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Advanced Flood Characterization Focused to Optimal City Protection Planning

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Abstract

Following the increasing demand for optimal protection of urban areas against natural multi-hazards, we developed an upgraded urban development planning (UUDP) method integrating four principal planning layers along with the initial zero-planning layer and its related sublayers that systematically characterize the potential natural disasters. The significance of pre-planning characterization for natural disasters was demonstrated through a flood disaster case study, which included the flood analysis options of the historic city of Peja. Herein, we systematically review the representative results from a study on the characteristics and magnitudes of flood waves in the Bistrica River generated by storm runoff within the basin, completed using advanced worldwide HEC-HMS software. Consequently, the advanced HEC-RAS analysis software was employed to evaluate the effects of 24-h precipitation events on both the extent and magnitude of flooding. Existing multi-hazard effects were systematically incorporated into planning through the upgraded zero multi-layered method, which involved a detailed characterization of all relevant multi-hazards. The original flood hazard analysis results, including total inundated area (141.5 - 432.8 ha), maximum water depth (4.28 - 5.94 m) and velocity (4.76 - 5.94 m/s), clearly demonstrated tangible improvements in implementing the new UUDP method for optimal urban multi-hazard protection solutions.

Keywords: Hydrologic Modeling; Flood Modeling; Bridge; HEC-HMS; Flood Hazard; Urban Development.

1. Introduction

Today, intensive urbanization persists across both urban and rural settlements worldwide as well as in southeast Europe. Urban planning for the future development of settlements, which range in size from large metropolitan centers to the smallest rural communities, presents urban planners with a series of specific and complex challenges that require comprehensive assessment. Nonetheless, three common objectives must be addressed when developing urban development plans. Specifically, urban planning must effectively ensure optimal functioning, requisite safety levels, and acceptable cost-effectiveness. Moreover, the complexity of urban planning continues to increase because several unavoidable natural factors require careful and integrated consideration during the adoption of new urban plans. Specifically, in the case of cities and settlements, urban planners confront the existing mixed development pattern that

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has progressively evolved over a long period. New urban plans should provide optimal functionality, safety, and cost-effectiveness for future urban environments. However, planning success is strongly conditioned by pre-existing factors. Functionality and cost-effectiveness are ensured by advanced expertise from specialists in related fields within the urban planning team, whereas ensuring adequate safety requires a more complex approach because of exposure to diverse natural phenomena with distinct destructive effects. Consequently, urban planning must comprehensively study and consistently incorporate potential natural hazards—including floods, earthquakes, soil instabilities, erosion, landslides, and wind effects—into modern development plans. This research focused on characterizing flood hazards in the historic city of Peja. The significance of detailed preliminary studies and proper integration of potential natural hazards into modern urban development plans was emphasized. Floods are widespread, devastating events that cause significant material, human, and economic losses and have been intensively studied in recent years across multiple regions worldwide.

In Europe, significant attention has been directed toward investigation of natural and technological hazards. The foundational framework bridging flood hazard mapping with spatial planning strategies is inherently a territorial development issue. It is critical for establishing a methodology that combines structural protection with land-use policies [1]. The European landscape convention [2], promoted during the 16th Council of Europe CEMAT symposium, is focused to integrating flood risk management directly into landscape and spatial planning strategies, moving beyond traditional engineering approaches. The reference supports the "territorial democracy". Promoted is concept for community-involved planning with aligns with the EU Floods Directive, highlighting the necessity of transnational cooperation for comprehensive urban protection. The WBIF 2015 report acts as a foundational policy and technical guide for advanced flood characterization, bridging theoretical modeling with practical urban protection planning. It provides crucial data on regional hazards, identifies gaps in current infrastructure, and outlines a methodology for prioritizing investment in compliance with the EU Floods Directive [3]. The EEA Report No 1/2016 [4], provides crucial evidence for integrating "green" nature-based solutions with traditional "grey" engineering to enhance long-term urban resilience. It supports advanced characterization by documenting historical floodplain degradation and offering a framework for optimal, multi-beneficial flood management that aligns with European environmental policies. The NSW Department of Planning and Environment's 2022 Flood Hazard Guide (FB03) is essential for advanced flood characterization [5], providing standardized methodologies for mapping flood danger based on velocity and depth. It directly contributes to optimal city protection by bridging hydraulic modeling with land-use planning and emergency flood management, facilitating risk-based decision-making. The International Sava River Basin Commission's HEC-RAS Technical Documentation Report provides the foundational methodology for high-resolution, transboundary hydraulic modeling and 2D flood simulations crucial for city protection planning. Shown is integration of LiDAR-derived terrain data with hydrological models to accurately map urban flood risks and evaluate levee failures [6].

Similarly, in the USA and UK, notable scientific advances in flood modeling and hazard assessment have been achieved [7–10] owing to the need for rapid mitigation of potential flood consequences. In Kosovo, where the historic city of Peja is located, flood studies have commenced in recent years through several international projects [11, 12]. An integral overview of modern flood risk analysis methods has been provided, with an emphasis on the advantages of their applications [13]. Recent years witnessed notable progress in the research of modern satellite imagery used for various purposes [14]. Additionally, advancements in flood study have emerged through specialized software packages permitting hydrologic and hydraulic modeling of flood hazards [15–18], as well as through published books and reports [19–20]. Highly specific phenomena investigated encompassed Atlantic hurricanes [21] and tropical cyclones [22]. Valuable insights were derived from flood case studies conducted in locations such as Korea [23], India [24], Romania [25], Vietnam [26], Bolivia [27], Italy [28], and Pakistan [29]. Floods cause damage or complete destruction to engineering structures, such as bridges, buildings, heritage sites, and industrial facilities. Flood-induced bridge failures have been documented worldwide [30–38]. Consequently, structural systems must be upgraded and protected against natural hazards. Investigated topics include riverbed erosion during debris flows [39, 40], bridge failure rates [41–43], and urban flood management via integrated modeling. The use of advanced software for analyzing structures subjected to flood and earthquake effects has facilitated the qualitative enhancement of structural systems [45–51].

This paper presents selected representative results from an advanced flood characterization study aimed at optimal urban protection planning. Based on the detailed flood hazard evidence derived from the completed case study for the historic city of Peja, important innovative multi-hazard planning components were introduced.

The introduced new upgraded urban planning concept comprise: (1) the unique integrating multi-hazard key protective mode (K-Protective mode), which incorporates active protection across three phases—pre-planning, during-planning, and post-planning—to ensure the integrated formulation of optimal urban multi-hazard protection solutions; (2) the unique integrating zero planning layer (Layer-0), which summarizes the generated detailed evidence of anticipated natural hazards; (3) the supplemental set of zero sub-layers providing a refined characterization of expected urban natural disasters; and (4) the original upgraded urban development planning (UUDP) method, an advanced and complete planning platform designed to assure optimal urban multi-hazard protection solutions.

2. Study Objectives

The conventional urban development planning concept organizes activities across three layers: (1) Layer-1, devoted to underground systems; (2) Layer-2, dedicated to network systems; and (3) Layer-3, which encompasses integrated occupation and urbanization activities. However, during the plan's development, the disaster mitigation measures proposed were generally insufficient or incomplete for determining optimal protective measures. Thus, the conventional approach lacks adequate conceptual integrity and cannot be integrated into the refined phases and specific characterizations of natural disasters. To address the prevailing lack of conceptual integrity and ensure a systematic approach for developing the most effective protection measures for urban areas exposed to natural multi-hazards, implementing a novel disaster prevention concept is essential. This study defined the following key objectives.

- Deriving an urban planning process that systematically integrates existing knowledge and advanced scientific methodologies developed by institutions and experts in the context of single hazards.
- Promoting the activation and enforcement of integrated multi-hazard education programs to encourage engagement by competent experts across global regions prone to multiple hazards.
- Strengthening the capacity of government officials proficient in enforcing new multi-hazard protection plans, thereby ensuring optimal safeguarding of urban areas exposed to multiple hazards.
- Establish a new UUDP method in areas susceptible to natural disasters. This method, given its potential for practical application, is expected to facilitate the generation of optimal protection solutions for urban areas facing multiple natural hazards.

3. Research Methodology

Moreover, the study aimed to characterize the natural flood hazards of the historic city of Peja. The municipality of Peja spans an area of 603 km², whereas Peja City itself occupies 20 km². The town of Peja is situated on a plain in western Kosovo, between 42° and 40° north latitudes and 20° and 18° east longitudes, at an altitude of 498 m. The urban elevation ranges from 450 to 520 m; the highest point, Yellow Stone, reaches 2522 m, whereas the city center lies at 511 m. The city of Peja is bisected by the Bistrica River near its confluence with the Drim River; the river spans 63 km, drains a catchment area of 514 km², and exhibits a discharge exceeding 300 m³/s. The landscape of Peja City and its environs represents a European paradise, where all four seasons can be experienced concurrently. This study aimed to demonstrate the significance and benefits of applying advanced concepts to the phenomenological characterization of natural disasters (CND) in modern urban planning. The research methodology is summarized in Figure 1.

