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ASSESSING FLASH FLOOD CONTROL USING UNIVERSAL RISK MATRIX

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Abstract: Flash floods have a significant impact on both natural and economic environments, making it essential to analyze their causes and develop mitigation strategies. This study evaluated flood mitigation in a selected area using a risk map created through the application of a risk assessment framework and the Analytic Hierarchy Process method, while risk levels were assessed with the Universal Matrix of Risk Analysis. No similar mapping approach and risk assessment had been used in the region before. The resulting map identified the Cseres Valley as a high-risk area. Analysis showed that implementing the proposed mitigation measures could reduce the negative effects of flash floods by about 65%, demonstrating the potential effectiveness of targeted flood protection strategies.

Keywords*: flash flood, Analytic Hierarchy Process, Universal Matrix of Risk Analysis, risk assessment*

1. INTRODUCTION

From the early 2000s to the present, countries worldwide have increasingly been affected by extreme weather events due to climate change. Both droughts, leading to water scarcity, and flash floods, resulting in excessive water accumulation, pose significant challenges to the sustainability of national economies. While drought management is typically handled by the state and can be addressed through water management tools and regulations, the sudden surges of flash floods often lack sufficient mapping methodologies and effective flood protection solutions. Moreover, no established risk assessment methodology applicable to these defense strategies has been developed. Flash floods are created by extreme storms, mostly caused by Mesoscale Convective System (MCS) in watersheds where watercourses may not necessarily exist or where measurable water flow data is missing. Consequently, due to the lack of watershed characteristics and precipitation measurements, considerable technical (engineering, statistical) uncertainty arises when determining the parameters necessary to study this phenomenon. The most significant damage caused by these flood waves occurs in confluence areas, typically in valley-bottom settlements and streambeds. In Hungary, protection against flash flood waves remains unresolved. Legally, these events are classified as *local water damage issue*, meaning that local municipalities are responsible for flood protection (Veres et al., 2021), however, technical assistance can be requested from the Water Management Authority and related agencies (Disaster Management, Civil Protection). These flash floods develop extremely rapidly (within six hours), unlike traditional river floods (such as those on the Sajó, Hernád, and Tisza rivers), where the lead time for preparation is typically 48-72 hours, depending on the forecast. This limited lead time is often insufficient for response agencies to prepare adequately (Szlávik and Kling, 2007; Pappenberger et al., 2006). Due to the lack of preparation time, various preventive measures need to be implemented during so-called peacetime, when no floods are expected (Kaliczka, 1998; Balatonyi, 2022; Szendrei, 2020; Dobai and Dobos, 2022). In addition to introducing new defense methods, local leaders and decision-makers face significant financial challenges in restoring flood-related damage. Furthermore, due to the periodic recurrence of flood events, newly repaired infrastructure (e.g., bridges, roads) may be damaged again by subsequent flood waves, leading to continuous and cumulative costs for municipalities. Therefore, the development of a comprehensive methodology for flash flood risk assessment is essential. Case studies on large watercourses and their catchments have contributed to the development of methodologies and decision-support systems (Zeleňáková, 2009; Zeleňáková et al., 2018; Vágó et al., 2019; Abdel and Islam, 2016; Blistánová et al., 2016). However, a standardized mapping methodology for small catchments has not yet been developed for Northern Hungary. Additionally, the impacts of flood defense measures (e.g., wooden structures, wickerwork, log barriers) and the implementation of flood defense systems have not yet been systematically evaluated. Therefore, the aim of this study is to provide a solution to this problem and assess the impact of potential hydraulic engineering interventions. The development of a flash flood susceptibility mapping and assessment methodology requires the establishment of an integrated GIS database that incorporates region-specific typological characteristics, along with the implementation of a flash flood-related risk assessment system. Since, as discussed earlier, these background databases are not available, the objective of this research is to develop a unique, practical mapping methodology applicable to flood defense and to assess green or brown engineering solutions and their risk evaluation for flood mitigation. A suitable method for mapping is the widely used Analytic Hierarchy Process (AHP), while the Universal Matrix of Risk Analysis (UMRA) is considered appropriate for validation and risk assessment. UMRA specializes in environmental impact assessments and has been proven useful for evaluating flood risks and protection methods in large catchments (Kubečka et al., 2014; Zeleňáková et al., 2017). The application of UMRA is based on the principle that similar risk factors (e.g., settlements, pollution sources) can be identified in small catchment areas as in large ones. However, significantly fewer stressors were considered in the context of flash floods. These methods can provide a reliable assessment for both database creation and risk evaluation.

