths and flow velocities for three different scenarios: floods with a low probability (extreme event scenarios), floods with a medium chance (likely return period ≥ 100 years) and floods with a high probability [10].

The flood risk, defined as a combination of hazard and damage potential, is assessed by interacting these two factors in a risk matrix. The primary numerical inputs for matrix formulation include the hazard intensity (flood depths and/or velocities) and vulnerability values of assets in the floodplains [11].

Table 1. Risk matrix definition [11].

		Vulnerability value		
		low	medium	high
Intensity	> 5 m or > 2 m/s	moderate (2)	high (3)	high (3)
	1 m – 5 m	moderate (2)	moderate (2)	high (3)
	0.5 m – 1 m	minor (1)	moderate (2)	moderate (2)
	0 m - 0.5 m	minor (1)	minor (1)	moderate (2)

To apply the mentioned methodology for flood hazard mapping and risk assessment, it was necessary to perform the hydrological and hydraulic computation to acquire the flood extent, depths, and flow velocities.

3. Materials and methods

3.1. Study area

Hydrodynamic modelling includes the evaluation of flow characteristics and geomorphic behaviour of rivers due to natural or artificial conditions. The most important results of the modelling are the prediction of water levels and velocities as time and location-dependent functions. The river Lim was chosen as a study area.

Two-dimensional modelling has many advantages compared to traditional one-dimensional modelling, allowing flow conditions to vary in two dimensions instead of one. Two-dimensional models calculate hydraulic results at locations within a mesh that covers the entire geographic extent of a river and floodplain [12]. Two-dimensional hydraulic models in HEC-RAS [13] were developed for flood hazard mapping for each APSFR in Montenegro.

Here is the presented model and results of the river Lim. These models are depth-averaged, assuming that velocity is averaged in the vertical (z) dimension and varies in the longitudinal and lateral (x,y) directions.

3.2. Data sets

Obtaining hydrological data and terrain data inputs was necessary to realise this research.

3.2.1. Terrain data inputs. Terrain data (for flood hazard purposes – hydrology and hydraulic analysis) is one of the essential input datasets for modelling. The quality of model results and mainly the following data processing depend significantly on the quality of the terrain data.

The terrain data was provided as Digital Elevation Models (DEMs) by the Montenegrin Real Estate Administration, created by LiDAR (Light detection and ranging) technology [14]. The resolution of the available elevation models is 5 m x 5 m, which, to a certain degree, satisfies the recommended resolution requirements of terrain data for flood risk management issues. However, this data should be combined with geodetic survey data (terrestrial and bathymetrical) to increase the accuracy of the details concerning buildings and other terrain structures near water bodies [11]. Unfortunately, no surveyed cross-sections were available for the mentioned project. No further surveying campaigns were feasible, considering the size of the study areas and limitations regarding the project timeframe and available funding. One of the future recommendations for improving the models would include surveying all buildings in and around the water bodies. Also, river cross sections, especially those occupied by water during the LiDAR survey, should be surveyed to build a stable model setting for hydraulic flow properties.

3.2.2. Hydrology inputs. The available measured hydrological data and existing historical data (from recorded historical events) were supplied by the Institute of Hydro-Meteorology and Seismology of Montenegro (IHMS). For each APSFR, datasets (water elevation, flow rate, precipitation, etc.) from the nearest measuring station were statistically processed. Parametric hydrology methods were applied to estimate the relevant flow rates and hydrographs for each selected return period: 10, 100 and 500-year events. These were then used as boundary conditions for the hydraulic models.

Hydraulic models are susceptible to roughness values (Manning's n). Hence, Manning's n needs to be chosen carefully and calibrated if possible (when discharge and flood extent of historic floods is available). The importance of Manning's n values for different land use classes increases with extensive flood plains. Other literature sources and recommendations were used to find an appropriate Manning's n value [12].

4. Results

Unsteady conditions for flow modelling were applied (considering the characteristics of the study areas and the common flood types) since an unsteady flood model can better display the dynamic scenarios. In this manner, the time-dependent flow was considered, due to which the system changes over time. When hydrograph data (from recorded historical flood events) was unavailable, synthetic flow hydrographs derived from parametric hydrology methods were used.

Three simulations were conducted for every study area, each one corresponding to different hydrological conditions in terms of occurrence probability: 10-year (10% probability), 100-year (1% probability), and 500-year (0.2% probability) event. Each analysed area's simulation duration was selected to depict the flood wave propagation best, while the Courant condition controls the time step.

Results of the simulation – flood extent and water depths (HQ10, HQ100, and HQ500) for the river Lim, which was one of the designated APSFRs, are shown in figure 2.

