PLUVIAL FLOOD INUNDATION MODELING OF EXTREME RAINFALL USING THE RAIN-ON-GRID METHOD IN MIKE+ HYDRAULIC MODEL: A CASE STUDY

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Abstract
This study aimed at prediction of pluvial flow depth and velocity using the rain-on-grid method in MIKE+ hydraulic model. The studied domain was represented by an upstream part of the Gidra River basin (1.51 km^2), where the Píla municipality (western Slovakia) is located. We simulated an extreme 58-minute rainfall event from 7 June 2011, which hit also wider surrounding area and caused a destructive flash flood on the Gidra River. The time series of rainfall intensities were recorded at the nearby Častá rainfall station. Based on the results, the largest flood extent was recorded after 32 minutes of rainfall, when 1.1 km^2 of the domain was represented by non-flood areas with flow depths <0.005 m. The flooded areas accounted for 0.41 km^2, out of which most of the flooded pixels belonged to the shallow flow depth intervals from 0.01 to 0.05 m (53.5%) and from 0.005 to 0.01 m (18.0%).

Keywords: *pluvial flooding, rain-on-grid method, extreme rainfall, hydraulic modeling*

INTRODUCTION

Pluvial flooding, caused by intense rainfall overwhelming natural and artificial drainage systems, has become an increasingly significant hazard in both urban and rural environments. Unlike fluvial flooding, which is associated with river overflow (Vojtek, 2023), pluvial floods originate directly from precipitation that exceeds infiltration capacity and surface drainage efficiency. These events are typically characterized by rapid onset, short duration, and high spatial variability, making them particularly difficult to predict and manage. In recent decades, the frequency and intensity of extreme rainfall events have increased in many regions, largely attributed to climate variability and change, thereby amplifying the risks associated with pluvial flooding (Rosenzweig et al., 2018; Bates et al., 2021). Small catchments are

especially vulnerable to pluvial flood events due to their limited storage capacity and rapid hydrological response. In such environments, even short-duration rainfall can generate significant surface runoff, leading to pluvial/flash flooding with potentially severe consequences for infrastructure, property, and human safety. The accurate prediction of flood extent, flow depth, and velocity in these settings is therefore essential for effective risk assessment, emergency planning, and the design of mitigation measures (Vojtek et al., 2023a, 2024).

Advances in physically-based modeling have significantly improved the ability to simulate complex surface runoff processes. Traditional hydrologic approaches often rely on simplified assumptions and lumped parameters, which may not adequately capture the spatial heterogeneity of rainfall and terrain. In contrast, two-dimensional (2D) hydraulic models provide a more detailed representation of overland flow by solving governing flow equations across a spatial grid (Yang et al., 2020). When combined with high-resolution topographic data and temporally detailed rainfall inputs, these models enable realistic simulation of flood dynamics at local scales (Teng et al., 2017; Vojtek and Vojteková, 2026a). One of the most effective approaches for modeling pluvial flooding within a 2D framework is the rain-on-grid method. This technique involves the direct application of rainfall onto each computational grid cell, allowing for explicit simulation of runoff generation, flow routing, and accumulation without the need for predefined inflow hydrographs (Montalvo et al., 2024). The rain-on-grid method is particularly advantageous for analyzing localized flood phenomena, as it accounts for land surface characteristics and micro-topography. As a result, it has become a widely used approach in recent flood modeling studies (Cea et al., 2025; Vojtek and Vojteková, 2026b).

The MIKE+ hydraulic modeling platform, developed by DHI, integrates advanced hydrologic and hydraulic capabilities, including the implementation of the rain-on-grid method. MIKE+ enables fully dynamic 2D simulations of surface flow, making it suitable for both urban drainage analysis and natural catchment studies. Its flexibility in handling complex terrain, combined with robust numerical solvers, allows for detailed investigation of flood processes under various scenarios, including extreme rainfall events (Xu et al., 2023). Extreme rainfall events provide valuable opportunities to evaluate the performance of hydraulic models under realistic and challenging conditions. These events are typically associated with convective storms, which produce high-intensity rainfall over short durations. The resulting runoff processes are highly nonlinear and influenced by multiple factors, including soil saturation, land use/land cover, terrain slope, and drainage network capacity. Capturing these processes accurately requires both high-quality input data and advanced modeling techniques (Mediero et al., 2022; Sañudo et al., 2025).

