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Impact of Different Rainfall Intensity and Duration on Flash-Flood Events on a Steep-Sloped Ungauged Watershed

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Changing climate conditions increase rainfall intensity and cause a growing number of flash flood events. Due to flash floods, problems with water damage prevention (urban area floods, erosion of natural watersheds) are increasing; these events also make the sustainable maintenance of watersheds more challenging. Hungarian watersheds are ungauged; very little historical or real-time data is available, making it difficult to understand the hydrological processes occurring during flash flood events. When only limited data is available, numerical models help predict peak flows and runoff volume. Additionally, a comparison of different models and parametrizations could be a helpful tool to reduce prediction uncertainty. This paper evaluates the impact of different rainfall intensities and durations on flash flood events at the ungauged watershed of the Morgó-creek on the northern side of Hungary. Land use conditions are primarily natural, with urban areas close to the outlet point. Hydrological and hydrodynamical models were used to apply different scenarios to determine the sensitivity of the whole watershed system based on typical precipitation events in time and intensity. The models predicted different peak flows and timing for flash floods. Using both models for comparison is recommended for flash flood prediction to compensate for the lack of measured data.

1. Introduction

Due to climate change, rainfall characteristics show a worldwide growth in intensity, shorter duration, and longer time between events (Westra et al., 2014). Flash floods give new challenges in water resources engineering, from water damage prevention to even parts of renewable energy systems (Ibrahim et al., 2021). These changes can also be observed in Hungary (Lindmayer, 2012). Flash flood events generate potential water damage threats in natural and urban areas. Short duration, intense rainfalls, and increased time between rainfalls create further problems in sustainable watershed management.

For sustainable watershed management, flash floods must be treated as a threat and an opportunity for water retention. In urban areas and local natural ecosystems, it is necessary to withhold as much water as possible for dry periods to maintain a natural water balance. Blue and Green Infrastructure is a new sustainable water resource management method, although there are still uncertainties in applying effective methods (Thorne et al., 2018). The main problem for the application and design is the lack of hydrological data in small watersheds. There are many ungauged small watersheds with an area <50 km^2. Larger steep-sloped watersheds are also often neglected despite the potential for water retention. To find potential problems and opportunities, examining the dynamic processes of flash floods in ungauged watersheds is essential. The General Directorate of Water Management currently provides the data for flash flood risk maps. These maps show the flash flood risk scaled from 1-5 at the outfall points of the watersheds.

Numerical modeling is a helpful tool for investigating flash floods and water retention opportunities in watersheds. The lack of meteorological and hydrological data can cause difficulties in selecting appropriate modeling methods and prediction uncertainties (Blöschl et al., 2013). Flash floods often have a severe environmental impact on the watershed; models do exist to evaluate such damage (Ballesteros et al., 2011). With hydrologic and hydrodynamic numerical models, the rainfall-runoff events can be simulated as a function of time. They can be used to predict peak flow, time to peak, and runoff volume. Machine learning-based models

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need large amounts of data (Akel et al., 2022). In this study, the main problem was the lack of data. The watershed's topographic, geological, soil, and land use map is usually available; this data has many uncertainties for modeling purposes. Combining hydrological and hydrodynamical models or comparing the two models can be applied to reduce caused by data uncertainty (Ámon, 2017). Conceptual hydrological and physical-based hydrodynamic models represent two different modeling approaches. Model predictions from these two methods can decrease the uncertainty of the parameters or detect errors in the parametrization (Ámon and Bene, 2023a). This paper applied different models and methods to a specific watershed with minimal data on topography, soil, vegetation, and channel characteristics.