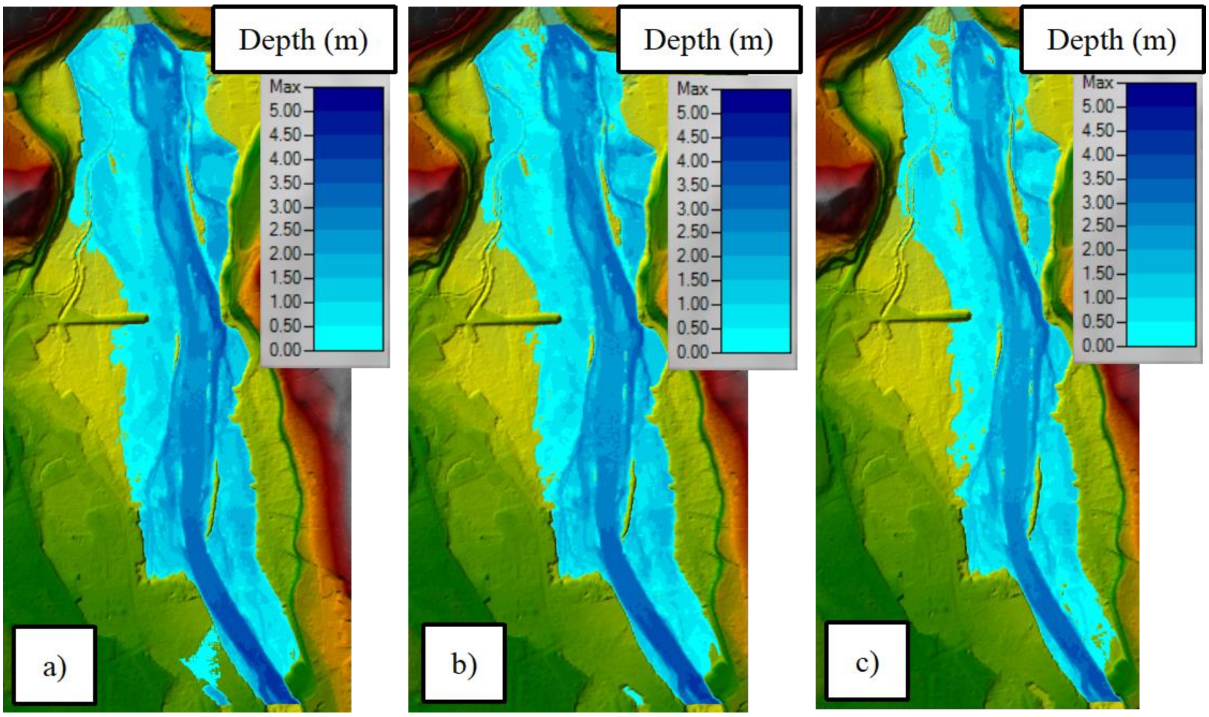

Figure 2. Flood extents for return periods HQ10 (a), HQ100 (b), and HQ500 (c).

After modelling, the results must be processed for all defined scenarios. The datasets required for further processing for hazard map production are flood extents, inundation depth, and flow velocities. Finally, the model outputs are exported as shapefiles and used for map building in GIS-based software.

Two different types of hazard maps are constructed:

- Flood Hazard Map shows the flood extents of the different return periods. Three layers representing flood extents for all three return periods are overlapped on the map, showing buildings, bridges, and river channels displayed over an orthophoto background (figure 3).
- Flood Hazard Map for each return period showing the inundation depths. For all three maps (each referring to one return period), calculated depths are classified into three ranges: 0 - 0.5 m, 0.5 - 1.5 m, and > 1.5 m, and shown as different layers. The flow area with velocities greater than 1m/s is also delineated on the map, along with buildings, bridges, and river channels displayed over an orthophoto background (figure 4).

Figure 3. Flood hazard map with flood extents for all return periods – example of river Lim.