This study focuses on pluvial flood inundation modeling under extreme rainfall conditions using the rain-on-grid method implemented in MIKE+. The selected case study from the Gidra basin examines a small catchment characterized by rapid hydrological response and susceptibility to pluvial/flash flooding. Such case studies are critical for understanding how extreme precipitation translates into surface runoff and flood hazard at the local scale. In this context, the present study aims to simulate pluvial flooding using observed rainfall data and high-resolution terrain information to assess the spatial and temporal distribution of flood inundation. Particular attention is given to the prediction of flow depth and velocity, as these parameters are critical indicators of flood hazard. While flood extent provides a general overview of affected areas, depth and velocity determine the severity of impacts, including potential damage to infrastructure and risks to human safety. In light of ongoing climate change and increasing urbanization, the need for accurate and reliable flood modeling tools is critical (Di Salvo et al., 2017; Rözer et al., 2021; Preisser et al., 2022). The methods applied in this study can support decision-makers and planners in developing effective flood risk management strategies and enhancing resilience to extreme weather events. By improving our understanding of pluvial flood dynamics, studies such as this play a key role in mitigating the impacts of future flood events and protecting vulnerable communities.

DATA AND METHODS

Studied domain

The studied domain was represented by 1.51 km^2 buffer along the Gidra River (3.1 km), which is located in western Slovakia. The elevation in the studied domain ranges from 213 to 371 m a. s. l. (Figure 1). One of the most sever flash floods in Slovakia affected the studied river section on 7 June 2011, from which the extreme rainfall intensity was taken to our analysis (Vojtek et al., 2023b, 2025).

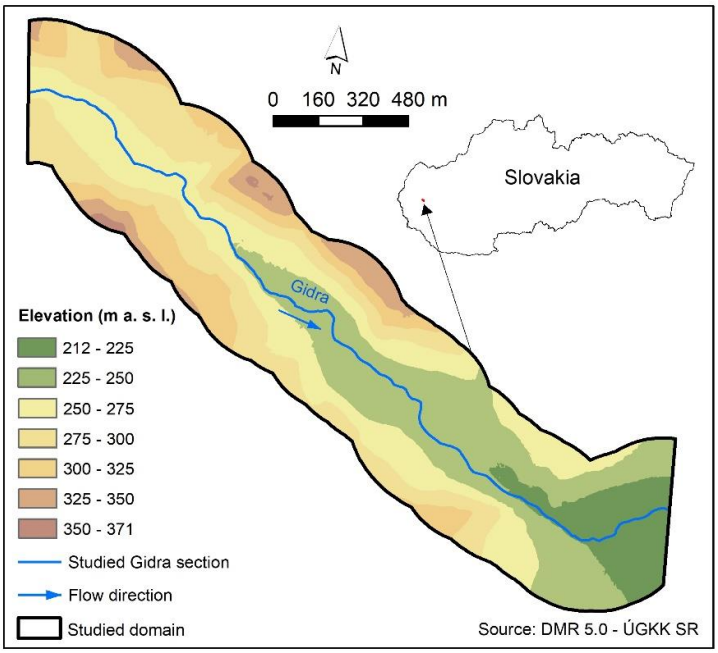


Figure 1. Studied domain and elevation ranges

Data

A variety of input datasets were required for the hydraulic modeling of pluvial flooding, most of which were processed within a GIS environment. A high-resolution digital elevation model (DEM) derived from airborne LiDAR data, with a spatial resolution of 1 m, was obtained from the Geodetic and Cartographic Institute. Land cover information for the study area was derived from the 2023 Basic Database for Geographic Information Systems (ZBGIS), also provided by the Geodetic and Cartographic Institute (Figure 2). Based on this dataset, initial hydraulic parameters were assigned to individual land cover classes. Manning's roughness coefficients (n) were allocated following the values proposed by Chow (1959), while infiltration losses were estimated according to the approach described by Rahmati et al. (2018). The assigned values of Manning's n and infiltration rates for each land cover class are summarized in Table 1. For the simulation of pluvial flooding, the rain-on-grid method was applied using the time-series from the extreme rainfall event on 7 June 2011, which is shown in Figure 3. The rainfall data were acquired from the Slovak Hydrometeorological Institute.