2. Study Area Description and Previous Results

The Morgó Creek watershed is located in northern Hungary, north of Budapest. Morgó Creek flows directly into the left bank of the River Danube at about rkm 1689, near the town of Kismaros. The watershed area is 52.63 km^{2,} with land use of approximately 70 % woodlands, 25 % agriculture, and 4-5 % urban area. Soils originate from underlying andesite and dacite rock, producing brown forest soils in woodland regions with a wide range of grain sizes from clay loam to sandy loam. The woodland areas may also contain moderate depths of forest litter. Fluvial washes located along the smaller streams may sort the parent soils to sizes from coarse sands to clays (Figure 1). The watershed slope is steep, averaging 4.6-9.1 %. In urban areas and along lower regions, the average slope is between 0.5-1 %. The watershed has a high risk for flooding. The only existing data at the outflow point was a flow measurement, Q = 53,3 cms, due to a 50-year return period (2 % frequency) rainfall. No other high-water data was measured on the creek (Ámon and Bene, 2023a).

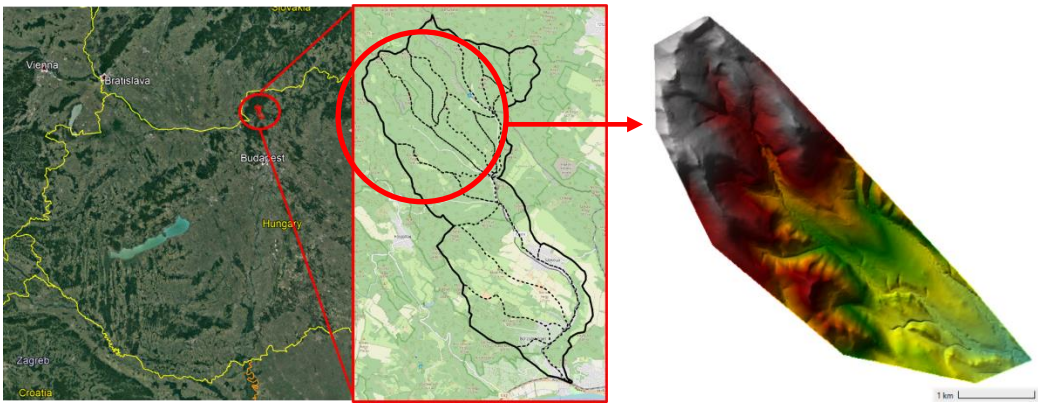

Figure 1.: Location of the Morgó watershed and Királyrét subbasin

2.1 Selected watershed - Királyrét

The smaller subwatershed of the Morgó watershed, the Királyrét (Figure 1) was used in the study. The computationally intensive hydrodynamic model used in this study worked better with a smaller domain, allowing the examination of a wider range of input parameters. The Királyrét's area is 6.4 km^2 with an average slope of 8 %, less than the 10-20 % in the entire Morgó area. The characteristic parameters of Királyrét, such as the channel bed, soil parameters, land cover, and topography, closely resemble the parent watershed.

2.2 Previous studies

Ámon and Bene (2023b) applied a hydrological model to verify peak flow for a 2 % frequency runoff event mentioned earlier. The Morgó watershed was assembled from subbasins and creek beds, forming a semi-distributed hydrological model. Rainfall intensity/duration corresponded to a one-hour, 2 % event with uniform intensity. Other input came from topographic and soil maps and orthophotos. The predicted discharge vs. time curve (Figure 2) compared well with the observed peak flow of 53.2 cms.

Additional studies focused on the possible impacts of climate change. Input parameters such as hydraulic conductivity, impervious area ratio, and rainfall duration were varied to determine their impact on runoff ratio and peak flow. For this study, a 1% frequency event was chosen to represent climate change impacts and comply with Hungarian design standards. Event durations lasted between 1 and 12 hours. The intensity vs. time was defined with a triangular distribution (Ámon and Bene, 2023a).

