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HYDRAULIC MODELING OF THE FLOOD AREA IN NORTH-WESTERN KOSOVO THROUGH HEC-RAS SOFTWARE

F. Bilalli[1*], **A. Bode**[2]
[1]Kosovo Regional River Basin Authority
[2]Faculty of Geology and of Mining Albania

*Corresponding author: fidan.bilalli@gmail.com

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Abstract

Flood risk assessment and delineation of flood prone areas are fundamental components of sustainable water resources management, especially in rapidly urbanizing river basins. In north-western Kosovo, the Sitnica River basin has experienced recurrent inundation events, exposing discrepancies between existing regulated design discharges and statistically derived extreme floods. This study develops an integrated hydraulic–legal assessment framework using one-dimensional (1D) and two-dimensional (2D) modeling with HEC-RAS (version 6.3.1) for floodplain delineation and public water asset definition under current national legislation.
Extreme value statistical analysis was conducted on a 21-year daily discharge record (1963–1985) at the Nedakoc station. The Gumbel distribution, complemented by comparative Log-Pearson Type III fitting, was used to estimate the 1 % exceedance probability discharge ($Q_{1\%}$). Results show that the previously adopted design discharge of 239.76 m^3/s underestimates the statistically derived $Q_{1\%}$ by approximately 95 % to 110 %, indicating significant hydraulic deficiency in the regulated river reach.
Unsteady 2D simulations highlight maximum flood depths up to 3.20 m and velocities up to 2.80 m/s in constrained morphological zones. A sensitivity analysis of roughness coefficients (±20 %) reveals a ±12 % variation in peak depths and ±8 % shift in inundation extent, underscoring model responsiveness to parameter uncertainty. Model calibration and validation against documented flood events (January 2021 and January 2026) yielded a Root Mean Square Error (RMSE) of 0.18 m and a Nash–Sutcliffe Efficiency (NSE) of 0.82, demonstrating good conformity between observed and simulated water levels.
The integrated hydraulic modeling approach provides a scientifically defensible basis for more reliable floodplain delineation and public water boundary definition under evolving environmental and regulatory conditions. Limitations include the relatively limited hydrological time series and absence of climate scenario analysis, which future work should address.

Keywords: water resources, floodplain, HEC-RAS, hydraulic modeling, flood risk management, Kosovo.

1. INTRODUCTION

Floods represent one of the natural hazards with the greatest socio-economic and environmental impact, especially in urban and rural areas of Kosovo. In recent decades, the intensification of infrastructural developments along rivers, climate change and anthropogenic interventions in riverbeds have led to a significant increase in exposure to flood risk.

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In this context, the accurate definition of flood zones and water resource boundaries is a key element for spatial planning, environmental protection and public safety. Historical approaches, based mainly on empirical observations or historical boundaries, often prove to be insufficient and subjective. For this reason, numerical hydraulic modeling has become the scientific standard for analyzing flow behavior and predicting flood extent.

This paper aims to contribute to the scientific literature by analyzing the application of hydraulic modeling with HEC-RAS in determining water resources, as well as discussing the technical and institutional implications of the results obtained.

The location of the thematic parcel of water assets, from an administrative aspect, lies in the territory of the Municipality of Mitrovica, which is located in the northern part of the Republic of Kosovo.

In the macro-spatial and hydrographic context, the study area is positioned along a segment of the Sitnica River, specifically between the mouth of the Sitnica River into the Ibar River and the mouth of the Trepça River into the Sitnica River. The Trepça River constitutes a sub-basin of the Sitnica River watershed, while the Sitnica River is a sub-basin of the Ibar River watershed, reflecting a hierarchical structure of the hydrographic network of the area.

From a hydrological perspective, the thematic hydrological profile of the river in this segment is an integral part of the Sitnica River catchment area. The spatial extent of the study area is presented in the relevant scheme, which is illustrated on the basis of the Topographic Map of Kosovo at a scale of 1:25 000. For hydrological interpretation purposes, the scheme is also accompanied by two hydraulic profiles of the Sitnica River, presented with red "line-by-line" symbols, as shown in the following figure.

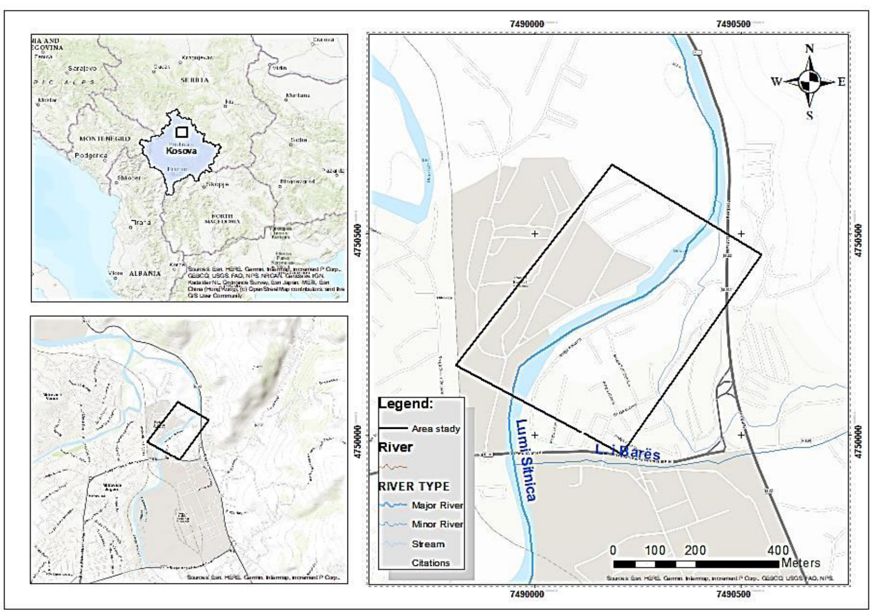

Figure 1. Extent of the study location

Vol. 11, No. 1, 2026, pp. 41-57
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From the figure above, it is clearly observed that the thematic river segment presents pronounced meanders both in the upper and lower parts of the watercourse. These meanders play an important hydromorphological role, especially in the process of alluvial transport and deposition, as well as in reducing the flow velocity during peak flow events and river floods (fig. 2).