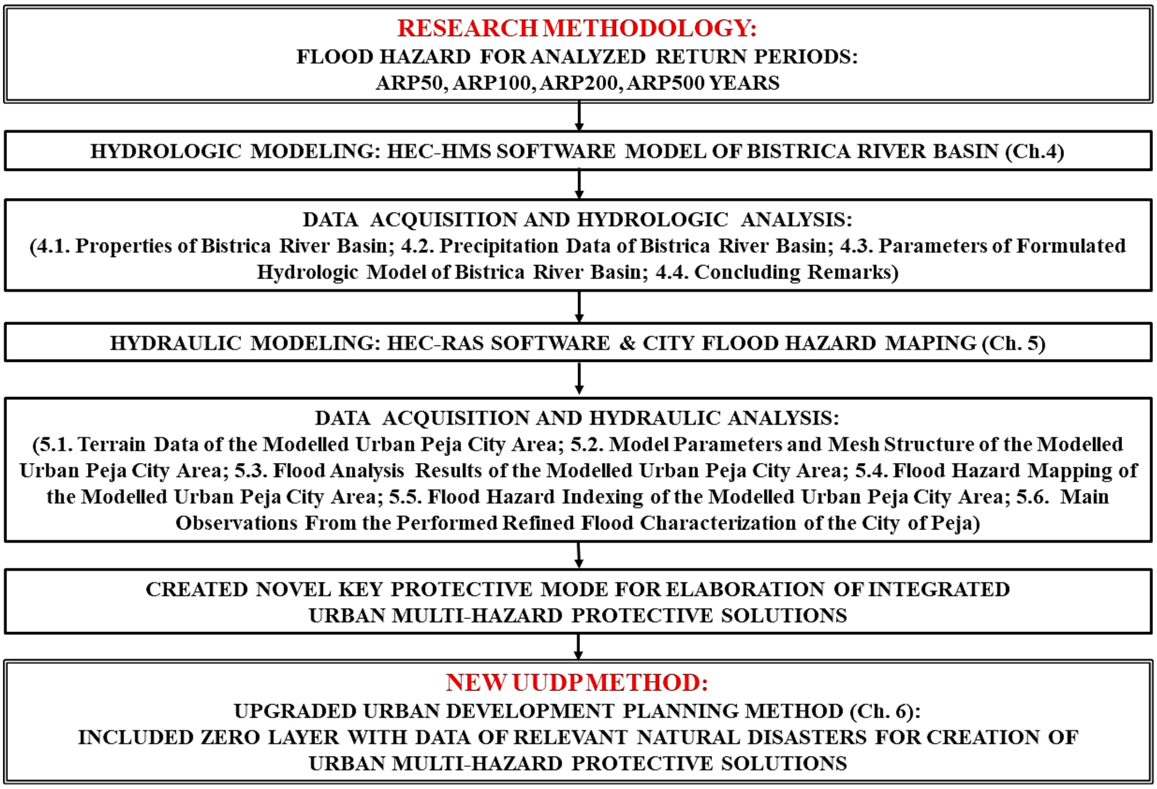

Figure 1. Flowchart of the implemented research methodology

The hydrologic analysis provided a detailed characterization of flood hazard sources, whereas the hydraulic analysis delineated flood hazard extent for various return periods. The comprehensive hydrologic study, conducted using advanced HEC-HMS software, yielded representative results. A detailed comprehensive hydraulic analysis determined the spatial and temporal characteristics and magnitudes of peak flood waves in the Bistrica River arising from storm runoff within its basin. A complementary assessment employed a refined two-dimensional flood inundation model via advanced HEC-RAS analysis software. Accounting for 24-h precipitation events across various return periods, the study evaluated both the spatial extent and intensity of flooding in the modeled urban city area and identified regions at flood risk. To effectively incorporate the destructive impacts of anticipated natural disasters into comprehensive urban planning, hazard levels must be characterized before development. Thus, integrating estimated hazard levels during planning is essential. The implementation of the UUDP method assured the conditions required to develop optimal protection solutions for urban areas exposed to multiple flood hazards.

4. Hydrologic Modeling and Outflow Analysis of Bistrica River Basins

The theoretical approach implemented in the HEC-HMS computer program focuses on representing the water balance and the transformation of excess precipitation into a discharge hydrograph. It utilizes a series of mathematical models to simulate four key processes: (1) Loss or infiltration methods determining how much water is "lost" to the soil; (2) Transform or surface runoff methods converting "excess" rainfall into a flow rate over time; (3) Base flow methods simulating the slow release of groundwater into stream channels; and (4) Hydrologic routing simulating the movement of water through channels using simplified storage-discharge relationships.

In this study, flood wave characteristics and magnitudes in the Bistrica River basin, generated by storm runoff, were analyzed using HEC-HMS software developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center [15–18]. The regulated riverbed beginning of the Bistrica River in the city of Peja served as the basin outlet; analysis employed the runoff curve method. The hydrologic results were subsequently applied as inputs in a hydraulic model developed in HEC-RAS to examine the flow regime in the lower basin reaches and downstream of the outlet, thus simulating potential flooding in Peja and adjacent areas. Calibration and validation procedures in hydrologic modeling using HEC-HMS were performed in an ongoing process using a complete set of available site data, verified literature parameters, and long-term expert experiences in similar studies.

4.1. Properties of Bistrica River Basin

The commune and city locations are displayed in Figure 2. The delineation of the Bistrica River Basin (Figure 2, left), including its sub-basins and river reaches, was performed in HEC-HMS using a raster Digital Terrain Model (DTM) with a 1 × 1 m pixel size. The basic characteristics of the DTM-derived basin are detailed in Table 1.

Table 1. Geomorphological characteristics of the Bistrica River basin

Basin area (km^2)	Basin perimeter (km)	Mean Slope (%)	Maximum Elevation (m)	Minimum Elevation (m)	Mean Elevation (m)
262.6	34.2	45.8	2518	531	1609

The computed digital elevation model provided: (1) Basin area (A); (2) Basin perimeter length (P); (3) Mean basin slope (Slp mean); (4) Maximum basin elevation (Z max); (5) Minimum basin elevation (Z min); (6) Mean basin elevation (Z mean). Thus, the basin slope was determined.

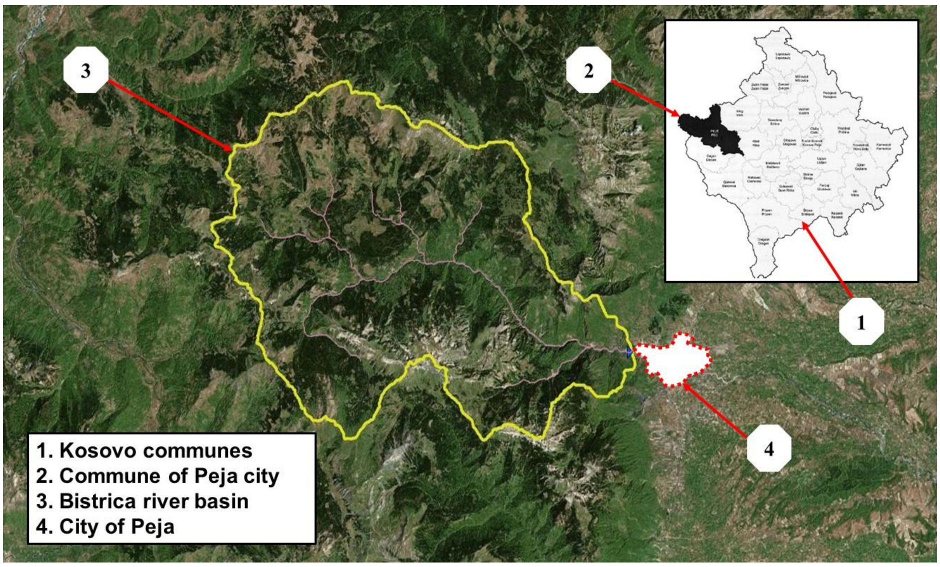

Figure 2. City of Peja with Bistrica river basin.