2. Materials and Methods

2.1. Study area

The study area, the Cseres Valley, is located within the watershed of the Harica Stream Basin, near the settlement of Kondó. Geologically, the area lies within the East-Borsod Coal Basin (Fig. 1). This basin consists of alternating layers of Neogene marine and lacustrine sediments of various ages, interspersed with Miocene pyroclastic deposits, often exhibiting erosional discordance (Kozák and Püspöki, 1995, 1998; Kozák et al., 1998; Harangi, 2001). Most of the Quaternary sediments have formed because of weathering from these older rock formations. Due to sequential tectonic processes from the Miocene to the Quaternary period, the area has been fragmented into a mosaic-like structure (Kozák and Püspöki, 1995; Pelikán, 2002). These geological and structural characteristics fundamentally shape the area's topography (Sütő, 2001).

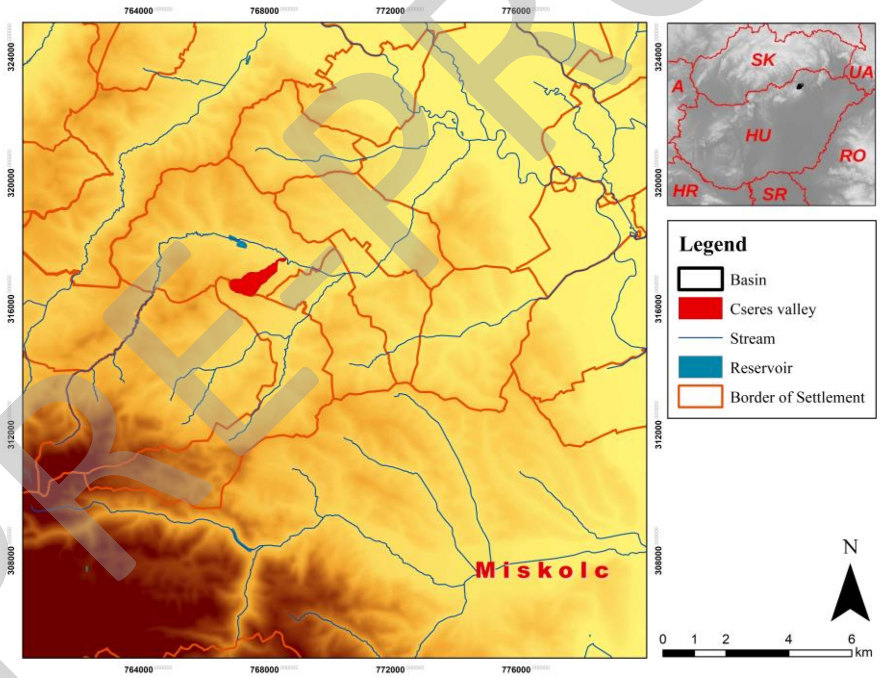

Figure 1
Location of the study area

The entire Cseres Valley belongs to the Egyházasgerge’s Formation (eMK), where gravel conglomerate is found at greater depths, overlaid by sand, sandstone, and finer silt and clay near the surface (Gyalog, 1996). The valley itself is V-shaped, spanning 1.6 km in length and 665 m in width, gradually narrowing at the valley bottom, with a watershed area of 0.76 km². The valley is incised into the terrain to depths of 4–5 m in certain locations. Several erosional gullies of varying development levels, primarily caused by rainfall, accompany the valley. Since 2010, these features have also been shaped by periodic flash floods occurring from spring to autumn (Vágó, 2012). The morphometric characteristics of the catchment (Table 1) indicate that, due to the narrowing of the basin towards the outlet, the flash flood wave exhibits an asymmetrical shape, with a gradual rise followed by a rapid recession. This pattern emerges because sudden, high-intensity precipitation events generate large runoff volumes that reach the outflow point early in the event (Galgóczy, 2004).

Table 1

Morphometric characteristics of the Cseres Valley catchment

Catchment area (ca) name	**Cseres Valley, Hungary**		
Area (km²)	**Water course length (km)**	**Max. length of ca. (km)**	**Max. width of ca. (km)**
0.76	1.80	1.90	0.60
Perimeter of ca. (km)	**Length-to-width ratio (Y)**	**Horton factor- (Rf)**	**Circularity of ca. (Rc)**
4.97	3.17	0.21	0.39
Gravelius factor (K)	**Channel gradient (%)**	**Manning's -n**	**Drainage density (km/km²)**
1.61	7.17	0.035	2.37