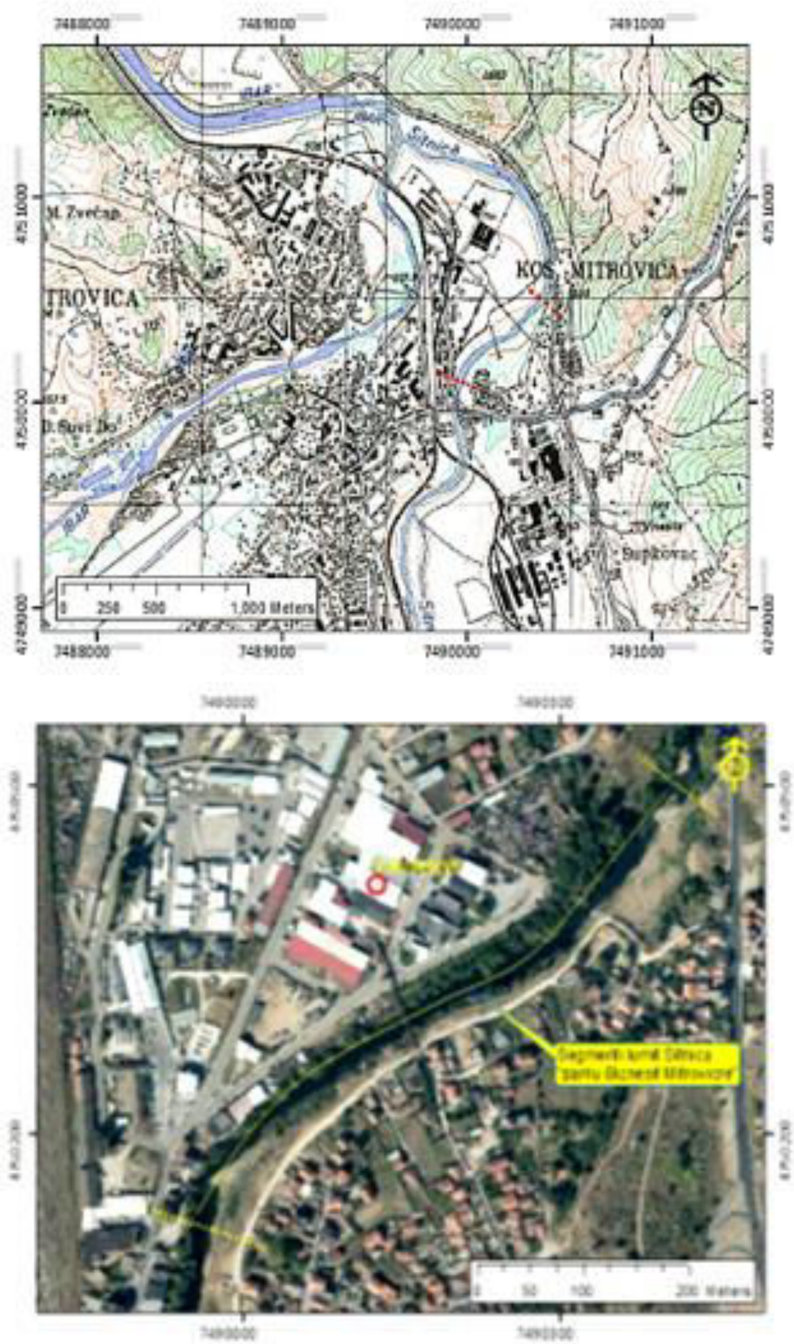

Figure 2. Macro-spatial layout of the Mitrovica Business Park

The main purpose of this paper is to assess the role of hydraulic modeling as a scientific basis for the determination of floodplains and water resources. Specific objectives include (fig. 3):

- analyzing the hydrological and hydraulic methodology used;
- interpretation of modeling results for flood risk management purposes;
- assessing the contribution of results to institutional decision-making;
- formulating recommendations for improving existing practices.

