Post-Fire Urban Runoff Assessment in a Mediterranean Basin Using Integrated UAV–SWMM–HEC-RAS Modelling

Alaa Kadora, Anna Brook, Lea Wittenberg
School of Environmental Sciences, University of Haifa, Haifa, Israel

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Abstract

Understanding urban hydrological systems in the Mediterranean environment is a crucial scientific and practical issue, particularly the disturbances caused by heavy rainfall and forest fires, which affect seepage dynamics, surface roughness, and drainage efficiency. This study presents an integrated hydrological spatial scenario combining high-resolution UAV-photogrammetry, GIS-based analysis, and SWMM-HEC-RAS-2D modelling to simulate the post-fire runoff response in a Mediterranean urban basin. A digital surface model derived from drones (0.2 m resolution) and an orthomossayic model (5 cm GSD) were used to extract topographic gradients, land cover classifications, and surface roughness parameters to generate hydrological inputs. The SWMM-HEC-RAS composite product was calibrated and validated using field rainfall and runoff measurements collected throughout hydrological seasons.

The model was largely successful in characterizing the variability of runoff generation based on observed rainfall intensities, demonstrating strong predictive ability during moderate storm conditions while exhibiting increased uncertainty during rare high intensity events. The spatial analysis showed that post-fire landscape changes and loss of vegetation cover affected soil hydrophobicity significantly exacerbated runoff and flow, and increased peak discharge volumes. This framework, combined with high quality geospatial data was able to effectively describe flood prone areas and quantify the influence of key urban parameters including surface infiltration, topographic slope and engineered drainage networks on flood dynamics. This research underscores the value of UAV data for improving hydrodynamic modelling and creating practical flood-risk and stormwater-management tools in fire-affected areas, while also supporting the broader ISPRS goal of using geospatial technologies to plan sustainable and climate-resilient water infrastructure.

1. INTRODUCTION

Urban drainage in Mediterranean areas is highly sensitive to hydrological disturbances caused by climate change rapid urbanization and recurrent fire events, These factors can change the vegetation composition in addition to soil properties and surface roughness which impair infiltration capacity and accelerate surface runoff (Shakesby & Doerr, 2006).
The impact of land cover change and natural disturbances alters rainfall-runoff relationships consequently increasing flow connectivity and increasing the frequency and magnitude of flood events and inundations (Sriwongsitanon & Taesombat, 2011). In environments with topographic complexity and high-density drainage infrastructures are often small or spatially fragmented causing localised flooding and flash floods during severe storm (Diakakis et al., 2020).

Traditional stormwater management approaches typically rely on static design assumptions and simplified hydrological representations that neglect spatial heterogeneity and temporal variability (Cristiano et al., 2017).
Conventional hydrological models, calibrated from the ground to natural basins, often fail to correctly calculate peak runoff in urban areas; this is because they fail to capture the effects of impervious surfaces,steep slopes, and artificial and engineered drainage connectivity. Furthermore, forest fires occurring between natural and urban areas create additional uncertainty (Thompson & Calkin, 2011). In addition, vegetation loss causes the formation of increased hydrophobic soil layers that increases surface runoff and shortens the time between rainfall and runoff flow, the combination of climatic and land-use factors poses significant challenges to accurately simulating hydrological behavior after a disturbance (Dwarakish & Ganasri, 2015).

Recent advances in high resolution remote sensing, particularly UAV photogrammetry, have transformed the ability to observe, quantify and analyze urban dynamics at fine spatial and temporal scales. UAV-derived digital surface models (DSMs) and orthomosaics enable accurate mapping of microtopography, surface roughness, and land cover distribution that directly affect runoff generation and flow routing. When combined with physics based hydrological and hydraulic models, such spatial data can significantly improve process representation and model calibration (Lendzioch, 2023).
Coupled modeling frameworks that link the Storm Water Management Model (SWMM) with the two-dimensional Hydraulic Engineering Center River Analysis System (HEC-RAS 2D) provide a comprehensive means to simulate both the temporal dynamics of rainfall–runoff processes and the spatial propagation of floodwaters.The SWMM component simulates rainfall–runoff generation, infiltration, and flow routing through the urban drainage network, whereas HEC-RAS 2D resolves the hydrodynamic distribution of water depth, velocity, and

flood extent across complex terrain. Integrating these tools within a Geographic Information System (GIS) environment allows the explicit consideration of land-cover variability, slope, and drainage connectivity derived from UAV-based datasets (Khatooni et al., 2025).