The area falls within the forest soil zone. The soils identified so far being luvisols (Alfisol), stagnic luvisols (Epiaqualfs), and gleysols (Aqualfs). Their common characteristic is their high compactness attributed to land use. Most of the valley has been used primarily as pasture or orchards, with smaller forests found on steeper slopes and in the valleys. Cultivated fields and meadows are located on more suitable areas of the slopes, where the signs of machinery work (machine tracks) are evident and are also reflected in the structure of the soils. Archive maps of the area suggest that land use has remained unchanged for several centuries. The distribution of soil types from higher elevations to lower ones is as follows: strongly eroded brown forest soil with levisage near the hilltops and watershed ridges, predominantly anthropogenic colluvial soil in the middle of the slope due to its local position, eroded and heavily compacted Luvisol on the north- and south-facing slopes. At the valley bottom, Gleysoils repeatedly buried by cyclical flash floods are found, followed by deposited meadow soil rich in anthropogenic materials at the edge of the settlement zone (Dobai and Dobos, 2023). According to climate classifications projected for 2050, the study area is categorized as moderately warm and moderately dry. The annual average temperature ranges from 8.8°C to 9.3°C. During the hottest summer days, the average maximum temperature reaches 31–33°C, whereas on the coldest winter days, the average minimum temperature drops to approximately -17°C. Annual precipitation amounts to 550–600 mm. The prevailing wind directions are northwest (NW) and southeast (SE), in alignment with the terrain, with an average wind speed of 2.5 m/s (Bihari et al., 2018).

2.2. Presentation of the precipitation caused by extreme precipitation in the study area

Between 2010 and 2019 (with the exception of 2017) precipitation levels capable of causing flash floods were recorded annually in the sample area and its surrounding region (Table 2). The data were obtained from the Hungarian Meteorological Service database and the annual hydrometeorological reports issued by the General Directorate of Water Management of Hungary, as well as records included in the Vis Major protocols of the Hungarian National Bank. Although the table does not encompass all precipitation data (e.g., in 2010, a total of 177.7 mm of precipitation was recorded between May 15 and July 25), it effectively represents the precipitation amounts and characteristic periods impacting the region. The majority of damages were observed in privately owned properties and built infrastructure (e.g., public roads, bridges), with total damages estimated to exceed 50 million HUF (BAZ 2020, Veres, 2021).

Table 2

24h precipitation totals recorded by GDWM's gauge network

Station	Homrogd			
Time of measurment	10.08.2018	13.08.2019	26.06.2020	23.06.2019
Precipitation (mm)	87,0	70	65	87,0
Station	**Jávorkút**			
Time of measurment	19.04.2017	10.08.2018	15.05.2010	23.06.2019
Precipitation (mm)	97,3	76,4	75	11
Station	**Miskolc-Sajópart**			
Time of measurment	29.07.2011	31.03.2022	22.06.2024	23.06.2019
Precipitation (mm)	52	46,9	46,7	28,3
Station	**Múcsony**			
Time of measurment	28.07.2016	13.08. 2019	19.08. 2015	23.06.2019
Precipitation (mm)	90,8	70	60,8	78,3
Station (based on Vis M. report)	**Varbó**			
Time of measurment				23.06.2019
Precipitation (mm)				94

Based on the Flood Calculation Guide issued by the General Directorate of Water Management of Hungary, the flood discharges calculated for the study area at the mouth of Harica-Nyögő Creek, with a specific discharge of Q_5% m³/s km², are as follows: Q_1% = 71.0 m³/s, Q_3% = 54.6 m³/s, Q_{10}% = 38.2 m³/s (Koris, 2021). Although the general water yield data does not justify the construction in the Harica catchment area, which includes the Cseres Valley, a water reservoir with a surface area of 13.6 hectares and a storage capacity of 410,000 m³ was constructed to protect the settlement of Kondó following the flood events caused by the precipitation events of 2010. Although the stormwater reservoir fulfills its purpose and, in accordance with its engineering design, retains and channels the flood waves caused by runoff precipitation, the settlement has continued to experience flooding from smaller surrounding catchments (e.g., the Cseres Valley, Varrom-stream) even after its construction. The causative link, however, has not been conclusively demonstrated, this conclusion could only be drawn based on observations derived from flood protection practices. The solution was provided by a basic mapping methodology (Dobai and Dobos, 2022), which is further developed in current research.

2.3. Presentation of the AHP-based weighting for risk mapping

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty, is a decision-making methodology designed for the structured and systematic analysis of complex problems. Within this framework, problems are represented in a hierarchical structure, with the decision goal positioned at the top level, followed by criteria and alternatives. A central feature of the method is pairwise comparison, whereby criteria and alternatives are evaluated along a predefined scale to express their relative importance (Choudhury et al., 2022; Costache et al., 2020). The evaluation process generates a comparison matrix, which is utilized for weight calculation and priority determination. Through its mathematical computations, the AHP method enables the objective ranking of alternatives. Additionally, a consistency ratio (CR) mechanism is incorporated to ensure the internal coherence of the pairwise comparisons (Eroglu and Meral, 2021). For the weighting of map classes, the scale proposed by Saaty was used. AHP-derived weights were calculated for each class in the flash flood susceptibility mapping process, and these weights were subsequently applied to classify the corresponding raster datasets.