The CORINE land-cover classification dataset's third level was employed for the land-cover classification, and the FAO classification defined the soil type and texture underlying the basin. The coverage of each land cover, soil type, and soil texture was realistically estimated. Figure 3 depicts the HEC-HMS map of the Bistrica River basin (left) and a satellite view of the city of Peja (right).

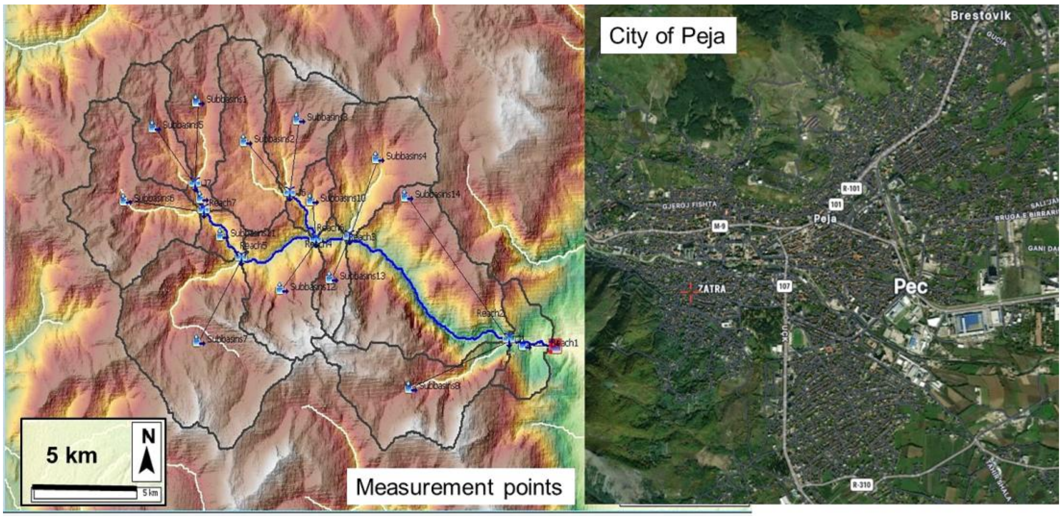

Figure 3. HEC-HMS map of Bistrica River basin (left) and satellite view of the city of Peja (right)

4.2. Precipitation Data of Bistrica River Basin

The precipitation data for simulating flood waves in the Bistrica River Basin were determined for various analyzed return periods (ARP) based on the annual maximum daily precipitation recorded at the Peja/Ramon meteorological station during 2006–2022. To determine the point-depth precipitation values for the ARPs, the empirical distribution of the precipitation time series was computed, and several theoretical probability distribution functions (Pearson type III, log-Pearson type III, and Gumbel) were tested for goodness of fit. The evaluations indicated that the log-Pearson type III distribution best represented the empirical probability distribution and thus was selected to define the point precipitation depth for the considered ARPs.

4.3. Parameters of Formulated Hydrologic Model of Bistrica River Basin

The necessary elements for characterizing the Bistrica River Basin were determined using HEC-HMS software. The DTM was processed through the following steps: (1) evaluation of a "sink-filled" DTM; (2) calculation of slope mode and flow accumulation grid for drainage processing; (3) stream identification; and (4) delineation of the basin outlet or breakpoint. The following basin elements were determined: (1) 15 sub-basins, (2) 7 river reaches, (3) 7 junctions, and (4) one sink or basin outlet. The primary characteristics of the subbasins and river reaches are listed in Table 2.

Table 2. Characteristics of Bistrica River Reaches

Reach Name	Length (km)	Slope (m/m)	Relief (m)	Sinuosity
R1	2.60755	0.02569	67.00000	1.15490
R2	10.75650	0.03198	344.00000	1.20745
R3	1.78042	0.02247	40.00000	1.09134
R4	4.39975	0.02500	110.00000	1.18232
R5	3.32074	0.03132	104.00000	1.21962
R6	2.87563	0.06572	189.00000	1.22451
R7	1.34785	0.05639	76.00000	1.13803

Four meteorological models were employed using an assumed hypothetical storm precipitation method, corresponding to four analyzed return periods (ARP): 50, 100, 200, and 500 y. These models comprised SCS Type II storms represented by a temporal distribution curve, with depth values assigned according to their respective probabilities. For all scenarios, a single control was implemented, with a 24 h simulation and 1 min solution time step. The selected calculation methods for model parameters were uniformly applied across scenarios. Precipitation loss was estimated using the SCS curve-number (CN) method, accounting for cumulative precipitation, soil cover, land use, and antecedent moisture. The hydrologic simulations were performed using the SCS Curve Number method under AMC II (average antecedent moisture) conditions. AMC II was selected to maintain consistency with the synthetic 24-hour design storms applied for 50, 100, 200, and 500 years return periods, as it represents the standard reference condition in SCS-based flood studies when long-term soil moisture observations are unavailable. Using AMC III in combination with extreme return-period rainfall would introduce compound conservatism and likely overestimate peak discharges for planning-scale hazard mapping, whereas AMC I would underestimate runoff response in an urban safety context. Model calibration and parameter verification were conducted using available site data and established literature values, and AMC II produced hydrographs consistent with the geomorphologic and hydrologic characteristics of the mountainous basin. Although full scenario mapping for AMC I and AMC III were not undertaken, preliminary hydrologic sensitivity checks indicated that AMC I reduces peak discharge by approximately 15–25%, while AMC III increases it by approximately 20–35%. However, subsequent 2D hydraulic simulations demonstrated that flood extent and hazard classification in the urban core are primarily governed by channel conveyance capacity and bridge backwater effects rather than moderate variations in runoff coefficient. Accordingly, for strategic hazard delineation within the UUDP (Upgraded Urban Development Planning) framework, AMC II is considered technically justified and representative condition. The analysis also considered subbasin average slope (%). Runoff transformation was determined via the SCS Unit Hydrograph method. The characteristic cross-sections were derived by averaging station–elevation values sampled from the DTM at 50 m intervals for each reach, and reach-routing lag times were estimated computationally. Using HEC-HMS, four scenarios of extreme 24 h precipitation events were analyzed for ARPs of 50, 100, 200, and 500 y. The four basin models were based on the conditions and inputs computed for AMC II, using CN2 values for each subbasin to determine lag times.

The basin outflow hydrographs and cumulative volumes for the evaluated scenarios are illustrated in Figures 4 and 5, grouped by AMC (representative CN value). The comprehensive model output reports, including input parameters, result summaries, hydrographs, and volume charts for all basin elements, were generated for each scenario.

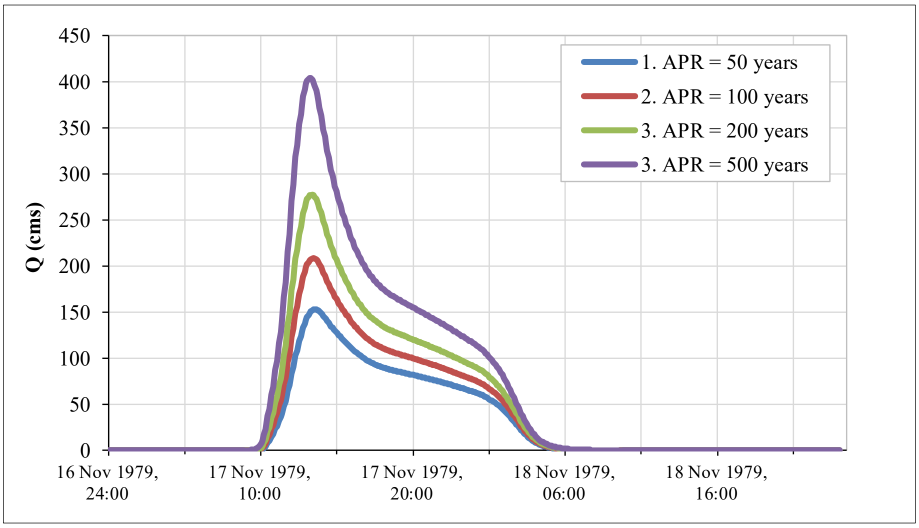

Figure 4. Bistrica river basin outflow hydrographs for the analysed different probability of occurrence (return periods)