This study applies such an integrative framework to examine and analyze the post-fire runoff behavior in a typical Mediterranean urban basin, combining drone topographic mapping, field hydrometric data measurements, and SWMM-HEC-RAS simulations. The study aims to improve the understanding of runoff responses under varying rainfall intensities and preconditions. The results contribute to the development of adaptive and data driven flood management strategies that improve the resilience of urban drainage systems in fire affected and rapidly urbanizing environments (Ahmad et al., 2025).

Several previous studies have applied SWMM–HEC-RAS coupling for urban flood modelling, and others have used UAV-derived terrain models for hydraulic simulations. However, limited research has combined high-resolution UAV-based land-cover classification and post-fire surface characterization within an integrated hydrological–hydraulic modelling framework in Mediterranean urban catchments. This study addresses this gap by integrating very high-resolution UAV-derived topographic and land-cover data into a coupled SWMM–HEC-RAS 2D framework for post-fire urban runoff analysis. Unlike conventional approaches that rely on coarse-resolution DEMs and simplified land-use information, the proposed framework enables a more detailed representation of surface roughness, impervious areas, and drainage connectivity at the sub-basin scale. The model is calibrated and validated using field measurements of rainfall and discharge collected after fire events, allowing quantitative evaluation of model performance under different storm intensities. By focusing on a wildfire-affected Mediterranean urban basin, the study improves understanding of how vegetation loss and altered surface properties influence runoff generation and flood behaviour, and demonstrates the practical value of UAV data for flood modelling in disturbed urban environments.

2. STUDY AREA AND DATA

2.1 Study area characteristics

The study area is a small Mediterranean urban basin located in a region with steep terrain and mixed land use. The basin contains built-up zones and natural open areas. This combination creates a complex surface that controls how water moves during storms. The urban section includes residential neighborhoods with multi-story buildings, paved roads and parking areas. The natural parts include patches of vegetation that were disturbed several times by wildfires, which is common in Mediterranean environments. The soil in the basin is shallow and in some locations lies directly above exposed bedrock. Many surfaces are covered with asphalt or concrete and these materials prevent water from infiltrating into the ground.

Due to these physical features the basin reacts quickly to rainfall. Moderate storms can generate noticeable surface runoff and heavy storms often cause rapid increases in flow. The steep slopes push water downhill at high speed. Burned soil, reduced vegetation, and large impervious areas limit infiltration. As a result the basin is highly sensitive to flooding after fire events.

To monitor hydrological behavior and understand how runoff forms, several measuring devices were installed in different parts of the basin. An automatic rain gauge with tilting buckets recorded rainfall intensity and duration during the rainy seasons. Two flow meters were placed near the main drainage outlets to measure the amount of water passing through the channels during storm events. Soil moisture sensors helped observe how the soil absorbed water under different conditions. All measurements were collected over two hydrological years. These data were then used to calibrate and validate the combined hydrological and hydraulic model applied in the study.

2.2 Fire event description and post-fire conditions

The study area was affected by a wildfire that occurred at the end of November 2016 during a period of extreme weather conditions. The event was part of a series of large fires that impacted the Haifa region and surrounding landscapes (Tessler et al., 2019). The wildfire significantly affected the watershed, particularly in the upper and middle sections of the catchment. As documented in previous studies, the fire resulted in substantial vegetation loss and increased exposure of bare soil and rock surfaces, thereby altering surface characteristics relevant to runoff generation and flood dynamics.

The hydrological monitoring period included rainfall events that occurred during the first rainy season following the November 2016 wildfire, allowing the analysis of runoff behaviour under early post-fire conditions. During this period, changes in surface properties such as reduced interception, increased soil hydrophobicity, and higher surface connectivity were expected to influence runoff generation and flow routing. These post-fire conditions provided an opportunity to examine how wildfire disturbance affects urban runoff response when combined with high-intensity Mediterranean rainfall events.

Figure 1 shows the delineated sub-basins and stream hierarchy of the study watershed derived from the UAV-based DEM analysis.

Figure 2 presents the monitoring infrastructure and the locations of the rainfall gauge and drainage outlets used in the study.