2.4. Presentation of the flash flood risk mapping methodology

As the first step of the research, the input data required for mapping and the weights assigned to the classes of the risk map were established since no flash flood susceptibility or risk map had been previously developed for the region. The aim was to produce a minimal yet informative, high-resolution map suitable for practical defense applications. Terrain-derived surface indices (e.g., DEM, channel distance, curvature, aspect) and indices derived from remote sensing (e.g., satellite images, NDWI, NDVI) were utilized, as they are fundamental in risk mapping methodologies (Youssef et al., 2011). However, inclusion of excessive and closely correlated variables (redundant data) was avoided to prevent overburdening the model and reducing predictive performance. Therefore, only parameters contributing novel information to the map were retained. This optimization of input data has been widely documented in the literature (Bui et al., 2019; Youssef and Hegab, 2019; Ngo et al., 2018; Khosravi et al., 2018; Khosravi et al., 2016; Youssef et al., 2016). Layers such as hillshade, which do not provide additional information, and those causing redundancy, such as Stream Power Index (SPI) and Sediment Transport Index (STI) (both based on slope and flow accumulation), were excluded. The aspect layer was also omitted due to the lack of meteorological forecasting systems capable of determining prevailing storm directions. Radar images from the Hungarian Meteorological Service indicated that MCS storm fronts approached the study area from the south on 23.06.2019, while on 13.08.2019, the front arrived from the east-northeast. Despite these observations, no characteristic storm direction or typical topographical exposure could be determined for this study. Thus, only eight rasters were included: slope, derived from a 5m-resolution DEM; classified Normalized Difference Vegetation Index NDVI (Dalezios et al., 2001); classified land use/landcover (LULC) layers, generated using Sentinel-2B satellite bands B2 (blue), B3 (green), B4 (red), B8 (NIR), and resampled B5 (VNIR) at 10m resolution; average soil thickness from the AGROTOPO hungarian soil database, Topographic Wetness Index (TWI), slope-weighted flow length (SWFL); time of concentration (Costache 2014), also a texture layer obtained from the E-Soter digital soil mapping methodology with 430 m spatial resolution, covering the CEU area. The E-Soter system, which integrates remote sensing morphological classification and classifies soils according to the WRB system (Dobos et al., 2007), was utilized. Flash floods were found to develop under precipitation intensities above 30 mm/h, depending on initial surface conditions, particularly soil moisture (Luong et al., 2021). During the mapping process, weights were assigned to each class using the Analytic Hierarchy Process (AHP) method. The weights were applied to each raster layer using the ArcMap-Lookup function of the Spatial Analyst toolset, which had been previously prepared and divided into appropriate categories. Then, the weighted values of the various factors were summed using the Spatial Analyst - Raster Calculator to create the weighted index of the hazard map in ArcMap. To homogenize the spatial units, the majority function of the Focal Statistics tool was employed, merging values based on neighboring cells to ensure continuity in map representation and spatial coherence across the calculated zones.

2.5. Assessment of Universal Matrix of Risk Analysis for the proposed flood protection

The construction of the flood protection facility (dam, sheet pile walls) discussed in the introduction requires an Environmental Impact Assessment (EIA). The EIA generally serves as a tool to assist authorities in making decisions regarding project approval and determining the appropriate conditions. As a decision-making instrument, the EIA aims to identify and evaluate the expected environmental consequences of certain planned development activities, with the aim of facilitating informed decision-making and ensuring thorough environmental management (Zeleňáková and Zvijakova, 2011). Among the most appropriate methodologies for such assessments is the Universal Matrix of Risk Analysis (UMRA), a logical-numerical expert method that utilizes a matrix for risk evaluation, assessing the interaction between hazards and vulnerable segments (Zeleňáková et al., 2017). UMRA provides a comprehensive methodology for evaluating risks within environmental and hydrological systems. The framework is structured around three primary components—Probability Index (Pi), Consequence Index (Ci), and Risk Index (Ri)—which collectively enable a systematic quantification and visualization of risk levels. The fundamental principle of the approach is to calculate the Risk Index, which represents the estimated level of risk posed to the environment by the proposed activity (Zeleňáková et al., 2017).

The application of this methodology in the environmental impact assessment of flood mitigation measures enables the evaluation of construction interventions, facilitating the selection of the optimal option during the permitting process. For the calculation of UMRA, the 'Pi' probability (ranging from 0.25 to 1) and the 'Ci' consequence (ranging from 0.25 to 1) are required, which are then incorporated into the calculation of the individual risk 'Ri' for each identified stressor effect on environmental components. A probability indicator and criteria at various levels are proposed for this purpose. Probability is commonly expressed on a scale from 0 to 1, and this scale was applied across four categories (from 0.25 to 1). The calculation of individual risk, denoted as Ri, which is necessary for impact assessment, is conducted using the following equation

$$\mathrm{Ri} = \mathrm{Pi} \times \mathrm{Ci} \tag{1}$$

where

R_i - individual risk associated with the impact of each stressor on environmental components;

P_i - probability of occurrence;

C_i - consequences.