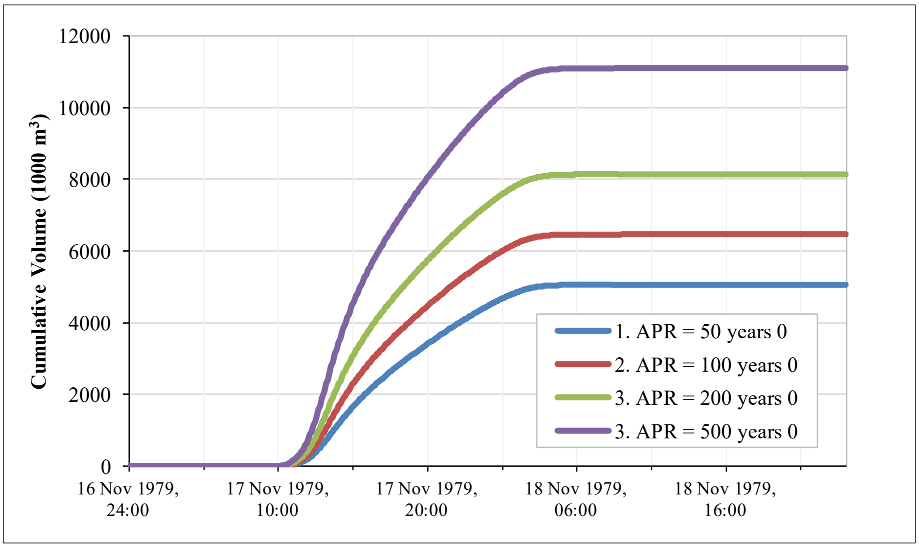

Figure 5. Cumulative volumes of Bistrica River basin outflow for the analyzed return periods

4.4. Concluding Remarks

Based on the hydrological analysis of the Bistrica River Basin, several key conclusions emerged:

- The peak basin outflow and cumulative outflow volume for each AMC increased as the ARP durations of the simulated precipitation events lengthened. This trend was anticipated because the point depths of the 24-h storms increased whereas their probability decreased.
- The results from the AMC II scenarios were accepted as realistic representative values for the subsequent flood study based on hydraulic analysis.
- The subsequent hydraulic analysis computed the associated complex two-dimensional flood patterns in the modeled urban part of the city of Peja for different return periods. Therefore, the flood characterization results provide critical background information for developing optimal flood risk reduction solutions.

5. Hydraulic Modeling and Flood Analysis of Peja City

To assess the spatial distribution of expected flood hazards and the magnitude of their consequences in the study area, a hydraulic analysis of the lower reaches of the Bistrica River near Peja was conducted.

The HEC-RAS software package—developed by the U.S. Army Corps of Engineers for evaluating river systems and open shallow water flows—was used for hydraulic analysis. This software enables the formulation of 1D, mixed 1D/2D, and fully 2D hydraulic models [15–18]. The theoretical approach in HEC-RAS focuses on the physics of fluid flow to predict water surface elevations and velocities. Its calculations are divided by the nature of the flow: (1) Steady 1D Flow based on the solution of the one-dimensional energy equation. It calculates water surface profiles for gradually varied flow, accounting for friction losses (via Manning's equation) and losses at structures like bridges or culverts; (2) Unsteady 1D flow providing solution of the full Saint-Venant equations (continuity and momentum) using an implicit finite difference method. This allows for the simulation of dynamic events like dam breaches or flood wave attenuation; (3) Unsteady 2D flow with slowing the 2D Saint-Venant Equations (also known as shallow water equations) or the simplified diffusion wave equations. These are solved over a computational mesh, making it the standard for urban flood mapping where flow can move in any direction across a city grid and (4) For hydraulic structures HEC-RAS uses specialized empirical equations for modeling pressure flow under bridges (e.g., sluice gate or orifice equations) and weir flow over embankments.

The proposed and used model, depicted in Figure 6, simulated various scenarios with defined inflow and outflow conditions. The outcomes determined the extent of flooding, mapped water surface elevations and flow velocities, measured bed shear stress, and provided additional outputs. These data are essential for flood risk assessments, environmental impact evaluations, and designing effective flood mitigation and erosion control systems. HEC-RAS was implemented to simulate floods in the studied Peja city urban area. The advanced two-dimensional models evaluated flooding resulting from 24-h precipitation events. The primary objectives involved determining flood extent and magnitude within the urban area.

The numerical 2D models incorporated elements representing flow areas, storage areas, and precise hydraulic-structure locations. The implemented model comprised a single 2D flow area defined by a hybrid mesh of discrete computational cells, break lines aligning cell faces with complex terrain geometry, and actual inflow and outflow boundary conditions.

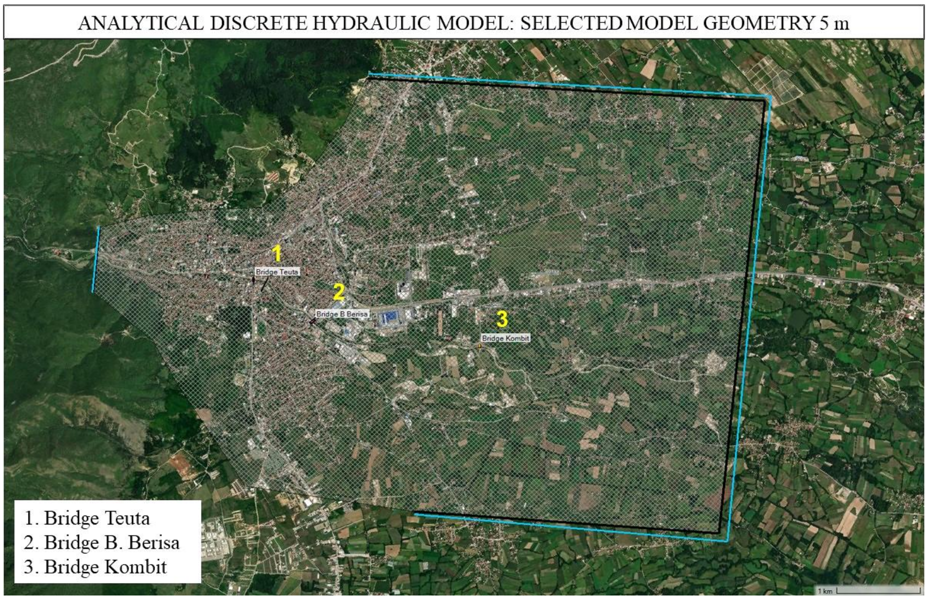

Figure 6. Formulated discrete analytical hydraulic model

5.1. Terrain Data of the Modeled Urban Peja City Area

The 2D HEC-RAS models represented subgrid models in which the 2D flow area accurately depicted the actual terrain (see Figure 7). The cells' hydraulic characteristics were defined by cell face profiles and stage–volume curves, accounting for terrain features at the subcell level. This approach ensured that terrain effects on the resulting maps were realistically simulated even when the cell size exceeded the specified unit pixel dimensions. The terrain models in the implemented HEC-RAS software were derived from georeferenced DEM data or existing Digital Terrain Model (DTM) data.

Bridges are considered in the hydraulic model to improve the accuracy of the predicted distributed flood parameters. The actual geometry of the bridges used in the model was defined with precise conducted field geodetic measurements. With considered blockage effects, the upstream flooding was reliably predicted. The locations of the integrated hydraulic structures (bridges) into the digital analytical model mesh are shown in Figure 8. The terrain within the modeled Peja city area was generated from topographic survey data of the riverbed at the bridge location and overlaid on the DTM from the State Cadaster Agency. A high-resolution DTM was produced using a suitable number of surveyed control points, ensuring high precision and accuracy. The terrain was modeled with unit cells of 5.0 × 5.0 m within the surveyed urban boundary of Peja City. Overviews of the modeled area and terrain configuration (DTM) are illustrated in Figures 6 and 7.

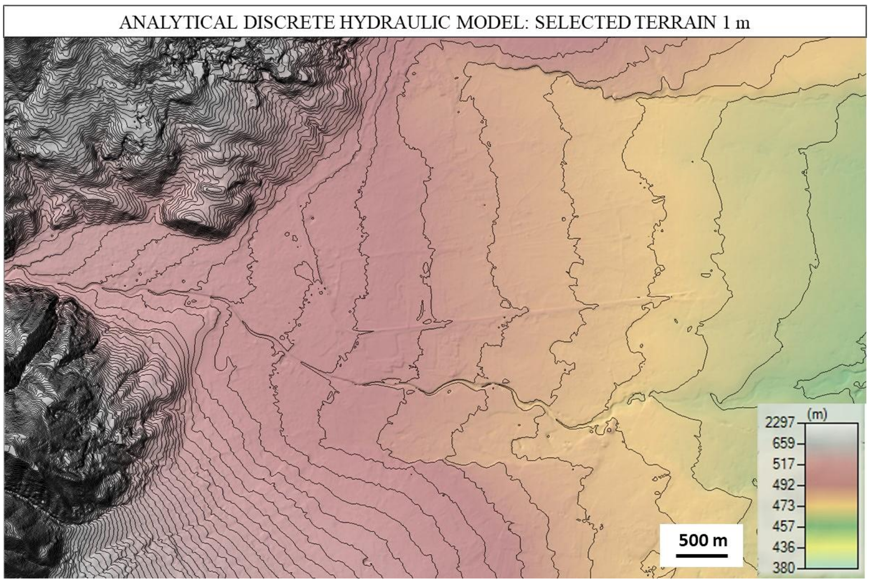

Figure 7. Digital elevation models

Figure 8. Measured and included actual bridge profiles in hydraulic model: Example of bridge B. Berisa

5.2. Model Parameters and Mesh Structure of the Modeled Urban Peja City Area

The 2D discrete model comprises a refined polygonal mesh with small cell sizes. The hydraulic model employed a hybrid 2D mesh consisting of 1×1 m cells in the main channel and near bridge structures, and 10×10 m cells in floodplain areas. This discretization strategy was intentionally adopted to balance hydraulic accuracy and computational stability.