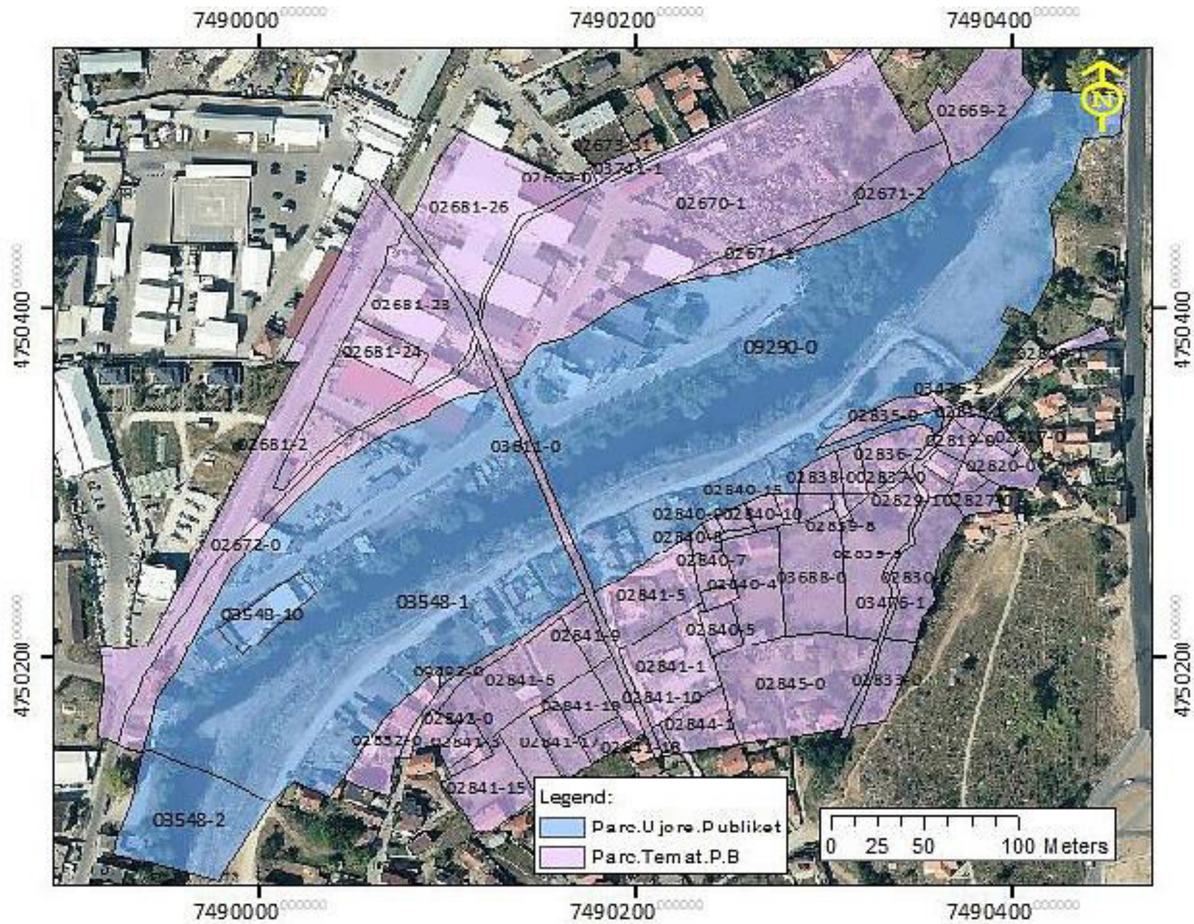

Figure 3. Thematic scheme of the study

While the hydraulic modeling procedures applied in this study follow established international engineering standards, the contribution of this research lies in the systematic integration of quantitative 1D/2D hydraulic simulation with formal legal criteria for delineating public water assets. This combined technical–regulatory framework represents an applied methodological advancement for transitional river governance systems where hydraulic modeling has not yet been institutionalized as a mandatory decision-support tool (IAHR, 2024).

Vol. 11, No. 1, 2026, pp. 41-57

http://ijees.ielas.org
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2. METHODOLOGY

The study is built on an integrated scientific approach, which combines hydrological analysis, numerical hydraulic modeling and technical interpretation of the results. The methodology follows the US Army Corps of Engineers guidelines for the use of HEC-RAS and international best practices for flood risk management.

2.1 Methodological framework

The methodology of this study is directly based on the technical document of hydraulic modeling performed with the HEC-RAS software, following the official guidelines of the US Army Corps of Engineers (USACE) and standard hydraulic engineering practices.

The methodological approach is built sequentially and includes: (i) preparation of input data, (ii) hydrological analysis, (iii) construction of the hydraulic model, (iv) simulation of flow scenarios and (v) analysis and interpretation of the results.

2.2 Data and their processing

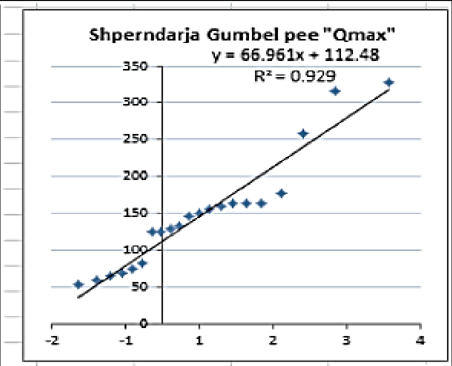
The basic data used in the modeling include:

- digital terrain model (DTM/DEM);
- longitudinal profiles and cross-sections of the riverbed;
- hydrometeorological data (precipitation and flow);
- land use and morphological characteristics of the bed.

Topographic data has been processed and harmonized into a unique coordinate system, ensuring geometric compatibility between the hydraulic model and the reality on the ground.

The reference hydrometric station was taken as the nearest Nedakoc Hydrometric Station (2590 km^2), from the data of the Kosovo Hydrometeorological Institute for daily flows of the chronological series 1963-1985 (21 years), initially those of (i) maximum monthly flows were processed and as a result of the latter also (ii) maximum annual flows of the respective series, after applying empirical/theoretical methods, the following results have resulted according to the Gumbel Method (Standard Typical Met.) (fig. 4):

Qmax-Nedakoc\IHMK					
Viti	Rangu	Qmax	Q.r.max	p=m/n+1	Y=-ln(-ln(p))
1963	1	328	53.6	0.045	-1.12851
1964	2	69.4	59.7	0.091	-0.87459
1965	3	316	64.4	0.136	-0.68936
1966	4	164	69.4	0.182	-0.53342
1967	5	53.6	75	0.227	-0.39313
1968	6	59.7	82.5	0.273	-0.26181
1969	7	164	125	0.318	-0.13552
1970	8	163	126	0.364	-0.01153
1971	9	128	128	0.409	0.11225
1973	10	178	133	0.455	0.23768
1974	11	126	146	0.500	0.36651
1975	12	64.4	151	0.545	0.50065
1976	13	259	156	0.591	0.64228
1977	14	151	159	0.636	0.79411
1978	15	133	163	0.682	0.95974
1980	16	156	164	0.727	1.14428
1981	17	146	164	0.773	1.35546
1982	18	125	178	0.818	1.60609
1983	19	82.5	259	0.864	1.92002
1984	20	159	316	0.909	2.35062
1985	21	75	328	0.955	3.06787



p=-ln(-ln(1-1/T))
Y=Q=66.96*p+112.48

T	p	Y
2	0.366513	137.0217
5	1.49994	212.916
10	2.250367	263.1646
20	2.970195	311.3643
50	3.901939	373.7538
100	4.600149	420.506