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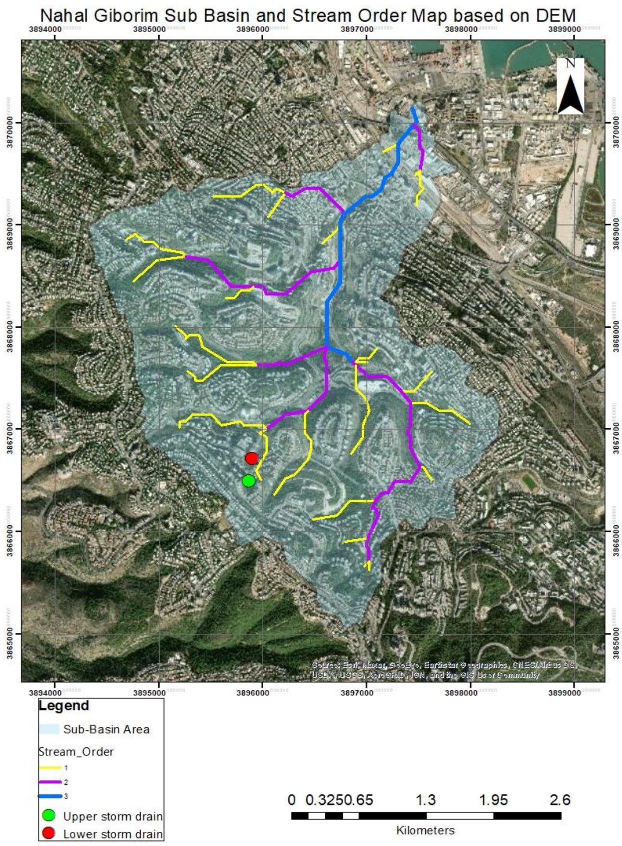

***Figure 1**. Sub-basin and stream order map of the Nahal Giborim watershed, derived from DEM analysis. The map displays stream hierarchy based on Strahler ordering (yellow = order 1, magenta = order 2, blue = order 3), along with the delineated sub-basin boundary. Green and red points represent the locations of the upper and lower storm drains, respectively.*

***Figure 2.** Monitoring infrastructure and measurement locations in the study area: the aerial orthophoto shows the locations of the rainfall gauge (installed at Romema kindergarten school), the upper drainage outlet (Tzolelet Dakar Street), and the lower drainage outlet (HaPerachim Street), marked with blue dots. Photographs on the left show the rain gauge and drainage conduits at the respective locations*

3. METHODOLOGY

3.1 UAV Data Acquisition and DSM Generation

A UAV survey was conducted over the study area to obtain high-resolution topographic and land-cover data. A DJI Phantom 4 Advanced UAV equipped with an RGB camera was used for image acquisition. The survey was carried out at an average flight altitude of 60 m above ground level. Flight planning was performed using Pix4Dmapper and followed a double-grid flight pattern to ensure sufficient image redundancy and coverage for photogrammetric processing.

The aerial images were processed using Pix4Dmapper software following a Structure-from-Motion (SfM) photogrammetric workflow. The processing steps included image alignment, dense point cloud generation, and surface reconstruction. The final Digital Surface Model (DSM) was generated at a spatial resolution of 0.2 m, and an orthomosaic with a ground sampling distance (GSD) of 5 cm was produced.

Georeferencing was performed using ground control points (GCPs) distributed across the study area. The vertical accuracy of the UAV-derived DSM was evaluated based on these control points, resulting in a vertical root mean square error (RMSE) of approximately 2 cm.

The high spatial resolution of the UAV-derived products enabled a detailed representation of micro-topography, surface features, and built structures, which are essential inputs for runoff routing and hydrodynamic modelling in complex urban environments. (Westoby et al., 2012).

3.2 Land Cover Classification and GIS Processing

Land-cover classification was performed using visual interpretation of the high-resolution UAV-derived orthomosaic. The classification was carried out manually in a GIS environment, based on spectral appearance, texture, and spatial context of surface features visible in the orthophotos. Six main land-cover classes were identified: buildings, roads, rock surfaces, bare soil, sparse vegetation, and tree cover.

To verify the reliability of the classification, field-based verification was conducted through site inspections at representative locations across the study area, covering the main land-cover classes. These inspections were used to visually compare the classified map with actual field conditions and to correct minor misclassifications. Due to the high spatial resolution of the orthomosaic (5 cm GSD), most land-cover types could be clearly distinguished, reducing uncertainty in class boundaries.