The probability (Pi) and consequence (Ci) of each impact are evaluated and combined to determine the individual risk posed by each stressor to environmental components. Individual risks (Ri) were calculated for all nine identified stressor impacts on environmental components. Risk levels are categorized into four semi-qualitative levels based on the universal matrix of risk analysis: negligible (Ri = 0.0625–0.25); low (Ri = 0.25–0.50); medium (Ri = 0.50–0.75); and high (Ri = 0.75–1.00). The resulting risk index (IR) as the sum of all individual stressor risks (Zeleňáková et al., 2017). The summation in Equation (2) is taken over all stressor impacts (i = 1…n), while j denotes the alternative under evaluation.

$$\mathrm{IR}_j = \sum_{\{i=1\}}^{\{n\}} (\mathrm{P_i} \times \mathrm{C_i}) \tag{2}$$

where

IR - risk index;

P - probability;

C - consequence;

j - rank of the alternative;

n - the number of stressor impacts on environmental components (n = 1… 70);

i - rank of probability and consequence.

In this study, a modified version of the UMRA methodology, adapted to small catchments and flash-flood processes, is applied for the general risk analysis. The modification consists of using a reduced set of flash-flood-relevant UMRA stressors with proportionally lower weights and calculating their effects and associated risks at finer resolution, thereby preserving the aggregated impact on overall risk while better reflecting the rapid and localized nature of flash-flood phenomena. The primary concern associated with flash-flood events is that, although they occur over limited spatial extents, they can generate severe impacts and may result in damage comparable to that caused by riverine floods (e.g., destruction of bridges, damage to wastewater treatment facilities, and further spatial socio-economic impacts).

3. RESULTS

3.1. Result of AHP method

The present study was prompted by practical experiences in flash flood protection, assuming a rainfall intensity above 30 mm/h, which is indicative of the occurrence of flash floods (Luong et al., 2021). Although the detailed analysis was carried out on a 1 km² sample catchment, the risk map was extended to the wider catchments of the Sajó, Bódva and Hernád rivers in order to provide the regional hydrological context of the study area. These larger catchments represent the upstream and downstream environments that influence both the boundary conditions and the potential propagation of flash-flood processes. By including the surrounding river catchments, the applicability of the proposed methodology could also be demonstrated at a broader spatial scale, beyond the small pilot area. The analysis conducted using variable-sized moving windows, together with the assessment of the catchments, is of particular importance, as our previous research demonstrated that six sub-catchments are situated around the settlement of Kondó (Dobai and Dobos, 2022). These catchments are located downstream of the flood-control detention reservoir and therefore constitute potential sources of flash-flood hazard. However, only three of them have critical surface-runoff characteristics. To enable a comprehensive hazard assessment and to accurately define the required input parameters, a detailed analysis encompassing nearly the entire Harica catchment is required. This example further demonstrates the crucial importance of high-spatial-resolution geospatial datasets for both risk mapping and the delineation of risk classes. Adequate spatial detail is essential to capture the heterogeneity of catchment characteristics, to represent local-scale hydrological responses accurately, and ultimately to produce reliable and operationally meaningful hazard assessments. The input raster layers and their flood risk hazard level (Table 3) and AHP values used for weighting were as follows (Table 4).

Table 3

Input rasters for flash flood mapping

Group name	Category (Qty)	Category range	Value range	Flood hazard risk level ranges
Slope (%)	5	min. <5% max. >25%	1-5	very low - very high /karst terrain
LULC	6	min. water max. concrete	0-5	none - very high /karst terrain
NDVI	10	min. water max. concrete	0-5	none - very high /karst terrain
Soil depth (cm)	5	min. >20 cm max. > 100 cm	1-5	none - very high /karst terrain
Texture	6	min. water max. clay	0-5	none - high
TWI	5	min. 0.9 max> 20	1-5	very low - very high /karst terrain
TCI	3	min. < 1h max. > 3h	0,1,5	none-very high/karst terrain
SWFL	3	min.< 1000m	0,1,5	none-very high/karst terrain

Table 4

Result of AHP weights for Risk Map

Groups	Slope	NDVI	LULC	Soil depth	Texture	TWI	TCI	SW-FL
AHP weigths	0.36	0.18	0.08	0.035	0.030	0.19	0.09	0.03
Risk matrix statistics	**Consist. Ratio (CR)**	**Consist. Index (CI)**	**λ max**					
	0.022	0.028	8.1					

According to the AHP method, the CR value is 0.02, indicating that the matrix is consistent (Eroglu and Meral, 2021). The individual risk classes were multiplied by the AHP weights, and new classes were generated based on these weights. Finally, they were categorized into four flash flood susceptibility groups (no risk, low risk, medium risk, high risk/karst terrain).