The river channel exhibits high velocities (up to 6.46 m/s) and localized contraction effects near bridges; therefore, fine resolution was required to properly resolve hydraulic gradients, contraction/backwater effects, and peak velocity fields while minimizing numerical diffusion. In contrast, floodplain areas are characterized by lower gradients and broader, shallower flow, where solution sensitivity to sub-meter discretization is considerably reduced. Furthermore, the HEC-RAS sub-grid terrain formulation preserves detailed topographic influence on stage–volume relationships even when larger computational cells are used. A formal grid-convergence (mesh sensitivity) analysis was not conducted within the scope of this study.

However, discretization adequacy was evaluated through numerical stability and consistency checks, including verification of stable hydrograph behavior at control sections, absence of oscillations, physically plausible spatial distribution of depth and velocity fields, and stable wetting/drying propagation. No numerical artifacts indicative of under-resolution were observed. Accordingly, the adopted hybrid mesh represents a technically justified compromise between spatial resolution and numerical robustness appropriate for strategic urban flood hazard mapping. Mesh cell faces were connected to the terrain geometry via break lines. Break lines were introduced at defined profiles near the bridges and incorporated into the model as representative hydraulic structures to minimize numerical diffusion and enhance mesh accuracy. The discrete model included the basic 2D flow-area mesh, actual boundary conditions, defined breaklines, and existing bridges as key hydraulic structures. The Manning friction coefficient (n) values for the floodplain were assigned based on observed land cover; coefficients for the river channel and bridge sections were adopted from the literature. The analysis included three extant bridges as hydraulic structures. The precise geometry of the bridges and the riverbed configuration in their vicinity were obtained via geodetic surveys. A detailed geodetic survey refined the numerical model used for the initial hydraulic analyses. The bridges examined were Bridge Teuta, Bridge B. Berisha, and Bridge Kombit. Two boundary conditions were applied to the analyzed geometries: (1) the actual inflow boundary condition (a defined flow hydrograph) and (2) the actual outflow boundary condition (a specified normal-depth condition). Realistic basin outflow hydrographs corresponding to average antecedent moisture conditions (AMC II – CN2) were adopted as inflow hydrographs, as presented in Figure 4. The storms selected for flow hydrograph boundary conditions were derived from actual data in the completed hydrologic analysis. Four models were implemented using established 24-h storm hydrographs for events with distinct return periods: (1) 500-y, (2) 200-y, (3) 100-y, and (4) 50-y (Table 3).

Table 3. Peak basin outflow runoff and total cumulative volume

Return period (y)	Q_{peak} (m^3/s)	V_{cum} ($\times 10^6$ m^3)
500	403.9	11.10
200	277.2	8.14
100	208.5	6.15
50	152.8	5.06

5.3. Flood Analysis Results of the Modeled Urban Peja City Area

The results of the four flood simulations are presented in eight maps—four depicting maximum depth and four illustrating velocity distribution. The maps for the 500-y return period are depicted in Figures 9 and 10.

The maps illustrate the predicted extreme values for specified parameters in each computational mesh cell; these extremes apply over the entire simulation period and may not occur concurrently. Selected statistical parameters from the maps and the total inundated floodplain area (A_{Ifp}) are summarized in Table 4. Moreover, the analysis defined the relationship between computed inundated area (ha) and flood event return period.

Table 4. Total inundated floodplain area, depth and velocity statistical parameters for the analysed alternatives

T (y)	Variable	Unit	Max	Mean	A_{Ifp} (ha)
500	Depth	(m)	5.94	2.41	432.8
	Velocity	(m/s)	6.46	0.59	
200	Depth	(m)	5.23	2.15	336.6
	Velocity	(m/s)	5.72	0.52	
100	Depth	(m)	4.71	1.99	258.9
	Velocity	(m/s)	5.20	0.49	
50	Depth	(m)	4.28	1.79	141.5
	Velocity	(m/s)	4.76	0.58	

5.4. Flood Hazard Mapping of the Modeled Urban Peja City Area

Evidence from previous events demonstrates that floods generate hazardous conditions that render people highly vulnerable; however, unoccupied floodplains pose minimal risk to the community. Indeed, human interaction with floodplains incurs flood risk when exposure to potential hazards occurs. For instance, typical flooding cases include those caused by shallow, fast water and those resulting from deep, slow water, both of which may endanger individuals or sweep vehicles. Consequently, floodwaters can exert significant detrimental impacts on built and exposed environments.

The structural and non-structural components of affected structures may sustain damage or be destroyed by strong floodwater forces and accumulated debris. Furthermore, costly structures are highly susceptible to prolonged floodwater exposure and may incur severe damage or complete destruction. Existing infrastructural systems are similarly vulnerable to flooding. Numerous urban elements can incur damage, including road surfaces, substructures, rail lines, electrical systems, water and sewage systems, and communication systems. Moreover, several human-made structures may exacerbate damage during specific flood events. Existing structures may alter flood paths, water depths, and flow velocities, or accumulate debris. Observed flood behavior along floodplains is generally linked to human safety and to damage of exposed infrastructure. Evaluating community flood vulnerability requires a comprehensive understanding of the range of flood behaviors. Efficient and optimal flood risk management decisions can be made only after a detailed study and complete understanding of these behaviors. The following definitions address flood hazards. (1) Hazards constitute sources of potential harm or conditions capable of causing loss. In this context, flooding constitutes a hazard capable of harming the community. (2) Flood hazard denotes a potential source of loss of life, injury, and economic disruption resulting from anticipated flood events. Its magnitude varies with flood intensity, which is characterized by flood behavior (expressed by flood extent, depth, velocity, isolation, rate of rise of floodwaters, and duration), prevailing topography, and implemented emergency management plans. Through floodplain-specific procedures, flood hazard assessment aids in determining the relative degree of hazard across a floodplain without requiring information on specific exposures. The present hazard mapping is intended to support strategic land-use planning within the urban floodplain of the city of Peja.

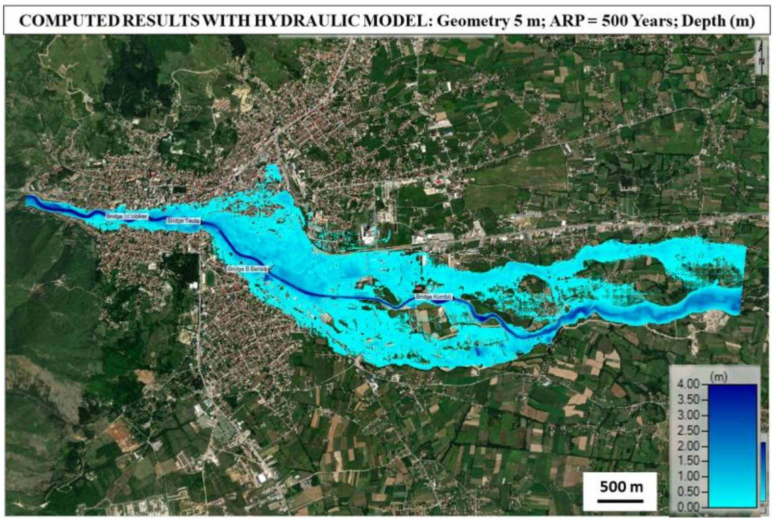

Figure 9. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 500 y; Depth (m)

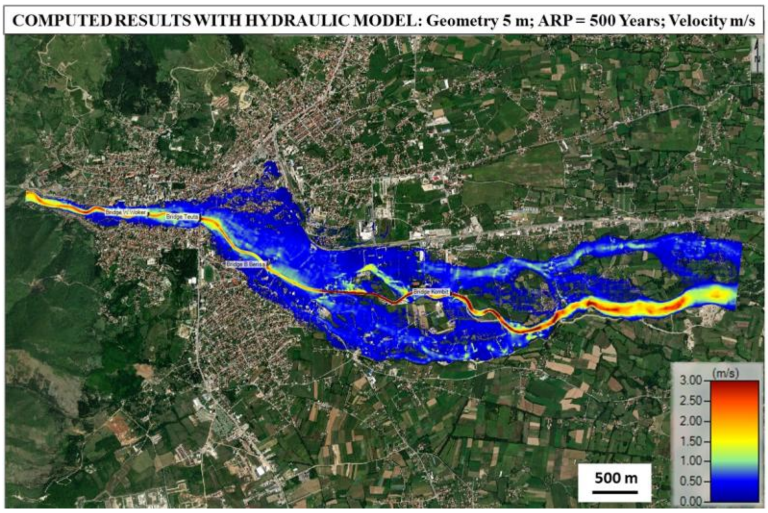

Figure 10. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 500 y; Velocity m/s

The estimated hazard was considered independent of the existing at-risk population. Assessing the vulnerability of people and built environments to flood hazards requires defining specific, measurable flood parameters for various flood events. Vulnerability analysis and/ or assessment represents specific and targeted evaluation of the susceptibility of people, various types of buildings, and various infrastructure systems to flooding in a particular exposed community.