Figure 4. Q1% according to Met.Gumbel

Within this framework, the hydrological scheme of thematic river basins is presented in relation to the Nedakoc Reference Hydrometric Station and their surfaces (see Fig. 5).

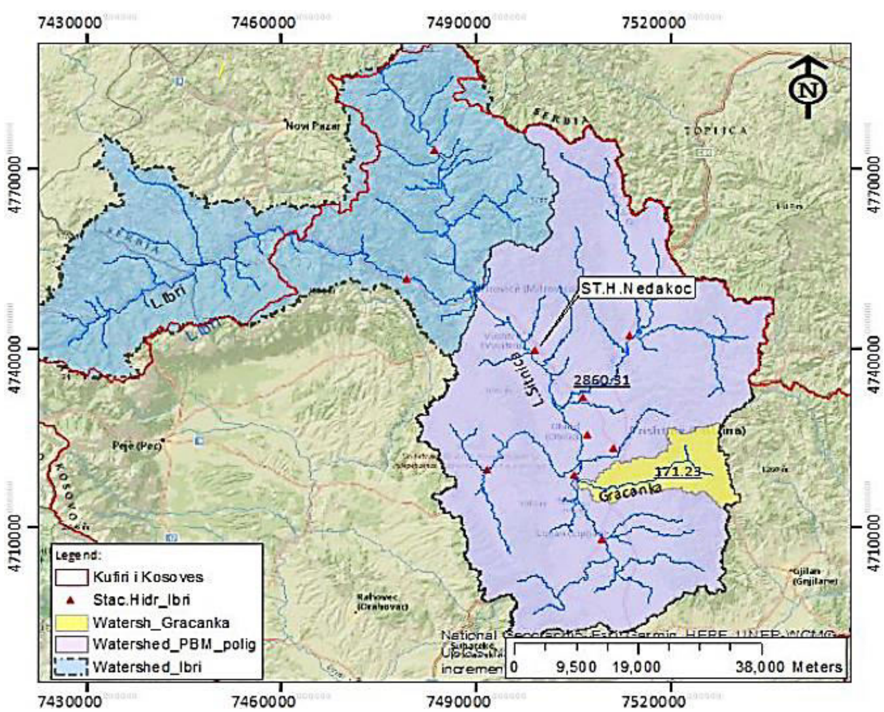


Figure 5. Hydrological scheme of river basins and Nadakovc Hydrometric Station

2.3. Hydrological analysis

The hydrological analysis focused on determining the maximum flows for different return periods with emphasis on the 100-year flow (T = 100 years), which is considered the reference standard for flood risk analyses. The design flow was calculated through statistical analysis of time series of hydrometeorological data, using the general expression:

$$Q_T = \mu + K_T \cdot \sigma$$

Where:

- Q_T represents the design flow,
- μ the average of the series,
- σ the standard deviation and
- K_T statistical frequency coefficient.

Although the Gumbel distribution is widely applied in European flood frequency analysis due to its simplicity and robustness for extreme values, a comparative fitting with Log-Pearson Type III distribution was also tested. The difference between the two methods for $Q_1\%$ estimation was below 6%, therefore Gumbel was retained as the representative model due to better graphical fit and lower standard error.

2.4. Hydraulic modeling with HEC-RAS

Hydraulic modeling was performed in the HEC-RAS environment, including the construction of the riverbed geometry, the determination of Manning roughness coefficients, the establishment of boundary conditions, and the simulation of the flow for selected flow scenarios. One-dimensional and two-dimensional models were applied to improve the accuracy of the results and to capture the spatial complexity of the floods.

Table 1. Characteristic values of Manning's coefficient (n)

Surface type	Manning (n)
Natural gravel bed	0.030 – 0.040
Bed with dense vegetation	0.045 – 0.060
Flooded urban area	0.050 – 0.080

Based on the hydrological data obtained in the previous section and based on the geomorphological data obtained from the 'DRON' recording through the HEC-RAS 6.3.1 software, the hydraulic model was realized.

The following is an Orthophoto and DTM of the Mitrovica Business Park area from the 'Drone' recording carried out by Mr. Fidan Bilalli, senior official of the Water Information System at the Kosovo Regional River Basin Authority (ARPL) - Ministry of Environment, Spatial Planning and Infrastructure (fig. 6).