The final land-cover map was used to assign surface roughness, imperviousness, and infiltration parameters required for the hydrological and hydraulic modelling. Each land-cover class was assigned representative infiltration and roughness values based on its physical characteristics. Impervious classes such as roads and buildings were assigned minimal infiltration values, while vegetated areas were assigned higher infiltration capacities. Post-fire surfaces were adjusted to reflect reduced infiltration due to soil sealing and vegetation loss. Although the classification was not based on automated or supervised algorithms, the manual approach allowed a detailed and context-aware representation of complex urban surface features. Potential limitations include subjective interpretation and reduced reproducibility; however, for the scale and purpose of this study, the classification quality was sufficient to support runoff and flood simulations.

3.3 Hydrological Modeling (SWMM)

The hydrological response of the study area was simulated using the EPA Storm Water Management Model (SWMM), which is widely applied for urban rainfall–runoff modelling and drainage system analysis (Abi Aad et al., 2010). The model was configured based on the delineated sub-basins derived from the UAV-based DSM and the mapped drainage network layout. Each sub-basin was parameterized using land-cover information, surface slope, and imperviousness derived from the GIS analysis, allowing spatial variability of urban surface characteristics to be represented.

Key hydrological parameters were adjusted during the calibration process, including surface roughness, percentage of impervious area, and infiltration capacity, following common practices in urban hydrological modelling (Cristiano et al., 2017). Infiltration was represented using the Green–Ampt method, which is suitable for event-based simulations and sensitive to changes in soil properties under disturbed conditions (Zhang, 2024). Parameter values were adapted to reflect post-fire soil conditions, where vegetation loss and altered soil structure are known to affect infiltration behaviour (Shakesby and Doerr, 2006).

Rainfall inputs were based on observed precipitation data recorded at the on-site rain gauge, and simulated runoff was routed through the drainage system using the dynamic wave approach, which allows realistic representation of unsteady flow conditions in urban drainage networks (Costabile et al., 2013).

Model calibration was performed using observed rainfall–runoff events recorded during the monitoring period. A total of 115 storm events were used for calibration and evaluation, covering a range of rainfall intensities and durations. Calibration focused on adjusting key hydrological parameters, including infiltration capacity, surface roughness, and imperviousness, to improve agreement between simulated and observed discharge.

Model performance was evaluated by comparing simulated and measured peak discharges at the upper and lower drainage outlets. The primary performance metric was the absolute difference between observed and simulated peak flow (ΔQ). Events with (ΔQ) values below a predefined threshold were considered successful simulations. The evaluation allowed assessment of model performance under different storm conditions, including moderate and high-intensity rainfall events.

3.5 Model Validation

Model validation was performed by comparing simulated and observed peak discharges for the monitored storm events at the upper and lower drainage outlets. Validation focused on assessing the ability of the coupled SWMM–HEC-RAS modelling framework to reproduce peak flow magnitudes under different rainfall conditions.

The validation results are summarized in Table 1, where storm events are grouped according to rainfall depth and event duration. Model performance was evaluated using the absolute difference between simulated and observed peak discharge (ΔQ). A threshold value of $\Delta Q \leq 5$ m³/s was adopted to define successful simulations. The threshold of 5 m³/s was selected to represent a practical tolerance for peak discharge differences in the study catchment, reflecting an acceptable level of uncertainty for urban drainage applications considering measurement errors, spatial variability in rainfall, and the scale of peak flows observed in the study area.

The results indicate that the model performed well for short-duration and moderate rainfall events, with a high proportion of successful simulations, particularly at the upper drainage outlet. Model performance decreased for high-intensity or long-duration storm events, especially at the lower outlet, where flow accumulation and routing complexity increase uncertainty. These results suggest that the modelling framework is reliable for typical storm conditions, while extreme events remain more challenging to simulate accurately due to nonlinear runoff responses and post-fire surface effects.

3.4 Hydraulic Simulation (HEC-RAS 2D)

A two-dimensional hydraulic model was developed using HEC-RAS to simulate surface flow depth, velocity, and flood extent across the study area. The model domain was based on a terrain representation derived from the UAV-based DSM, while spatially distributed Manning’s roughness coefficients were assigned according to the land-cover classification (Yalcin, 2020). The HEC-RAS model was dynamically coupled with SWMM by using SWMM-generated hydrographs as inflow boundary conditions, enabling the integration of rainfall–runoff generation with two-dimensional flood propagation and providing a spatially explicit representation of urban flooding processes (Khatooni et al., 2025).