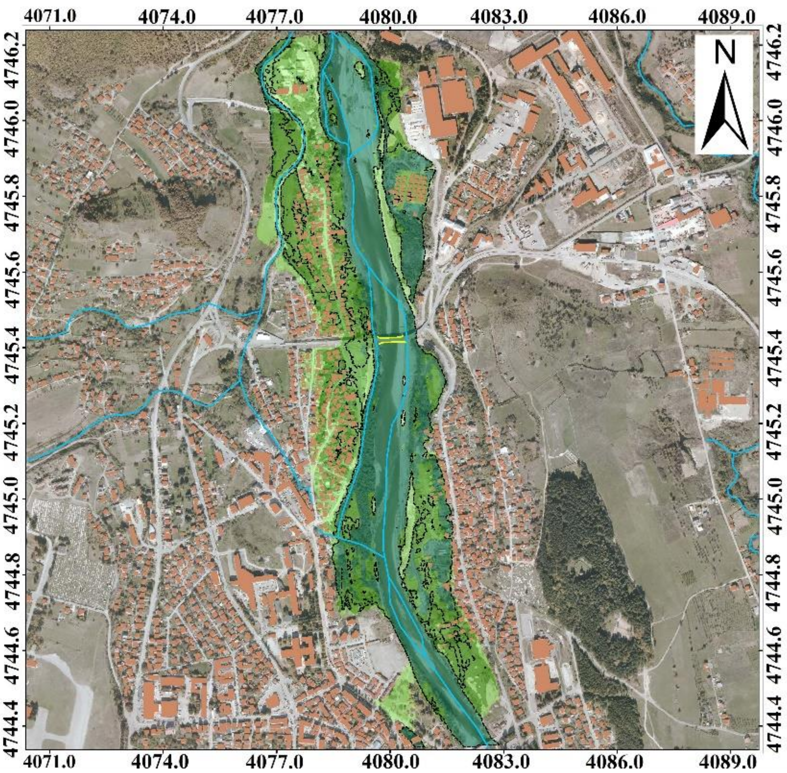

Figure 4. Flood hazard map with inundation depths for HQ500 – example of river Lim.

The computed inundation depths from the model also represent a basis for further risk assessment. According to the suggested risk-matrix method (table 1), the risk is calculated by combining flood exposure and vulnerability. The first factor, flood exposure, is defined using intensity classes showing different inundation depths. Therefore, computed depths must be classified according to table 2 and exported to formats appropriate for subsequent risk calculation.

Table 2. Classification of intensities of inundation depths (for the definition of flood exposure) [11].

Water depth	Class
< 0.5 m	1
0.5 - 1 m	2
1 - 5 m	3
> 5 m	4

5. Conclusion

Assessing and reducing the risk of floods in the entire country represents a permanent task by improving the protection of the most critical damage centres (cities, populated areas, business entities, traffic infrastructure, etc.), and regulation works and measures on watercourses represent priority activities. Therefore, flood hazard and risk maps are important information bases for different user groups to reduce the risk and damage caused by flood events. Based on the information in the maps, users integrate hazard and risk information into their decision-making, planning, and instruments [11].

The National flood risk assessment, as the principal legal document on this matter, offers a scenario-based methodology for determining the levels of risk. The most prominent disadvantage of such an approach is using a few arbitrarily selected scenarios (which rely on historical flood data) to depict the flood risk for the whole country's territory. This may lead to overlooking critical scenarios – catastrophes can be neglected, and at the same time – low probability-high consequence events are classified as medium-risk events by definition (table 1). Montenegrin NRA does not include any hazard maps. In addition to this, risk maps (existing only for the selected scenarios) show uniform risk descriptions for the entire scenario-designated area, regardless of the position of risk assets in the floodplain (dedicating the same level of risk for the objects at the very border of the floodplain, and the objects that may be located in the river channel itself, which are exposed to much greater flood depths and velocities).

However, the water management strategy in Montenegro recognises projects whose implementation would have an extremely significant positive effect in protecting against floods. One of them is *Support for implementing and monitoring water management in Montenegro*. Therefore, flood hazard map production for all APSFRs in Montenegro is among the critical products expected upon the realisation of this ongoing project. They are meant to visualise essential parameters describing the intensity and character of a flood:

- The flood extent – shows the inundated area for different flood scenarios.
- The inundation depth – indicates, for example, up to which height a building will be flooded and on which floors assets and persons will not be affected by the flood.
- Velocity – describes how fast the water is moving. Depending on the flow velocity, the risk of adverse consequences to human health, the environment, cultural heritage, and economic activity might increase. At high velocities, people and objects are more likely affected by floods.

These parameters could only be obtained through hydraulic computation of the study areas. For these purposes, two-dimensional hydraulic models were developed because complex flow situations (as with extensive flood plains, levees, multiple directional flows, etc.) are handled more suitably with the two-dimensional approach. In addition, two-dimensional models provide a more intuitive graphical representation of results than cross-sections and tables from a one-dimensional model [12]. However, preparing the inputs for the model (especially terrain data) should be done with great care since the reliability of the results depends significantly on the quality of the input data. There is always room for improvement of the newly developed models (when the time comes to update the maps), particularly regarding additional geodetic surveying, which would further enhance and improve the used DEMs.

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