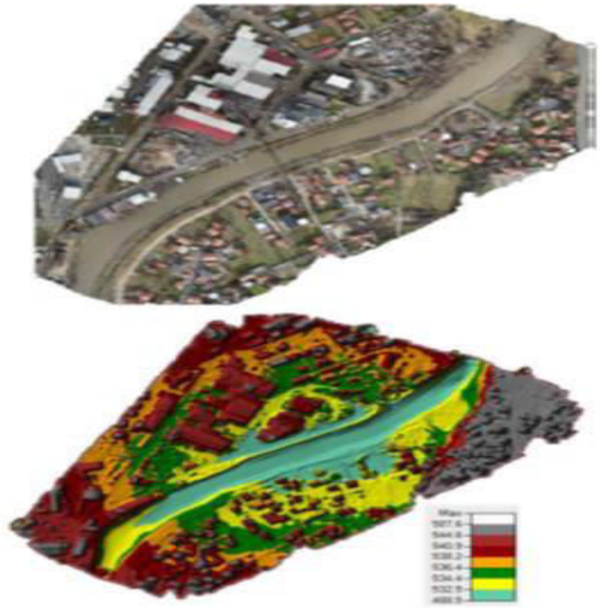


Figure 6. Ortho-Photo and DTM with Drone of the Mitrovica Business Park (Kosovo, F. Bilalli)

From the orthophoto analysis it is concluded that the Mitrovica Business Park lies along the left bank of the Sitnica River. The area is bordered to the southeast and west by local roads that follow the river bank, clearly defining the functional boundaries of the plot. It is also noted the presence of several commercial buildings built on the edge of the watercourse, beyond the embankment on the river side, which from the regulatory and professional aspect of protection from harmful water actions represent a deviation from the standards of sustainable water management. According to the water legislation, these buildings are treated as informal constructions, the problem of which, in accordance with regional practices, requires treatment through relevant legalization procedures.

The digital terrain model (DTM) shown in the following figure (fig. 6) was obtained from aerial drone recording carried out by the ARPL Inspection Service and serves as a technical basis for the hydraulic analysis of the area.

2.5. Model Calibration and Validation

Model calibration was conducted by adjusting Manning's roughness coefficients within a ±15% interval based on field inspection and post-event water level observations from the January 2021 flood.

Model performance was evaluated using Root Mean Square Error (RMSE) and Nash–Sutcliffe Efficiency (NSE), expressed as:

$$RMSE = \sqrt{\Sigma(H_{obs} - H_{sim})^2 / n}$$

$$NSE = 1 - [\Sigma(H_{obs} - H_{sim})^2 / \Sigma(H_{obs} - H_{mean})^2]$$

The calibrated model yielded RMSE ≈ 0.18 m and NSE = 0.82, indicating good agreement between simulated and observed water levels.

2.6. Sensitivity and Uncertainty Analysis

A sensitivity analysis was performed by varying Manning's roughness coefficient by ±20% and the design discharge by ±10%.

The results show that roughness variation produced approximately ±12% change in peak flood depth and ±8% variation in inundation extent. Discharge variation led to ±15% change in maximum velocity values.

These findings indicate moderate parameter sensitivity while confirming the robustness of floodplain delineation for planning purposes.

3. RESULTS AND DISCUSSION

The results obtained from the HEC-RAS simulations represent the spatial distribution of the main hydraulic parameters for the 100-year flow scenario. These results are presented in the form of thematic maps, longitudinal profiles and numerical tables.

Table 2. Main hydraulic parameters extracted from the model (T = 100 years)

parameter	Min	Average	Max
Water depth (m)	0.30	1.45	3.20
Flow velocity (m/s)	0.25	1.10	2.80
Flood zone width (m)	15	65	120
Specific energy (m)	0.80	1.95	3.60

The results show that flow depth and velocity increase significantly in segments with narrow sections and in areas with anthropogenic interference, increasing the potential for structural damage.

The following is an analysis of the non-stationary hydrological flow regime for the probability of exceeding Q_{1}% (100-year return period) modeled through the flood scenario represented by the corresponding hydrograph. Based on this hydraulic simulation, the main hydromorphological parameters of the floodplain have been calculated and interpreted, the results of which are presented in the following sections (Fig. 7).

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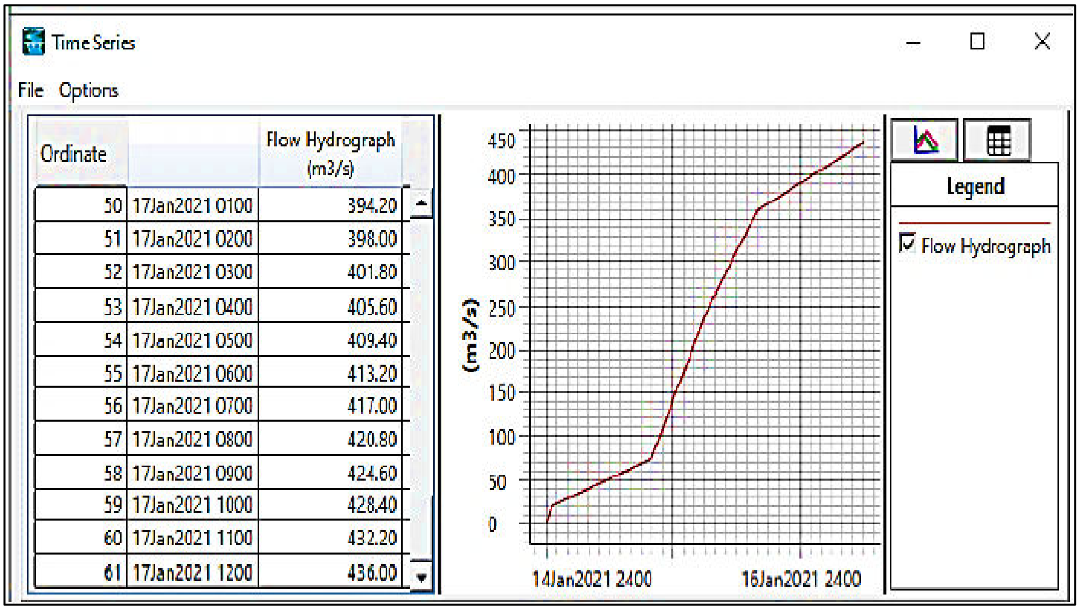

Figure 7. Flood scenario hydrograph

In accordance with the criteria set out in Article 7.3 of the MESP Administrative Instruction No. 19/2015 on Protection from Harmful Actions of Water, the following presents the results of the hydraulic modeling of the distribution of flood depths in the floodplain, calculated for the maximum flow with a return period T = 100 years.