To evaluate the hydrological and hydraulic response of the study area under different rainfall conditions, three rainfall scenarios were defined. These scenarios represent moderate, high-intensity, and extreme storm events, selected based on the range of observed rainfall depths and durations during the monitoring period. The use of three scenarios allows examination of model behaviour across typical and critical conditions, with particular emphasis on post-fire runoff sensitivity. The modelling workflow illustrated in Figure 3 summarizes the integration of UAV-derived data, hydrological modelling using SWMM, and two-dimensional hydraulic simulations using HEC-RAS. High-resolution UAV data were initially used to generate a detailed DSM, which was subsequently processed into a DTM with a spatial resolution of 1.5 cm for the hydraulic simulations, ensuring numerical stability while preserving key topographic features.

3.6 Model Calibration and Performance Evaluation

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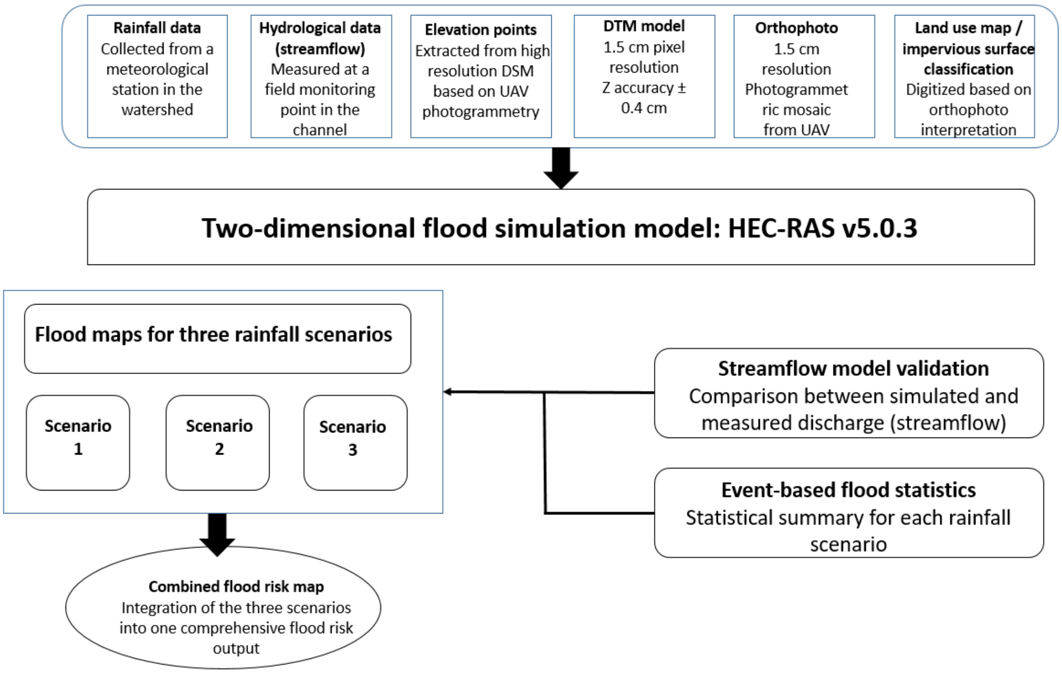

Figure 3. *presents the general workflow used to simulate post-fire flood risk in the Shazar urban watershed using the two-dimensional HEC-RAS v5.0.3 model. The workflow combines several types of input data that were collected or derived from different sources. Rainfall information came from a meteorological station, while streamflow was measured at the monitoring point inside the channel. Elevation points were extracted from a high-resolution UAV-based Digital Surface Model, and the DTM was produced at 1.5 cm resolution. Orthophotos from the UAV survey were used to prepare land-use and impervious-surface maps, which helped describe the physical conditions of the basin. These datasets were then used to simulate flood extents for three different rainfall scenarios. After running the model, the simulated discharge was compared with the measured discharge for validation. Basic flood statistics for each scenario were calculated. Finally, the flood maps from the three scenarios were combined to produce one comprehensive map that describes the overall flood risk in the area.*