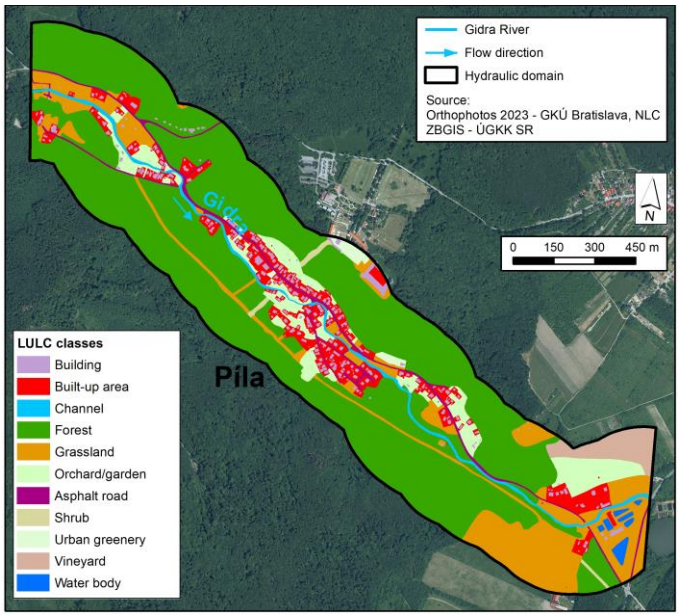


Figure 2. Land cover classes in the studied domain

Table 1. Manning´s n roughness values and the infiltration losses of land cover classes

Land cover class	Manning´s n values (s/m$^{1/3}$)	Infiltration rate (mm/h)
Building	1.00	1
Built-up area	0.04	5
Channel	0.04	0
Forest	0.15	40
Grassland	0.05	30
Material/waste dump	0.03	5
Orchard, garden	0.07	20
Road (asphalt)	0.02	1
Shrub	0.06	30
Urban greenery	0.05	20
Vineyard	0.035	10