5.5. Flood Hazard Indexing of the Modeled Urban Peja City Area

Following comprehensive analysis and quantification of expected flood hazards the urban area of Peja City, the projected flood flow potential capable of causing damage or danger was indexed against established vulnerability curves delineating the corresponding hazard thresholds. Societal and asset vulnerability was estimated using thresholds characterizing the stability of pedestrians, drivers navigating floodwaters, buildings, and other infrastructure components. The flood vulnerability curves, developed in relation to potential flood hazards, serve as a critical measure in designing the new urban development plan for Peja city, thereby providing optimal flood risk protection.

This study provided essential information for reducing flood risk in Peja. For example, strategic land-use planning required the integration of hazard and vulnerability evidence represented by these curves. Table 4 presents the computed representative vulnerability curves outlining the general classification of predicted flood hazards in the urban areas of Peja [52].

The widely used curves developed by Smith et al. [52] based on extensive studies were implemented for the present objectives. A series of flood hazard maps, depicted in Figures 11–14, were produced for the analyzed flood return periods: ARP = 500, 200, 100, and 50 y. For each analyzed scenario, the computed summary of areas covered by each hazard class and their contribution to the total inundated area are listed in Table 5.

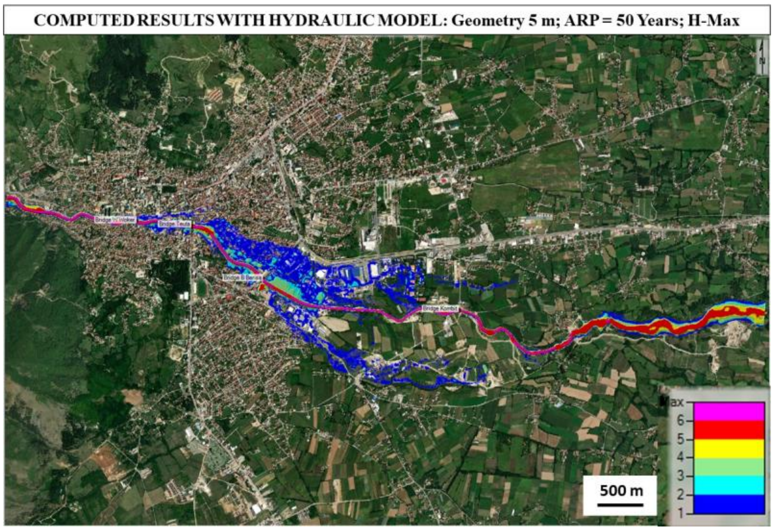

Figure 11. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 50 y; H-Max

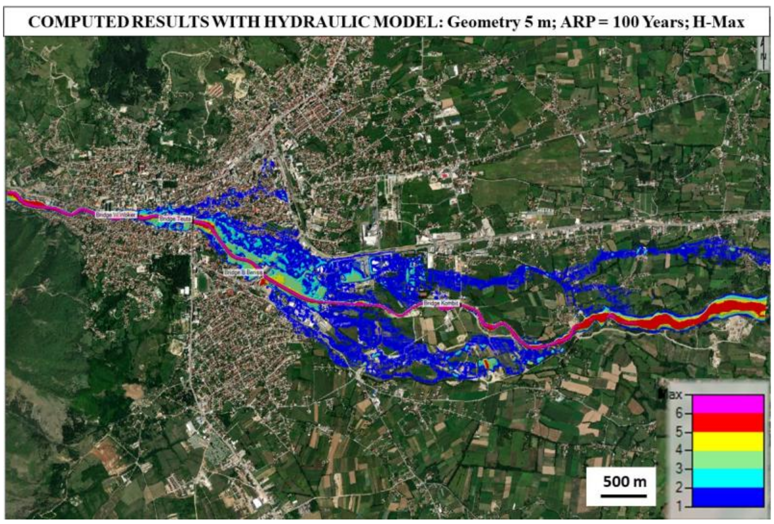

Figure 12. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 100 y; H-Max

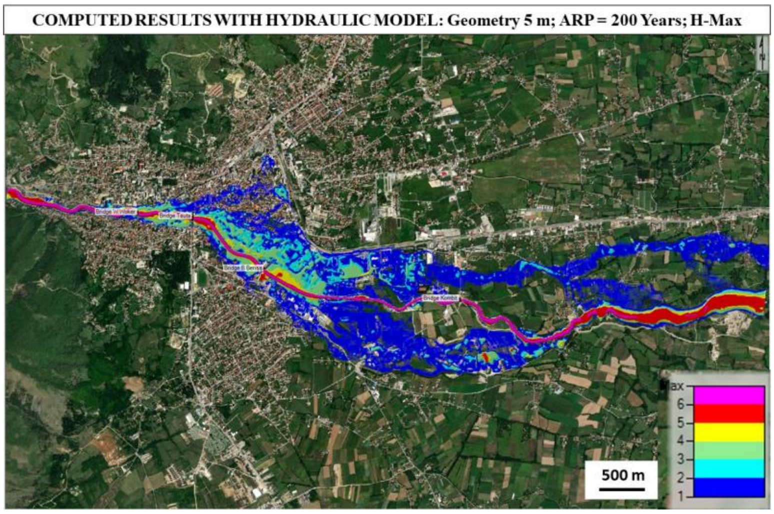

Figure 13. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 200 y; H-Max

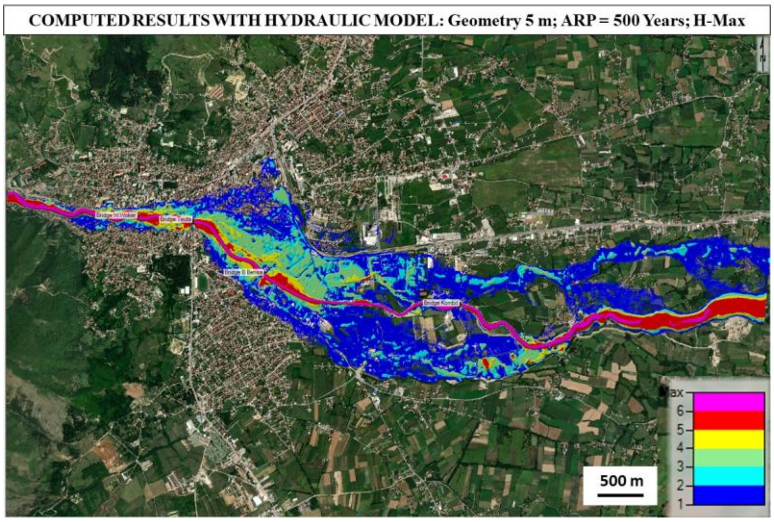

Figure 14. Computed Results with Hydraulic Model: Geometry 5 m; ARP = 500 y; H-Max

Table 4. Combined hazard curves–vulnerability thresholds

Hazard Vulnerability Classification	Description
H1	Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.