The best results for the distribution of the classes were achieved using the geometric interval and the natural break (Jenks) methods. The Jenks natural breaks classification was particularly suitable because it adapts to the inherent variability of the dataset by identifying statistically meaningful discontinuities in the value distribution (Gui et al., 2025). This allowed the susceptibility classes to follow the actual clustering and skewness present in the flash-flood–related parameters, resulting in more realistic spatial delineation compared to uniform or quantile-based schemes. To further refine the map, manual threshold adjustments were also applied. The resulting map is shown in Figure 2.

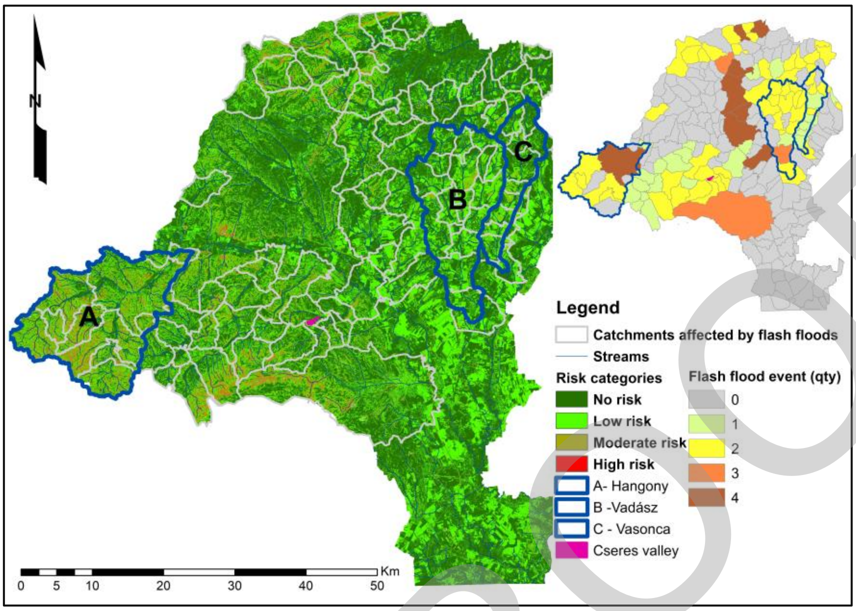

Figure 2

Results of risk mapping and flash flood events (2010-2024)

The results indirectly indicate the geological structure, with the most characteristic areas being the Lower Triassic and Permian limestone (gT1, avT1; nP2) in the Bükk Mountains, and the Middle-Upper Triassic limestone and dolomite (wT2-3m, wT2-3d) formations along the Bódva River (Gyalog, 1996). In contrast, the northern and eastern sections of the risk map (Fig. 2) provide an adequate explanation for the occurrence of flash floods within the Hangony-Hódos, Vadász, and Vasonca catchments. For each category, recommended defense methods can be assigned.

In the No Risk and Low Risk areas, it is advisable to review the affected watershed, potentially examining historical records and archival data to verify any past damage caused by major storms or flash floods. In general, for these areas, the maintenance of municipal rainwater drainage systems and local infrastructure (such as road culverts and streambed regulation) is sufficient. It is worth noting, however, that even on small watershed scales (<100 km²), no areas fall exclusively into this category. Additionally, for agricultural lands, appropriate agrotechnology and adherence to plowing and soil cultivation boundaries are recommended to mitigate risks related to erosion and improve runoff conditions, as these factors pose significant risks to the watershed (Dobai and Dobos, 2023). In the Medium Risk category, it is advisable to construct small dams, weirs, and other hillside structures made from local materials, either at the target area or at runoff points, while considering the potential for water retention in the landscape. These structures, which may include permanent installations, could require water management permits (Balatonyi, 2022; Sušnik et al., 2022). For areas classified as High Risk, Very High

Risk, or Karst Terrain, detailed surveys, risk assessments, and environmental impact studies are necessary. Water defense solutions in these areas must align with these evaluations and may also incorporate the measures suggested for the previous categories. Additionally, robust, low-maintenance, and cost-effective solutions should be identified. Such measures may include sills, sheet piles, or constructions made of building stones placed in Gabion mesh, designed to increase surface accumulation time and slow runoff. Among agrotechnological practices, the establishment of terraced cultivation is a viable option (Alessandro et al., 2002). Municipal defences should also be addressed. Due to the lack of preparation time, traditional labour-intensive methods, such as sandbag defences, are impractical. Instead, the construction of modern, temporary barriers made of plastic materials that can be easily and quickly deployed in urban areas is recommended. The hazard categories of the Cseres Valley and its surroundings, which constitute the study area, have been identified in previous studies: a total of six sub-catchments are located downstream of the aforementioned flood reservoir, three of which exhibit critical surface runoff characteristics based on runoff condition assessments (Dobai and Dobos, 2022). The results of earlier analyses have been further refined by the current mapping: the 'no risk' and 'low risk' categories together constitute 47.12% (361.45 m^2) of the total watershed area, while the 'medium risk' category accounts for 50.88% (390.32 m^2), the 'high risk' category for 1.92% (14.72 m^2), and the 'very high risk' category for 0.08% (0.625 m^2). The predominance of medium-risk areas, combined with the proximity of the valley's discharge point to the settlement, explains the high level of vulnerability to flash floods in the region. Within the catchment, the most optimal solution for flash flood mitigation was found to be the multi-stage installation of 116 Larssen-type sheet piles, measuring 8.00 x 6.00 x 0.6 meters each, with a total length of 70 meters distributed across three locations (Dobai and Dobos, 2022). Following chapters, the risk-reducing effects of sheet pile walls installed in the Cseres Valley will be evaluated using the UMRA method.