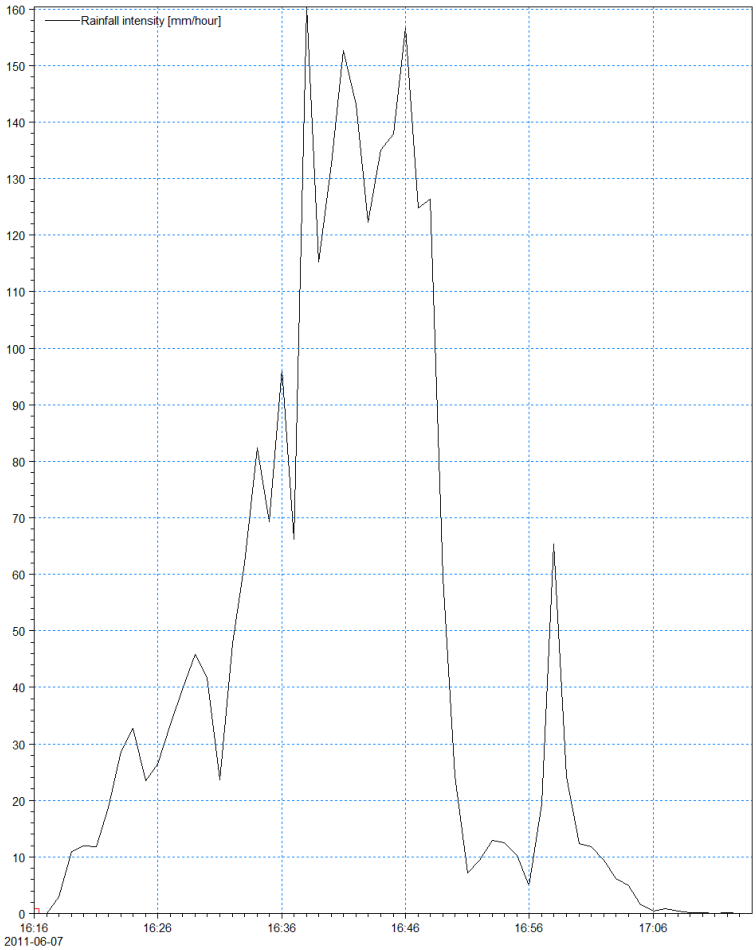


Figure 3. Time-series of the extreme rainfall event from 7 June 2011

Methods

In this study, a two-dimensional (2D) hydraulic modeling approach was implemented using the integrated MIKE+ platform. Previous research has applied MIKE+ (e.g. Welten et al., 2024) as well as its predecessor, MIKE Flood (e.g. Ho et al., 2023; Xu et al., 2023), for the simulation of pluvial flood processes.

To accurately represent the computational domain, a flexible mesh was generated using the MIKE Zero environment. The floodplain area was discretized using a triangular mesh. In contrast, the river channel was modeled using a structured quadrangular mesh, with a maximum element length of 3 m in the longitudinal direction and 1 m in the transverse direction, ensuring adequate resolution of channel hydraulics.

The resulting computational grid contained a total of 800,256 elements, with the maximum mesh element size of 5.37 m², reflecting the varying level of detail required across different parts of the modeled domain. More details on the applied 2D overland numerical scheme and water equations can be found in MIKE+ documentation (https://manuals.mikepoweredbydhi.help/2025/MIKEPlus.htm#Documentation).

The computational time step for all simulations was set to 10 seconds, in line with recommendations by DHI for achieving a balance between computational efficiency and numerical stability in high-resolution hydraulic models. The Courant-Friedrichs-Lewy (CFL) condition was controlled using a maximum factor of 0.8 to ensure stable numerical performance throughout the simulations.

RESULTS

Flow depths derived by MIKE+ model

Based on the results, the largest flood extent was recorded after 32 minutes of rainfall, when 1.1 km^2 of the domain was represented by non-flood areas with flow depths <0.005 m. The flooded areas accounted for 0.41 km^2, out of which most of the flooded pixels belonged to shallow flow depth interval from 0.01 to 0.05 m (53.5%), followed by the interval 0.005 – 0.01 m (18.0%). The flow depth interval from 0.10 to 0.50 m included 13.0% of pixels and the flow depth interval from 0.05 to 0.10 m recorded 10.8% of pixels. The interval with the lowest percentage distribution of flow depths was the last interval from 0.50 to 1.86 m (4.7%). The mean flow depth value was 0.09 m (Figure 3).