Table 5. Summary of the inundated areas covered by each hazard class across all the analysed scenarios

Return Period	Area (ha) / Percent of total inundated area	Hazard Class					
		H1	H2	H3	H4	H5	H6
500	ha	221.4	57.4	67.2	24.2	39.5	23.2
	%	51.2	13.3	15.5	5.6	9.1	5.4
200	ha	197.6	39.4	39.1	13.8	28.8	17.9
	%	58.7	11.7	11.6	4.1	8.6	5.3
100	ha	162.1	24.3	24.0	8.8	24.5	15.2
	%	62.6	9.4	9.3	3.4	9.5	5.9
50	ha	76.4	12.0	12.5	7.5	20.8	12.2
	%	54.0	8.5	8.8	5.3	14.7	8.7

5.6. Main Observations from the Performed Refined Flood Characterization of the City of Peja

The refined flood characterization results for urban part of Peja support the following conclusions:

- The employed research methodology and HEC-RAS software constitute an advanced analytical concept capable of developing a fully two-dimensional model and accurately evaluating the effects of 24-h precipitation events in urban areas.
- This concept effectively assesses flood extent and magnitude and identifies areas at risk from flood hazards in urban environments. A flood development study in the historic city of Peja confirmed these findings.
- Specifically, the formulated models incorporated four representative 24-h storm hydrographs: (1) a 500-y return period event, (2) a 200-y return period event, (3) a 100-y return period event, and (4) a 50-y return period event.
- The findings indicate that the primary river flow concentrates in the Bistrica River, where maximum flow parameters—depth and velocity—were recorded. The surface flow in the modeled area is oriented west–east. For floods with a return period of 50 y, overflow commenced immediately downstream of the W. Woker Bridge; for events with a return period of 500 y, overflow occurred immediately after the river entered the city of Peja.
- The integral flood study results are presented as representative maps of the modeled area. The maximum surface water depths ranged from 5.94 m to 4.28 m for events with return periods of APR = 500 and APR = 50 y, respectively. Minimum depths approached 0 m, whereas average water depths ranged from 2.41 m to 1.79 m.
- The average maximum flow velocities varied from V_{max} = 6.46 m/s to 4.76 m/s for APR = 500 and APR = 50 y, respectively. The flow velocity exhibited a nonuniform spatial distribution, with absolute maximum values recorded in the riverbed.
- Flood hazard classes were clearly delineated and presented as representative maps. Notably, flood hazard decreased from class H6 near the river to class H1 in adjacent inundated areas. The most vulnerable structures included bridges crossing rivers, infrastructure, and buildings proximate to the river.
- The implemented research methodology and advanced flood characterization study of selected, representative urban areas yielded novel, detailed baseline data platforms. Consequently, the flood-hazard characterization layer became the fundamental planning resource, pivotal for developing effective flood-hazard protection strategies for the historic city of Peja.

6. Created Upgraded Urban Development Planning Method

6.1. Concept of UUDP Method

Although natural hazards were traditionally examined independently across scientific fields, recent findings indicate that topics involving natural hazards and disasters require integrated study [53]. Experts and government officials have significantly contributed to loss reduction from natural disasters. Considering the location and environment of urban settlements, various natural disasters may arise, each featuring distinct sources and consequences as follows:

- ***Flood disaster:*** (1) Predominant sources of severe flood disasters typically include heavy rainfall or anthropogenic water impacts resulting from constructing extensive critical infrastructure networks or urbanization; (2) characterization of flood hazards in urban areas requires complex analyses to assess anticipated flood extent, water depth, and flow velocity; and (3) flood-impact reduction can be achieved in urban planning through detailed studies or by implementing design measures that mitigate the vulnerability of exposed elements. Optimal flood-risk mitigation strategies must be identified to achieve the targeted reduction in flood impacts.
- ***Earthquake disaster:*** (1) Common sources comprise movements of the Earth's crustal plates along active faults or ruptures. Fundamental research deepens our understanding of earthquake magnitude and seismic-wave frequency content. (2) Urban-hazard characterization studies entail preparing micro-zonation maps. The analysis provides detailed understanding of hazard variability within the area, accounting for factors such as soil type and epicentral distance. (3) Urban planning and construction of earthquake-resistant structures mitigate the impacts of earthquake.
- ***Landslide disaster:*** (1) Common causes comprise poor soil compaction, erosion, and vegetation removal. Triggers include heavy rainfall, earthquakes, human construction activities, and deforestation; (2) Characterization of landslide disasters requires investigation of primary causes, triggering factors, and failure mechanisms; and (3) Impact reduction is achieved through urban planning and methods such as slope-stability analysis with safety-factor calculations to assess risk.

- ***Soil instability and liquefaction:*** (1) Earthquake-induced liquefaction causes ground failure. Seismic ground shaking reduces the shear strength of saturated, loose soils, causing them to behave like liquids; (2) Realistic characterization of soil instability can be undertaken via field investigations, laboratory tests, and computational models; (3) Mitigating soil instability impacts is achievable through comprehensive hazard assessments and the development of effective mitigation strategies.

- ***Wind disaster:*** (1) Generally characterized by strong winds, often accompanied by heavy rainfall; (2) modern characterization examines meteorological factors, such as wind speed, and impacts on infrastructure and the environment; and (3) mitigation of wind impacts should be integrated into disaster preparedness and post-event investigations, with meteorological stations employed to forecast and manage future wind damage.

Given these characteristics, natural disasters remain challenging to predict. However, assessing risk and mitigating disaster effects has traditionally been the responsibility of governments and individuals. Mitigation activities encompass engineering projects, governmental policies, and public education. Land-use planning often reduces losses from natural disasters. Urban development plans typically incorporate interactive planning activities organized into three main layers: (1) Layer-1 focuses on underground systems; (2) Layer-2 addresses network systems; and (3) Layer-3 involves comprehensive urban occupation and development (refer to Figure 15).

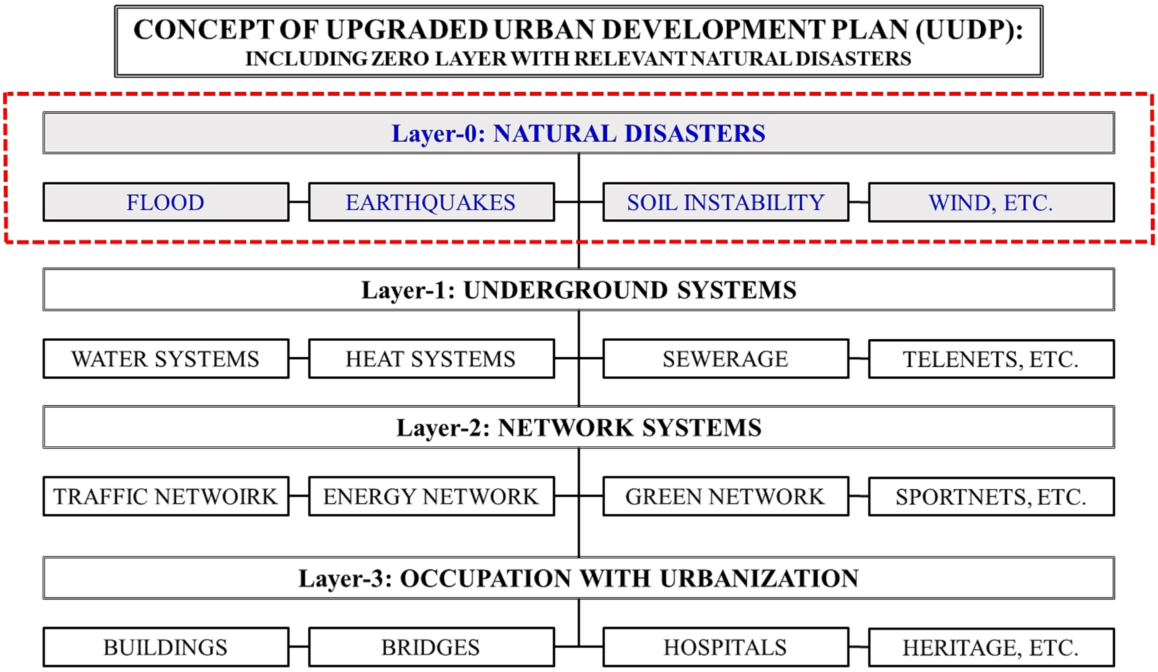

Figure 15. Concept of upgraded urban development planning (UUDP) method

In developing these plans, disaster mitigation measures are integrated as specific components within each planning layer. To ensure optimal protection for urban areas exposed to specific natural hazards, detailed strategies must be implemented across three planning phases: (1) a pre-planning phase for characterizing natural disasters (CND); (2) an intermediate phase incorporating protective measures during the enhanced planning process; and (3) a post-planning phase dedicated to advanced hazard-protective structural design.