3.2. Results of UMRA

Understanding flood-related risks requires a systematic assessment of the environmental, social, and landscape components that may be affected during an extreme hydrological event. Within this framework, the Cseres Valley serves as a representative case study, where the interaction between natural processes and human activities creates a complex risk environment. In this context, individual risk values (Ri) were calculated based on documented damage reports and existing flood-mitigation practices. These risks were evaluated through a set of environmental stressors identified in the literature (Zeleňáková et al., 2017). Accordingly, nine primary stress factors were defined (Table 5): population (1), water conditions (2), soil (3), flora, fauna, and their habitats (4), landscape structure (5), protected areas and their buffer zones (6), urban areas and land use (7), the territorial system of ecological stability (TSES) (8), and cultural and historical heritage, including intangible cultural values (9). Two scenarios were considered for each stressor: ver.

1, representing ineffective flood protection, and ver. 2, representing effective flood protection.

Table 5

Comparative assessment of flood risk for scenarios

The impact of the stressor on individual components	**Determining probabilities (Pi) ver 1. / ver 2.** (ver. 1: ineffective flood protection / ver. 2: effective flood protection)		**Determining consequences (Ci) ver 1. / ver 2.**		**Calculating risk (Ri) ver 1. / ver 2.**	
Impact on 1.	local flood hazard risk – medium		health consequences of flooding			
	0,25	0,25	0,75	0,75	0,19	0,19
Impact on 2.	high-level flood alerts (qty/ per year)		water discharge Q (m³/s) – maximum Q			
	0,10	0,10	1	1	0,1	0,1
Impact on 3.	condition of flood-protection structures		soil permeability			
	1	0,25	0,25	0,18	0,25	0,047
Impact on 4.	local flood hazard risk – medium		vulnerability of fauna, flora, and their habitats (–)			
	0,25	0,25	0,125	0,125	0,0313	0,0313
Impact on 5.	local flood hazard risk – medium		changes in landscape structure			
	0,25	0,25	0,25	0,25	0,063	0,063
Impact on 6.	local flood hazard risk – medium		(ver. 1) / (ver. 2)		extent of impacts outside the buffer zone	
	0,25	0,25	0,75	0	0,188	0
Impact on 7.	condition of flood-protection structures		impact on the local ecological stability system			
	0,75	0,25	0,13	0	0,09	0
Impact on 8.	local flood hazard risk – in urban areas		(ver. 1) / (ver. 2)		flooded area: 1–50 km²	
	0,5	0,5	0,5	0	0,25	0
Impact on 9.	local flood hazard risk – medium		quantity of affected values			
	0,25	0,25	0,25	0,25	0,06	0,06
Version 1. - without protection structure	∑ PI = 3,60		∑ CI= 4,01		∑ IR= 1,22	
Version 2. – with protection structure	∑ PI = 2,35		∑ CI= 2,56		∑ IR= 0,49	

Two distinct scenarios were analyzed: the current state, which lacks flood protection measures and has a baseline risk value of 1.22, and the scenario where a sheet pile wall system was installed, resulting in a risk value of 0.49 (it is 59,8% decrease), indicating a reduction to below the risk threshold. The validation of these results is performed by comparing them with previously occurred flood disasters. The Hungarian National Bank is legally mandated to prepare so-called vis Major reports for insurance companies and municipal leadership related to flash floods and other events (e.g., windstorm, earthquake). If the damage recorded in past events shows a similar pattern to the calculated Ri values, the modeled effect of the proposed measures (e.g., a sheet pile wall) can be considered reliable. That is, if the model predicts that the flood protection reduces the risk to 0.49, and the historical event data indicates that the Ri without effective protection would have been approximately 1.22, the consistency validates the accuracy of the estimation. Thus, the reports allow for the quantification of the direction of the flash flood wave and the extent of damage, which aligns with the findings obtained during the analysis.