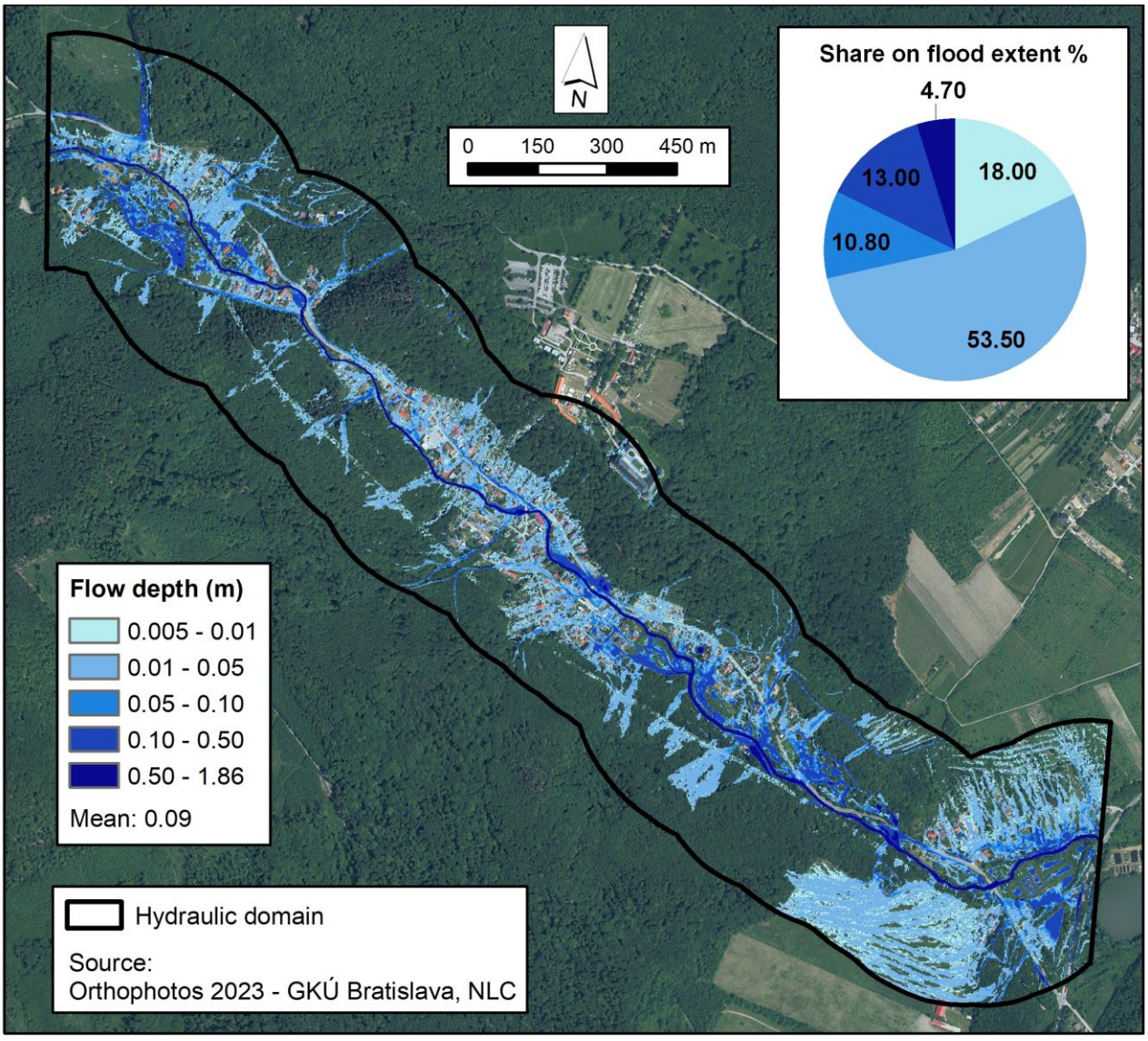


Figure 3. Hydraulically modeled flow depths for the extreme rainfall from 7 June 2011

Flow velocity derived by MIKE+ model

In case of flow velocity, the highest share of pixels was included in the flow velocity interval from 0.00 to 0.50 m/s (71.4%), followed by the interval 0.50 – 1.00 m/s (20.2%). The flow velocity intervals from 1.00 to 1.50 m/s and 2.00-5.69 m/s both included 3.4%. The interval with the lowest percentage distribution of flow velocities was the interval from 1.50 to 2.00 m/s (1.6%). The mean flow velocity value was 0.48 m (Figure 4).