In order to verify and validate the hydraulic model calculated for the Q_1% flow based on the corresponding hydrograph, the following is a photographic documentation of the real flood event that occurred on 13.01.2021 and 06.01.2026 in the study area. The visual comparison shows a significant correspondence between the real extent of the flood zone and the results generated by the hydraulic model, confirming the reliability of the simulation performed (Fig. 8, 9 and 10).

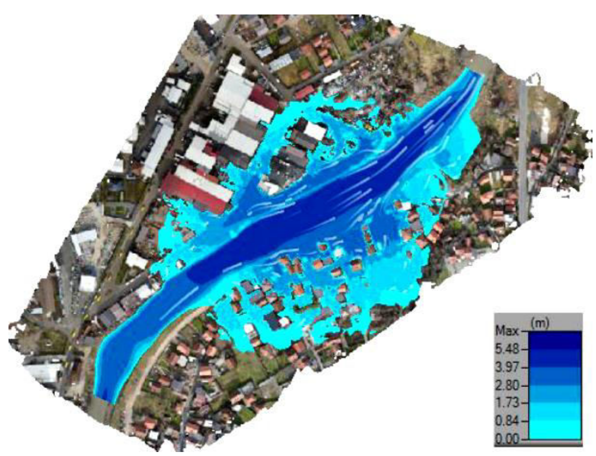

Figure 8. Depth of the flood zone Figure

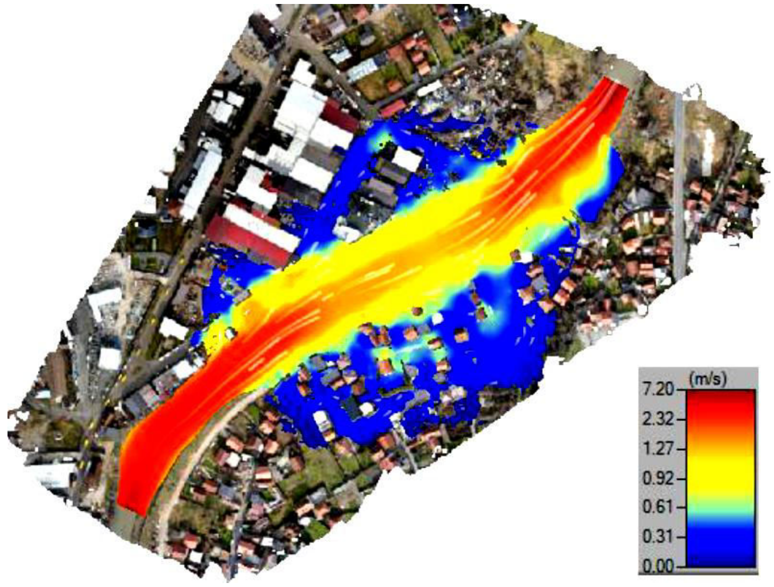

Figure 9. Velocity model in the flood zone

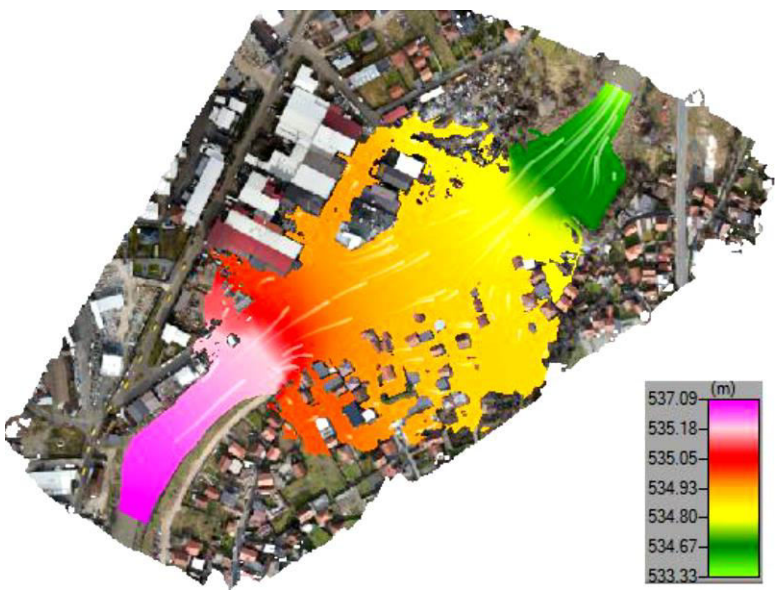

Figure 10. Model of elevations in the flood zone

The flood map (*Inundation Map*) generated as a result of two-dimensional hydraulic modeling (2D Flow) in the RAS Mapper environment of the HEC-RAS program, has been exported to ArcGIS format (*.shp*) for the purpose of cartographic and formal standardization of the presentation of the extent of the flood surface, as shown in Fig 11.