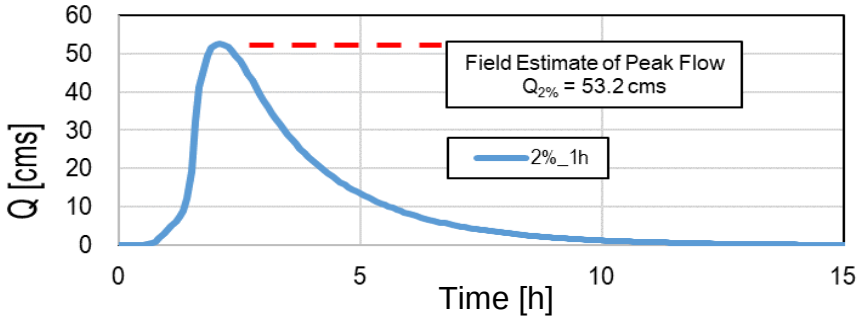

Figure 2.: Model calibration for 2 % frequency peak flow on the Morgó watershed (Ámon and Bene, 2023a)

Table 1 shows the influence of rainfall duration on typical outflow parameters. Peak flow, runoff volume, and runoff ratio (excess rainfall volume/rainfall event volume) are more than double for the one-hour rainfall compared to longer durations. The six-hour event produced the lowest outflow volume, slowly increasing for longer rainfalls. The model results are close to 10 % for the runoff ratio, except for the one-hour event. There is no significant difference in outflow volume between events (except for one one-hour duration). The difference in the runoff ratios shows that high-intensity and short-duration rainfall events can cause a higher risk of flash floods. The significant differences in peak flow and outflow volume will impact flood protection and water retention decisions.

Table 1: Results of floods from different rainfall events (Ámon and Bene, 2023b)

Rainfall event	Q_{max} (cms)	Volume Precipitation (1,000 m^3)	Volume Outflow (1,000 m^3)	Runoff ratio
1 %, 1 h	93.35	3,160.37	934.27	29.6 %
1 %, 2 h	43.68	3,758.76	478.04	12.7 %
1 %, 4 h	30.91	4,439.26	444.18	10.0 %
1 %, 6 h	27.42	4,894.50	489.53	10.0 %
1 %, 8 h	24.54	5,461.84	524.48	9.6 %
1 %, 12 h	20.36	5,778.66	578.01	10.0 %

3. Model development

Two models with different approaches, conceptual and physically based, were used to represent the dynamics of overland flow in a single ungauged watershed. The models use different methods and inputs to predict overland flow caused by intense rainfall.

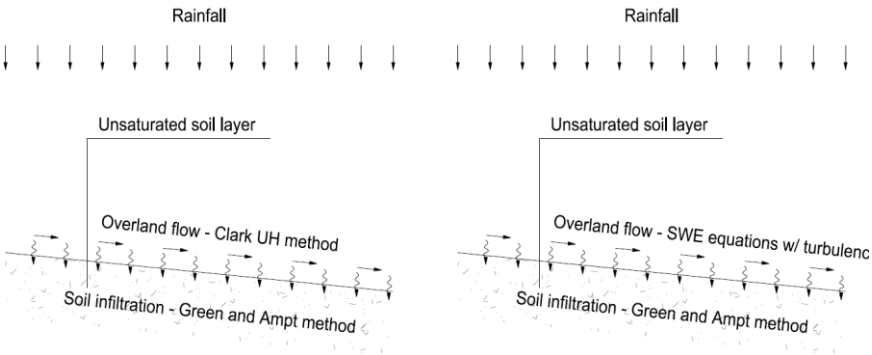

Figure 3: Schematics of the two different model types, left: hydrological model, right: hydrodynamical model

3.1 Modeling concept

The hydrological model used lumped parametrization in each subbasin area. The Clark Unit Hydrograph method (Bartles et al., 2021) was applied for overland flow modeling. The unit hydrograph was determined by routing the discrete, time-area-method, unit-runoff hyetograph through a linear reservoir (Ponce, 1989). It was based

on two variables: the time of concentration and a storage coefficient. The parameters were calculated with regression equations using data from the watershed (Ámon and Bene, 2023a).
The hydrodynamical model was a depth-integrated model that solved the full 2D shallow water equations (SWE) with an additional Smigorinsky-Lilly eddy viscosity solver (Brunnel, 2020). Overland flow as a Riemann problem can be calculated more precisely by estimating the full hydrodynamical equations with a turbulence model (Huang et al., 2011). Both models calculated rainfall-induced overland flow and infiltration into the unsaturated soil layer (Figure 3).
The Green and Ampt method was selected to calculate infiltration (Bartles et al., 2021). The infiltration was calculated using lumped parameters on the entire watershed for the hydrological model, while the hydrodynamic method calculated infiltration distributed over the 2D mesh.