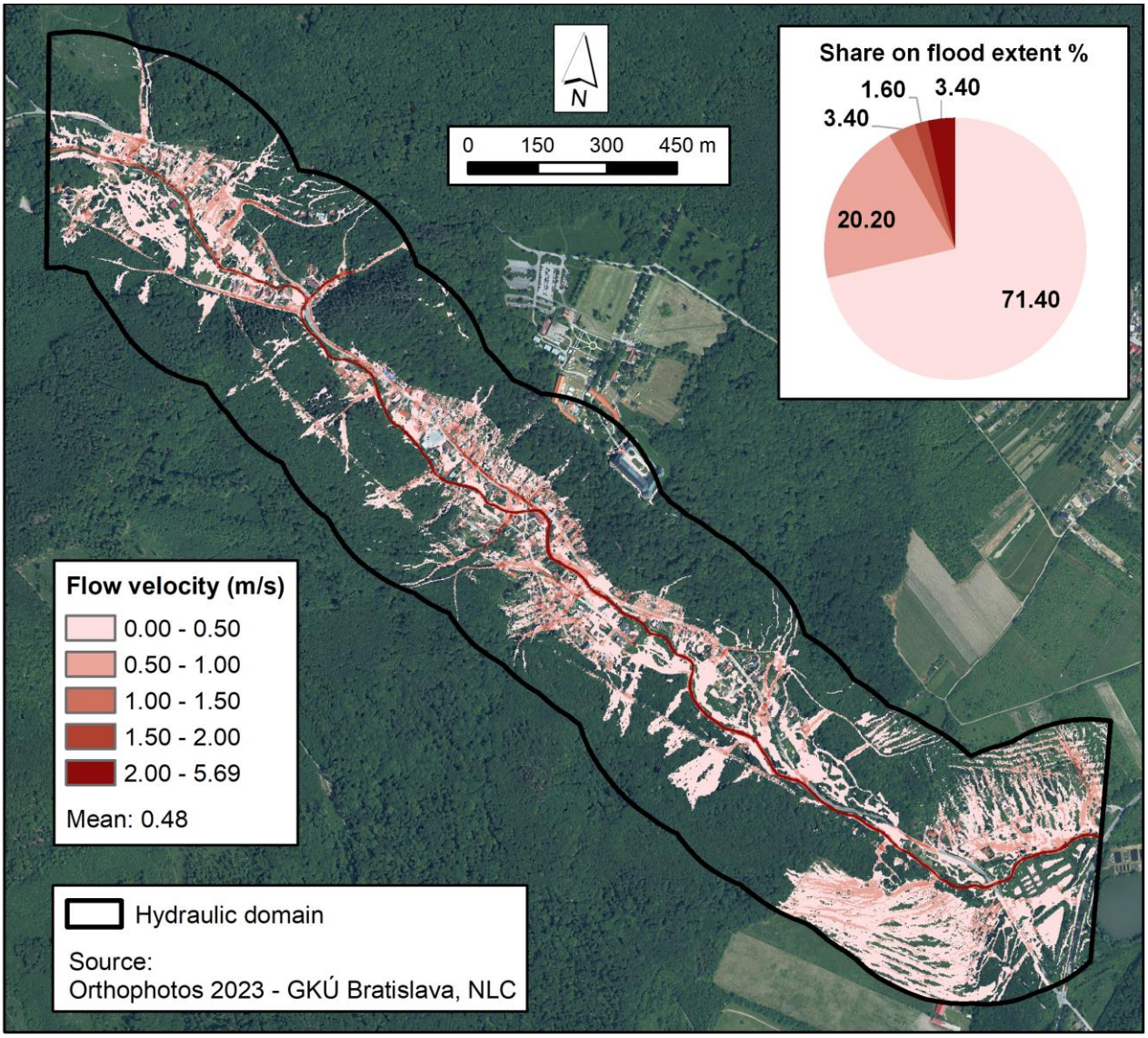


Figure 4. Hydraulically modeled flow velocity for the extreme rainfall from 7 June 2011

DISCUSSION AND CONCLUSION

The results of this study demonstrate the applicability and effectiveness of the rain-on-grid approach implemented in the MIKE+ hydraulic model for simulating pluvial flood dynamics in small catchments under extreme rainfall conditions. The model successfully captured the spatial and temporal variability of flood extent, flow depth, and flow velocity, providing detailed insights into the behavior of surface runoff during a short-duration, high-intensity rainfall event.