Flash floods can be summarized in terms of probability and impact (Pi-Ci) for risk assessment as follows. The probability of the phenomenon has increased frequency in the last two decades, with an expected value ranging from 0.50 to 0.70, and, in the event of occurrence, it is associated with extreme water discharge. However, regardless of the probability of occurrence, the level of damage is consistently significant (ranging between 0.75 and 1), especially when the storm occurs on saturated or impermeable soil. Real storm events indicate that the greatest destruction is caused when MCR zones experience a return period of 12-24 hours (e.g., summer of 2010, 2019). Since the phenomenon primarily occurs from early to late summer, land cover — regardless of storm frequency — has a significant impact on surface runoff retention. Practical flood protection experience has shown that the flood wave predominantly flows along concentrated drainage networks (such as dirt roads, pedestrian paths, and roadways) in addition to streambed and watercourses, therefore, complex landscapes must be considered. Thus, with the construction of the flood protection system, a low-risk level (0.49) will be achieved for the valley and the surrounding natural and socio-economic landscapes. The implementation of the flood protection system will result in the elimination or significant reduction of the vulnerability of stressors, such as buffer zones, TSES, and man-made infrastructure (bridges, roads, etc.). The impact of the phenomenon could be reduced by the proportion of arable land; however, due to eroded surfaces, improper agrotechnological practices, and land management, agricultural areas (on different genetic soil types) are typically compacted and severely eroded. Similarly, the degree of forest cover could exert an effect, but the developmental stage of the forest associations and their age significantly affect surface infiltration. Collectively, these factors contribute to the determination of both preventive and reactive mitigation measures (such as risk mapping and natural embankments made of local materials), which can potentially reduce flood risk levels (Sušnik et al., 2022; Balatonyi, 2022).

4. DISCUSSION AND CONCLUSIONS

Regarding the mapping methodology, the interpretation of the study results is limited to Hungarian territories, as local risk assessment maps lack a methodological framework that incorporates such diverse input data. An exception is the flood sensitivity mapping methodology proposed by Sarkadi et al. (2022), which, although targeting a national scale, also incorporates finer spatial resolution and is based on equally weighted conditional factors. A comparison of the two methodologies was conducted, and the general watershed-based flash flood susceptibility index (FFSI_ws) and the settlement-level index (FFSI_smax), based on the maximum raster value, showed similarity to the present method. These results suggest that, despite differences in the spatial resolution of the input data, the maps may still provide a suitable basis for the development of future risk mapping methodologies (Dobai and Dobos, 2025). At the level of international methodologies, the input data's AHP weights fall within a similar range (Grozavu et al., 2017; Kanani-Sadat et al., 2019). However, this research focuses on eight input variables rather than the average of 10–12, primarily concentrating on surface runoff to avoid redundant data. In this study, the detailed classification of NDVI and TCI layers proved to be particularly useful. The strengths of the methodology include improved spatial resolution, interpretability at the small catchment level, and the first-time use of a region-specific digital soil map in mapping rather than relying solely on general national soil databases. The methodology’s weakness is that it requires further development. One potential solution is to analyze NDVI changes during the March–October period and only identify areas with stable floodwave-reducing characteristics as those where high NDVI values change minimally. Another potential improvement is comparing forestry databases with NDVI values, as forest types and planting ages may vary, making it inappropriate to treat specific areas as uniform forests (Korchagina et al., 2020). These refinements would require significant storage capacity and dedicated research. However, once addressed, they could provide a robust foundation for AI methodologies (e.g., neural networks, Random Forest). Despite its drawbacks, the methodology can significantly support flood defense agencies and municipalities, complemented by research findings specialized in calculating flash flood discharge (Dobai et al., 2024).

Municipalities, depending on the affected settlements, are responsible for flash-flood protection, as technical defense measures receive only partial support from the relevant authorities (e.g., water directorate, police, disaster management agencies, etc). Given economic sustainability concerns and the increasing frequency of extreme weather events, an innovative shift in perspective is necessary. This study presents an interdisciplinary methodology to mitigate the harmful impacts of flash floods in basin catchments. Using high-resolution spatial data, derived DEM indices, and statistical weighting methods (AHP), a reliable mapping database can be developed to identify flash flood hazards. The UMRA methodology demonstrates that its matrix properties enable effective application, particularly as stress factors (e.g., municipal waste storage, wastewater treatment plants, and critical infrastructure) are also present in smaller watersheds. The method generates mapping layers, assesses environmental risks, identifies locations, recommends defense strategies, and evaluates risks associated with proposed mitigation measures. Based on previous damage assessments (approx. HUF 50 million), mitigation costs could be covered for a fraction of the corresponding insurance payouts (approx. 8–10 million HUF) (Veres et al., 2021). As a result, this approach can significantly reduce municipal and national budgetary expenditures while positively impacting the natural systems across the region.

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