3.2 Available geometrical data and input parameters

The hydrologic model of Királyrét watershed is similar to the Morgo Creek model. Interception and surface storage were not applied. The Green and Ampt model was used to determine infiltration, the Clark Unit Hydrograph was used to calculate the overland flow (Ámon and Bene 2023b), and the Muskingum Cunge routing method was used to model channel flow.
The hydrodynamic 2D model used a digital elevation model with a 5x5 m resolution (Lechner Nonprofit Ltd.). The adaptive mesh was generated with cell sizes from 10x10 m to 100x100 m. Manning's n value was determined based on three types of land cover: forest, roads, and creek bed.
The soil parameters were from two databases, Mining and Geological Survey of Hungary soil maps (server map.mbfsz.gov.hu) and 3D hydrosoil map (Tóth et al., 2017). There is one type of soil in the Királyrét watershed (Ámon and Bene 2023b). The Green and Ampt parameters for sandy soil are shown in Table 2. The initial water content was assumed to be well below saturation levels. In the hydrodynamic model infiltration and overland flow may occur at the same time in different regions, causing non-continuous shallow flow conditions and reducing average depths. In these cases, the surface shear stress had a higher impact on the flow movement.

Table 2: Soil parameters for the Green and Ampt method

Wetting front suction (mm)	Hydraulic conductivity (mm/h)	Initial Soil water content	Saturated soil water content
199.97	35	0.17	0.36

A value of 10 % imperviousness was used in the hydrological model. In the hydrodynamic 2D model, three types of land use were defined: roads, water surfaces, and forests. To attain 10 % imperviousness in the hydrodynamic model, imperviousness was 100 % in roads and water surfaces and 9 % in forested areas. The calculated time of concentration applied in the hydrologic model was very close to the simulated time of concentration produced by the hydrodynamic model.

3.3 Model simulations

For both computational methods, three different rainfall durations were evaluated: 1, 6, and 12 h, with a triangular intensity vs. time distribution. Peak intensity was twice as much as the uniform intensity value, and the peak was 0.375 (3/8) times the event duration. A summary of rainfall parameters is in Table 3.

Table 3: Parameters of rainfall events for Cases 1, 2, and 3

	Case 1	Case 2	Case 3
Rainfall duration (h)	1	6	12
Rainfall depth (mm)	60.48	92.98	109.8
Rainfall peak intensity (mm/h)	121	31	18.3

4. Results

Since the watershed is ungauged, the classic calibration-validation process is not possible. Instead, a comparison of models with different physical backgrounds was used to estimate the model's precision. Three types of output values were selected to compare the two computational methods: (1) peak outflow (Q_{max}), (2) runoff volume, and (3) runoff ratio. The hydrological model was used as a baseline for comparison. Three different rainfall events were applied with hydrological and hydrodynamic modeling approaches (Table 4).

Table 4: Simulation outcome summary of the hydrologic and 2D hydrodynamic models for Case 1-3

	(1) Q_{max} (cms)			(2) Runoff volume V (m^3)			(3) Runoff ratio		
Rainfall duration (h)	1	6	12	1	6	12	1	6	12
Hydrologic m.	3.20	2.22	1.92	62833	54077	69584	17	10	10
2D Hydrodynamic m.	3.72	2.71	2.13	52214	51045	69102	14	9	10
Difference	0.52	0.49	0.21	10619	3032	482	3	1	0
Relative difference	16%	22%	11%	17%	6%	1%			

The three simulations, Case 1, Case 2, and Case 3, produced different results between the two numerical approaches and between rainfall durations. Considering rainfall duration, the highest peak flows occurred during the one-hour event. Qmax was about 50 % for one hour for both approaches compared to the six and twelve-hour events. Rainfall duration had less impact on runoff volume; the 12 h duration produced slightly higher volumes.