The findings indicate that the majority of the study area experienced relatively shallow inundation depths, with more than half of the flooded pixels falling within the 0.01–0.05 m range. This suggests that while the flood was spatially extensive, it was predominantly characterized by low water depths, which are typical for pluvial flooding in small catchments. However, even shallow water depths can pose significant risks, particularly in urbanized or built-up areas where drainage systems may be insufficient. The presence of deeper water levels (up to 1.86 m) is limited in spatial extent mainly to the watercourse itself.

Similarly, the analysis of flow velocities revealed that most of the area experienced low velocities (below 0.50 m/s), indicating relatively slow-moving surface runoff. Nevertheless, areas with higher velocities, although less frequent, represent critical zones where erosive processes and damage to infrastructure may occur. These localized high-velocity flows are particularly important from a risk management perspective, as they can significantly increase the destructive potential of pluvial flood events.

The temporal evolution of flooding, with the maximum extent occurring after 32 minutes of rainfall, underscores the rapid response of small catchments to extreme precipitation. This rapid onset highlights the challenges associated with early warning and emergency response in such environments. The results confirm that high-resolution input data, including LiDAR-derived DEM and detailed land cover information, are essential for accurately representing micro-topographic features and surface characteristics that control runoff generation and routing.

Despite the strengths of the applied methodology, several limitations should be acknowledged. The model relies on assumptions related to infiltration rates and roughness coefficients, which may introduce uncertainties into the simulation results. Additionally, the inclusion of direct validation data, using observed flood extent, may enhance the overall performance of the model outputs. Future research efforts should therefore aim to incorporate field observations or remote sensing-based flood mapping to improve model validation and reduce uncertainties.

In conclusion, this study confirms that the rain-on-grid method within the MIKE+ framework is a robust and suitable tool for modeling pluvial flooding in small catchments. The approach enables detailed assessment of flood hazard characteristics, including depth and velocity distributions, which are critical for risk evaluation and mitigation planning. The results contribute to a better understanding of pluvial flood processes under extreme rainfall conditions and provide valuable information for local authorities and planners in developing effective flood risk management strategies. Given the expected increase in the frequency and intensity of extreme rainfall events due to climate change, the application of such advanced modeling techniques will become increasingly important for enhancing resilience and reducing flood-related impacts in vulnerable regions.

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REFERENCES

Bates, P.D., Quinn, N., Sampson, C., Smith, A., Wing, O., Sosa, J., Savage, J., Olcese, G., Neal, J., Schumann, G., Giustarini, L. (2021). Combined modeling of US fluvial, pluvial, and coastal flood hazard under current and future climates. *Water Resources Research*, 57(2):e2020WR028673.

Cea, L., Sañudo, E., Montalvo, C., Farfán, J., Puertas, J., Tamagnone, P. (2025). Recent advances and future challenges in urban pluvial flood modelling. *Urban Water Journal*, 22(2):149–173.

Chow, V.T. (1959). *Open-Channel Hydraulics*. McGraw-Hill Higher Education, New York.

Di Salvo, C., Ciotoli, G., Pennica, F., Cavinato, G.P. (2017). Pluvial flood hazard in the city of Rome (Italy). *Journal of Maps*, 13(2):545–553.

Ho, B.Q., Hguyen, T., Vu, K., Dao, K., Dung, N.A., Huynh, N. (2023). Apply MIKE models to study the impacts of climate change on flooding and design adaptation measures in Can Tho City in the Vietnamese Mekong Delta. *IOP Conference Series: Earth and Environmental Science*, 1247:012016.

Mediero, L., Soriano, E., Oria, P., Bagli, S., Castellarin, A., Garrote, L., Mazzoli, P., Mysiak, J., Pasetti, S., Persiano, S., Santillán, D., Schröter, K. (2022). Pluvial flooding: High-resolution stochastic hazard mapping in urban areas by using fast-processing DEM-based algorithms. *Journal of Hydrology*, 608:127649.

Montalvo, C., Reyes-Silva, J.D., Sañudo, E., Cea, L., Puertas, J. (2024). Urban pluvial flood modelling in the absence of sewer drainage network data: A physics-based approach. *Journal of Hydrology*, 634:131043.