Group	**Rainfall (mm)**	**Event duration (min)**	**No. of events**	**ΔQ_U ≤ 5**	**ΔQ_U > 5**	**Model success upper culvert (%)**	**Model failure upper culvert (%)**	**ΔQ_L ≤ 5**	**ΔQ_L > 5**	**Model success – lower culvert (%)**	**odel failure – lower culvert (%)**
A	0-30	0-100	91	74	17	81%	19%	52	39	57%	43%
B	0-30	101-200	18	12	6	67%	33%	12	6	67%	33%
C	>30	>200	5	3	2	60%	40%	1	4	20%	80%
D	>30	0-100	1	0	1	0%	100%	1	0	100%	0%

Table 1. *presents the model performance for different rainfall groups based on rainfall depth and storm duration. Each group shows how many events were recorded and how well the model predicted peak discharge at the upper and lower culverts. The values ΔQ_U and ΔQ_L represent the absolute difference between observed and simulated peak flows. Smaller values indicate better agreement. The results show that the model performed well during short and moderate storms in Group A, where most events had small differences between observed and simulated peaks. Group B also shows reasonable performance for longer storms with low rainfall. However, in Groups C and D, which include heavier rainfall or very long storm durations, the model accuracy decreased. These groups show higher differences between observed and simulated values, especially at the lower culvert. Overall, the table helps to identify the conditions under which the model works well and the conditions where it becomes less accurate.*

4. RESULTS AND DISCUSSION

The results of this study show that combining the UAV data with the SWMM and HEC-RAS models helped us understand how runoff develops and moves across the basin. In general the model was able to predict the timing of runoff and the places where water accumulated. Furthermore the simulated values during the calibration phase were close to the measured discharges, especially during normal or moderate rainfall events. However larger errors appeared during strong and less frequent storms because these storms may include sudden changes in infiltration, more surface flow coming from burned slopes or temporary blockages in the drainage system.

The validation results, as shown in Table 1, indicate clear differences in model performance across rainfall conditions and drainage outlets. For moderate rainfall events (Groups A and B; rainfall ≤ 30 mm), model performance at the upper culvert was relatively high, with success rates of 81% (Group A) and 67% (Group B). When considering all moderate events together, 86 out of 109 events (approximately 79%) were classified as successful simulations ($\Delta Q \leq 5$ m³/s) at the upper outlet.
At the lower culvert, performance was lower for short-duration moderate events (57% success in Group A) and similar for longer-duration moderate events (67% success in Group B), indicating increased routing complexity downstream.
For higher-intensity and longer-duration events (Groups C and D; rainfall > 30 mm), model performance declined. At the upper outlet, success rates were 60% in Group C and 0% in Group D, although Group D includes only one event. At the lower outlet, success was 20% in Group C and 100% in Group D, again reflecting the limited sample size. Overall, the modelling framework performs reliably for moderate rainfall events, while performance becomes more variable under high-intensity or extreme storm conditions.

In addition to the temporal behavior the spatial analysis showed that the physical structure of the basin plays an important role in shaping the runoff pattern. Steeper slopes force water to move faster and increase the chance of concentrated flow. Additionally the high percentage of impervious surfaces reduces infiltration and produces faster surface runoff. After fire events these effects become stronger because vegetation loss and reduced infiltration create more connected flow paths. Consequently floods become more intense and peak runoff increases more quickly than before the fire.

5. CONCLUSIONS

This study shows that using UAV-based data in combination with hydrological and hydraulic models can improve the understanding of urban runoff in Mediterranean regions. The approach performed well under conditions influenced by forest fires and rapid urban development. The high-resolution topography and detailed land-cover information helped the models represent the basin more accurately, while the use of time-varying hydrological inputs made the runoff simulations more realistic and supported the identification of areas susceptible to flooding.

This study further demonstrates that integrating high-resolution UAV-derived data into a coupled SWMM–HEC-RAS modelling framework improves the representation of post-fire urban runoff processes. The results indicate that the model performs reliably under moderate rainfall conditions, while performance decreases during extreme events due to nonlinear runoff responses and increased flow complexity. These findings highlight both the potential and the limitations of high-resolution, data-driven modelling approaches for post-fire flood assessment in urban environments, and show that the proposed framework can support stormwater management planning and the design of more resilient drainage systems under changing climate conditions.

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