The results for both numerical approaches are similar for peak flow, runoff volume, and runoff ratio. The hydrodynamic approach predicted higher maximum flows with less volume for all cases. Runoff ratios were very similar.

In Hungary, watersheds with woodland areas should produce a runoff ratio close to 10 %. Table 2 shows that the six and 12-hour rainfall events are close to a 10 % runoff ratio for both models except for the 1-hour event, where the runoff ratio is much higher for the hydrologic model, the hydrodynamic model is moderately higher; only 14 %.

Simulated hydrographs are shown in Figure 4. In Case 1, the peak flow is higher in the hydrodynamic 2D simulation; the difference in flow is 0.52 cms. The hydrodynamic model predicts time to peak much sooner than the hydrological model (~1.7 vs. 3.8 h). In Case 2, differences decrease at the six-hour-long rainfall duration. The peak flow is higher in the 2D simulation by 0.49 cms, while the time to peak is still faster in the 2D model (4.4 vs 6.2 h). In Case 3, the difference in peak flow decreases to 0.2 cms, and the peak time for both models remains apart (7.2 vs 9.4 h).

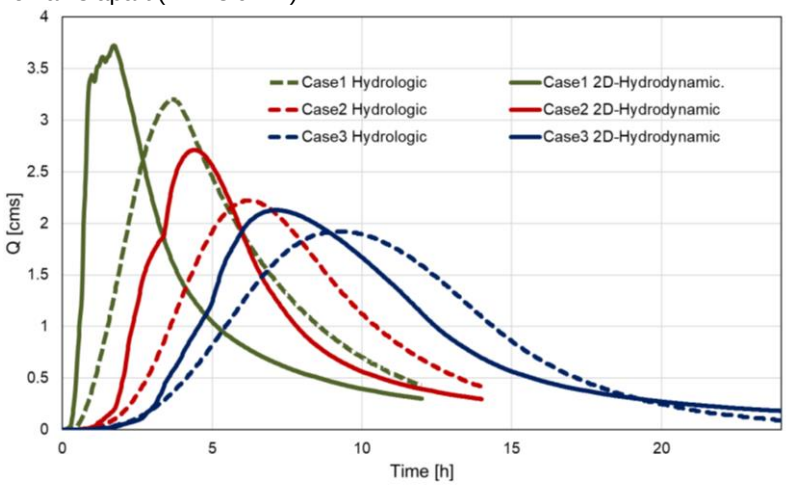

Figure 4: Simulation results of the hydrologic and 2D hydrodynamical models for Cases 1-3

5. Conclusion

This research examined output flow and volume predictions for hydrologic and 2D hydrodynamic numerical methods. The watershed used for comparisons was 6.4 km^2 with an average slope of 8 %, mostly woodland, with fairly uniform soil conditions. Since a previous study demonstrated that rainfall duration played a significant role in determining peak output flow volume, comparisons between the two were performed for a 1 % frequency event with a duration between 1 and 12 h. Results were compared for peak outflow, total outflow volume, and runoff ratio.

The most critical was the 1-hour duration event for both computational approaches, where peak flows reached 50 % higher than the longer duration events. The 2D hydrodynamic approach predicted higher peak flow and a much shorter time to peak. Total output volumes for all events were less variable, ranging between 50,000 and

70,000 m^3. The differences between the models for the 1-hour rainfall duration predictions indicate that careful consideration needs to be taken to apply these models for flash-flood prediction. Therefore, models that predict a faster time to peak are recommended for flash-flood damage prevention planning to increase the safety factor. In sustainable watershed management, flash floods should be considered as an opportunity to apply blue-green infrastructure (water storage/impoundment) elements. Comparing different modeling results can be a valuable tool to predict flood volume and water retention capacities more reliably for environmentally-conscious water management. Continuous updating and refining of these models using new surveys and adding monitoring data should help increase prediction accuracy and safety.

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