Preisser, M., Passalacqua, P., Bixler, R.P., Hofmann, J. (2022). Intersecting near-real time fluvial and pluvial inundation estimates with sociodemographic vulnerability to quantify a household flood impact index. *Hydrology and Earth System Sciences*, 26:3941–3964.

Rahmati et al. (2018). Development and analysis of the Soil Water Infiltration Global database. *Earth System Science Data*, 10(3):1237–1263.

Rosenzweig, B.R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., Iwaniec, D., Davidson, C.I. (2018). Pluvial flood risk and opportunities for resilience. *WIREs Water*, 5(6):e1302.

Rözer, V., Peche, A., Berkhahn, S., Feng, Y., Fuchs, L., Graf, T., Haberlandt, U., Kreibich, H., Sämann, R., Sester, M., Shehu, B., Wahl, J., Neuweiler, I. (2021). Impact-based forecasting for pluvial floods. *Earth's Future*, 9:e2020EF001851.

Sañudo, E., Gabrcía-Feal, O., Hagen, L., Cea, L., Puertas, J., Montalvo, C., Alvarado-Vicencio, R., Hofmann, J. (2025). IberSWMM+: A high-performance computing solver for 2D-1D pluvial flood modelling in urban environments. *Journal of Hydrology*, 651:132603.

Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F., Dutta, D., Kim, S.J.E.M. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, 90:201–216.

Vojtek, M. (2023). Indicator-based approach for fluvial flood risk assessment at municipal level in Slovakia. *Scientific Reports*, 13:5014.

Vojtek, M., Janizadeh, S., Vojteková, J. (2023b). Riverine flood potential assessment using metaheuristic hybrid machine learning algorithms. *Journal of Flood Risk Management*, 16(3):e12905.

Vojtek, M., Moradi, S., De Luca, D.L., Petroselli, A., Vojteková, J. (2024). Fluvial and pluvial flood hazard mapping: combining basin and municipal scale assessment. *Geomatics, Natural Hazards and Risk*, 15(1):2432377.

Vojtek, M., Moradi, S., Petroselli, A., Vojteková, J. (2025). Comparative analysis of hydraulic and GIS-based Height Above the Nearest Drainage model for fluvial flood hazard mapping: a case of the Gidra River, Slovakia. *Stochastic Environmental Research and Risk Assessment*, 39:2657–2675.

Vojtek, M., Vojteková, J. (2026a). Applying 2D MIKE+ hydraulic model for fluvial and pluvial flood inundation modeling: Evidence from a case study in Slovakia. *Acta Scientiarum Polonorum: Formatio Circumiectus*, 25(1):29–43.

Vojtek, M., Vojteková, J. (2026b). Fluvial Flood Inundation Modeling: a Comparative Assessment of 1D and 2D Hydraulic Approach Using MIKE+. *Water Resources Management*, 40:24.

Vojtek, M., Vojteková, J., De Luca, D.L., Petroselli, A. (2023a). Combined basin-scale and decentralized flood risk assessment: a methodological approach for preliminary flood risk assessment. *Hydrological Sciences Journal*, 63(3):355–378.

Welten, S., Holt, A., Weber, J., Klopiers, E.M., Schüttrumpf, H., Decker, S. (2024). Generation of harmonised pluvial flood hazard maps through decentralised analytics. *Journal of Hydroinformatics*, 26(2):534–548.

Xu, L., Yang, X., Cui, S., Tang, J., Ding, S., Zhang, X. (2023). Co-occurrence of pluvial and fluvial floods exacerbates inundation and economic losses: evidence from a scenario-based analysis in Longyan, China. *Geomatics, Natural Hazards and Risk*, 14(1):2218012.

Yang, Y., Sun, L., Li, R., Yu, D. (2020). Linking a Storm Water Management Model to a Novel Two-Dimensional Model for Urban Pluvial Flood Modeling. *International Journal of Disaster Risk Science*, 11:508–518.

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