Therefore, ensuring efficiency in urban protection planning requires a detailed understanding of natural disasters' actual impacts prior to their integration into urban planning. To facilitate the systematic procedure and establish conditions for optimal protection solutions, we propose an UUDP method (Figures 15). The UUDP method integrates four primary planning layers, including the novel zero-planning layer (ZPL) with location-relevant sublayers offering a detailed phenomenological characterization of related natural disasters (CND). Utilizing the upgraded zero multi-layered (UZML) method, the planning platform enables systematic consideration of multi-hazard events, such as floods, earthquakes, soil instabilities, and landslides. The application of the integrated UUDP method (Figures 16) can optimally mitigate substantial economic losses, infrastructure damage, fatalities, property damage, and environmental impacts resulting from multi-hazard effects.

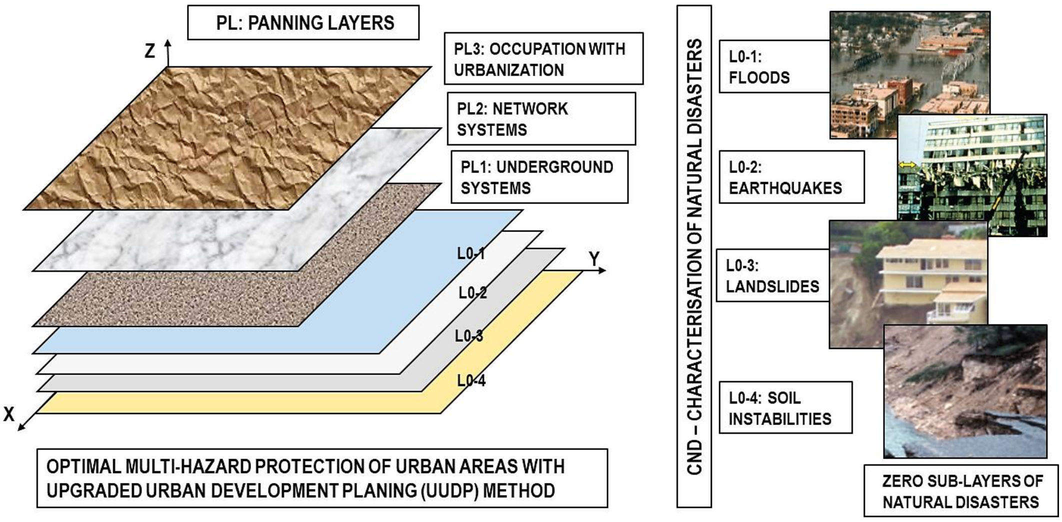

Figure 16. Layered view of the proposed UUDP method

6.2. Implementation of the Created UUDP Method

Historically, the city of Peja and its surroundings have developed a rich cultural and artistic heritage in traditional architectural style. Historical and archaeological evidence confirms the existence of ancient settlements, including Peja's castles, churches, mosques, inns, bridges, fountains, public springs, and urban houses. The traditional marketplace represents the oldest economic sector. Peja exhibits extensive cultural development, as reflected in its numerous historical and archaeological monuments. Municipal development planning is primarily based on existing provisions and policy manuals. Regulatory manuals address central and municipal spatial development. The new master development plan (MDP) should encompass a range of planning domains, including (1) housing; (2) informal settlements; (3) strategic locations and economic development ports; (4) areas with high agricultural value; (5) national parks; (6) heritage preservation and development; (7) mining and energy zones; (8) waste treatment sites; (9) key transport nodes; (10) transport corridors; (11) waste and industrial water treatment plants; and (12) outdoor sports and recreation, among others. According to 2024 sources, Peja has a population of 42,497. Peja's architecture embodies a diverse mixture of structures reflecting foreign influences throughout the city. The city's buildings were constructed under Byzantine, Serb-Byzantine, Ottoman, former Yugoslav, and modern architecture. Thus, numerous churches, mosques, and other notable edifices are present.

In Peja, many structures categorized by use represent dominant at-risk elements, including (1) low-rise housing buildings; (2) high-rise housing buildings; (3) educational facilities; (4) healthcare buildings; (5) tourism structures; (6) industrial buildings; (7) bridges; (8) infrastructural elements; (9) water supply systems; (10) transportation systems; (11) agricultural land; (12) green areas; (13) illegally constructed buildings; (14) natural heritage; (15) cultural heritage; (16) parks; and (17) buildings of government, municipal, and security institutions. Various structures may be exposed to the multi-hazard effects generated by natural disasters, such as (1) floods, (2) earthquakes, (3) soil instabilities, (4) landslides, (5) erosion, etc.

The advanced flood characterization data obtained for return periods 50, 100, 200, and 500 years, provides a technical foundation for realization of respective optimal city protection planning. These results can be applied across several domains to reduce flood loss, including: (1) Risk zoning and land use planning (Flood hazard mapping, urban development control, strategic resettlement); (2) Structural protection (Infrastructure design, flood mitigation structures, Building-level adaptation); (3) Emergency management and public safety (Evacuation routing, Stability threshold analysis, Early warning systems); (4) Economic and financial analysis (Damage assessment, insurance pricing, cost-benefit analysis, etc.). Respectively, seismic hazard analysis (SHA) results, specifically the distribution of peak ground acceleration (PGA) across multiple return periods, provide a scientific foundation for transforming urban resilience. These data are used for shifting from reactive disaster response to proactive seismic loss reduction, including: (1) Urban planning and land use management (Seismic micro zoning maps, risk-informed development, density regulation); (3) Engineering and structural safety (Site-specific design spectra, retrofitting prioritization, fragility analysis); (3) Critical infrastructure and lifeline protection (Utility network assessment, emergency route planning, Hazard de-aggregation); (4) Emergency preparedness and policy (Loss estimation modeling, insurance and financial planning, public awareness). Similarly, the advanced landslide characterization data and susceptibility maps are essential tools for transitioning from reactive to proactive disaster management. These results can be applied across several key areas to reduce landslide-related losses, including: (1) Strategic urban and land use planning (Risk-informed zoning, Update master plans, building regulations); (2) Infrastructure protection and engineering (Critical facility assessment, transportation network resiliency, utility safeguarding); (3) Early warning and emergency preparedness; (4) Environmental and nature-based solutions; (5) Bioengineering and reforestation; (6) Public awareness. To ensure the pilot implementation of the UUDP method and provide optimal multi-hazard protection solutions, a detailed characterization of related hazards for the city of Peja will be conducted in subsequent study phases.

7. Conclusions

Based on the flood hazard characterization for optimal protection planning in the historic city of Peja, the following conclusions were drawn:

- Efficient and optimal protection for urban areas exposed to natural hazards requires implementing the derived results in three planning phases: (1) the pre-planning CND, (2) the incorporation of protective measures during the improved planning process, and (3) the post-planning application of advanced structural protective design.
- The flood hazard characterization for the selected historic city of Peja exemplified advanced concepts for the phenomenological CND. The hydrologic analysis identified the basic flood hazard sources, whereas the hydraulic analysis delineated the flood hazard extent for different return periods.
- The completed hydrologic study, utilizing advanced HEC-HMS software, generated significant results. This hydraulic study provided realistic estimates of the characteristics and magnitudes of expected flood waves in the Bistrica River from basin storm runoff.
- A complementary hydraulic investigation was conducted using the refined two-dimensional flood model in advanced HEC-RAS analysis software. Considering the estimated impacts of 24-h precipitation events for various return periods, the study evaluated the extent and magnitude of flooding in the modeled Peja City area and identified areas potentially endangered by flood hazards.
- Considering their impacts throughout urban planning is crucial to avoid the potential destructive consequences of natural disasters. Implementing the UUDP method established the conditions required for developing optimal protection solutions for urban areas.
- The UUDP method integrates four major planning layers, including the newly introduced ZPL with relevant sublayers that depict the phenomenological CND. The importance of pre-planning characterization was demonstrated by flood disaster analysis conducted for the historic city of Peja.
- Furthermore, the UZML served a planning platform enabling realistic consideration of natural multi-hazards, including floods, earthquakes, soil instabilities, landslides and others, during advanced urban disaster prevention via upgraded urban development plans.

8. Declarations

8.1. Author Contributions

Conceptualization, D.R., I.G., V.H., D.I., J.R., and L.M.; methodology, I.G., D.R., V.H., D.I., L.M., and J.R.; software, V.H. and D.I.; validation, D.R., I.G., D.I., J.R., and V.H.; formal analysis, V.H. and D.I.; investigation, V.H., D.I., J.R., and L.M.; resources, V.H., D.I., D.R., and L.M.; data curation, V.H., D.R., and D.I.; writing—original draft preparation, D.R., V.H., D.I., J.R., and L.M.; writing—review and editing, V.H., L.M., J.R., and D.R.; visualization, V.H., L.M., and J.R.; supervision, D.R. and I.G.; project administration, V.H.; funding acquisition, D.R., V.H., and J.R. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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