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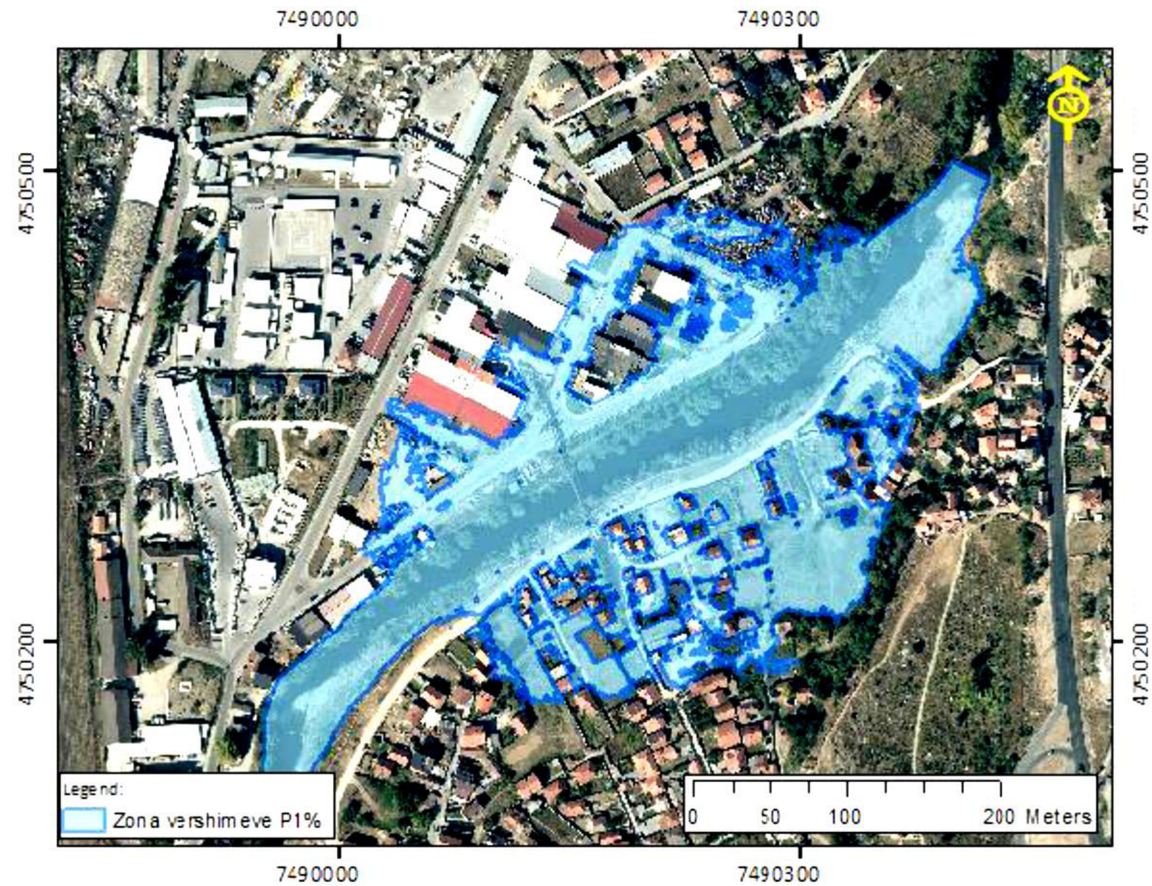

Figure 11. Map of the flood zone in the Mitrovica Business Park area

From the analysis of the flood zone map presented above, it is concluded that during the flood scenario for the maximum flow with a 100-year return period, the water flow exits its natural bed and floods the surrounding areas, generating a flood zone with an irregular geometric configuration. This irregular shape of the flood extent is mainly the result of anthropogenic interventions and existing constructions within the area under consideration, which directly affect the hydraulic dynamics of the flow during extreme events.

In accordance with Article 4 of the MESP Administrative Instruction No. 05/2016 on the Regulation of the Status of Water Resources, where "water resources of flowing waters" are defined as the watercourse bed and the coastal strip, and where the "coastal strip" is defined as the land strip adjacent to the watercourse bed, the criterion of a minimum width of 10 meters is applied for large waters in urban areas. In this context, the redefinition of the boundaries of water resources is carried out based on the results of the extension of the flood surface obtained from the hydraulic modeling through RAS Mapper (HEC-RAS).

The computational results of determining the coastal strip along the perimeter of the flood zone, which appears with irregular geometry, including the flooded surface itself identified on the previous map, are graphically illustrated in Figure 12.

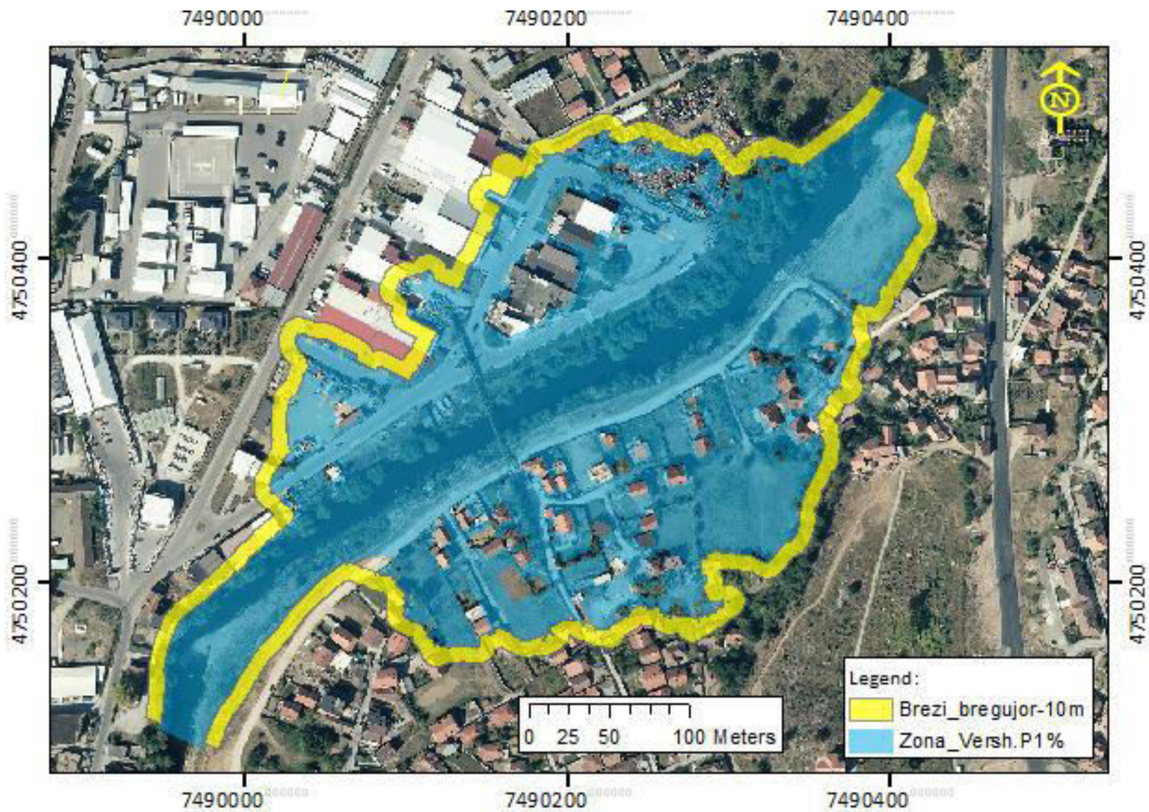

Figure 12. Flooded area for Q1% and 10 m wide coastal strip

From the analysis of the flood zone map for the Q_1% flow, together with the 10 m coastal strip, an irregular geometric configuration of this strip is observed, conditioned by the non-linear shape of the perimeter of the flood surface and by anthropogenic interventions through constructions with non-water functions. Until their treatment, according to the legal legalization procedures, these objects are classified as informal constructions within the framework of the water legislation. The integration of the flood map with the coastal strip on the background of cadastral parcels enables spatial clarification of the status of water assets in the Business Park area, differentiating between public and private water assets.

The simulated depth and velocity ranges are consistent with findings reported by Horritt and Bates (2002) for low-gradient floodplains. Compared to recent reviews on flood inundation modeling (Teng et al., 2017), the present study confirms the importance of 2D modeling in urbanized environments with irregular geometry and anthropogenic obstructions.

3. CONCLUSION AND RECOMMENDATIONS

The results of this study clearly show that based on the results of numerical hydraulic modeling performed with the HEC-RAS software (1D/2D) as well as the comparative analysis between numerical simulations and empirical evidence of real flood events, the following conclusions are drawn:

- Hydraulic modeling with HEC-RAS has proven that the existing design solution for the regulation of the Sitnica River in the Business Park segment is technically inadequate due to the use of an unrealistic and underestimated hydrological input parameter. The maximum designed flow of $Q = 239.76\ m^3/s$ turns out to be about 100% lower than the merit flow $Q_1\%$, which makes the existing design hydraulically unsafe and unprotected against extreme flood events.
- Hydraulic modeling with HEC-RAS has demonstrated high capability for realistic representation of flow dynamics and floodplain extent, providing verifiable, reproducible and scientifically defensible results. The agreement between the flood maps generated by the model and real flood observations confirms the methodological validity of the approach used.
- The application of unsteady flow and two-dimensional (2D Flow) modeling in RAS Mapper is essential for the accurate analysis of the urban area under study, as this approach adequately captures the complex interaction between flow, topography, protective structures, and anthropogenic constructions, which cannot be accurately represented through simplified one-dimensional models.
- The modeling results for the $Q_1\%$ flow (T = 100 years) clearly demonstrate that the existing hydraulic capacity of the Sitnica riverbed is insufficient, leading to overflow and flooding of the surrounding areas. This situation reinforces the conclusion that any design intervention based on flows lower than $Q_1\%$ poses a serious risk to public safety and infrastructure integrity.
- The use of underestimated input hydraulic parameters, especially the maximum design flow, as evidenced in the existing Sitnica River regulation projects, is technically unacceptable and contrary to international best practices in hydraulic engineering. Modeling with HEC-RAS shows that this approach leads to misleading results and systematic underestimation of flood risk.
- Numerical hydraulic modeling proves to be the only objective and scientific tool for determining the boundaries of public water resources, as it integrates hydrological, geometric and morphological elements into a unified analytical framework. Any administrative determination of water resource boundaries without relying on scientifically verified hydraulic modeling is methodologically incomplete and potentially legally contestable.

RECOMMENDATIONS

Based on this study, the following mandatory technical and institutional actions can be recommended:

- Hydraulic modeling with HEC-RAS (1D/2D) should be is recommended to be adopted as a standard technical practice as a mandatory technical criterion for every river regulation project, water resource determination and spatial planning in urban and rural areas. Administrative decisions taken without this scientific basis should be considered technically unsound.
- Any future Sitnica River regulation project should be redesigned from scratch, relying on Q_1% merit flows, non-stationary regime analysis and two-dimensional modeling, as well as respecting contemporary principles of natural river restoration (nature-based solutions).
- The use of underestimated design flows should be prohibited as a professional practice, as it poses a direct risk to hydraulic safety and conflicts with international standards of river engineering and flood risk management.
- The boundaries of public water assets should be determined exclusively on the basis of verified hydraulic modeling results, integrated with legal criteria for the coastal strip. Any conversion of water assets into construction land without this procedure should be reviewed and may require reassessment under updated hydraulic criteria.
- Existing constructions within the area identified as public water assets by the HEC-RAS model should be treated with high priority, through conditional legalization, relocation, or removal, depending on the level of hydraulic risk identified by the model.
- It is strongly recommended that the competent authorities establish a national hydraulic database, based on periodically updated HEC-RAS models, as a key instrument for long-term flood risk management and protection of public water assets.

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