

 <https://doi.org/10.71573/0jyr9z41>

© Authors. This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/)

Development of an innovative approach for modelling urban surface flow during stormwater events

Leonardo Bayas-Jiménez¹  <https://orcid.org/0000-0001-8957-7604>,
Aurora Gullotta^{1,*}  <https://orcid.org/0000-0003-3782-8015> & Alberto Campisano¹  <https://orcid.org/0000-0002-8664-8996>

¹University of Catania, Department of Civil Engineering and Architecture, Catania, Italy

*Corresponding author email: aurora.gullotta@unict.it

Abstract

The paper presents a methodology for the simulation of surface flows on urban streets during stormwater events. In a novel way with respect to past research, the sewer capacity is dynamically evaluated based on simulations to account for its variability on time during the flood event. Specifically, the methodology is based on the use of a 1D model of the sewer network and of a 1D model of the urban surface network. First, the sewer network model is used to calculate actual sewer capacity during the flood. Such results are then used to obtain a “reduced” hyetograph, which is adopted as input for the simulation of the surface network model. The methodology was applied to an urban catchment in southern Italy affected by problems of pluvial flooding. Field data - comprising direct measurements and indirect estimations (from video-clips) of flows in streets - were used for calibration and validation of the methodology. The outcomes demonstrated good agreement between simulated and observed data, indicating the reliability of the methodology for urban surface flow modelling.

Highlights

- Urban pluvial flood modelling with dynamic simulation of sewer capacity
- Calibration and validation with field data including video-based estimations
- Full transferability with balance of computational efficiency and results accuracy

Introduction

The increase in urbanisation has reduced the infiltration and evapotranspiration capacities of cities. Coupled with the rise in intense stormwater events, this has exacerbated surface flow issues in urban catchments (Tabari, 2020; Hu et al., 2020; Cea and Costabile, 2022). During heavy rainfall events, sewer networks tend to become overloaded, thus causing water levels to rise in the streets and leading to flooding in urban areas. Understanding the behaviour of surface flows on urban streets can serve as a tool for identifying adequate mitigation actions. Surface flow modelling has emerged as a viable possibility to carry out this task. However, the task presents significant challenges due to the multifaceted nature of the involved processes and the inherent complexity of urban topography (Henonin et al., 2013).

In the literature, various studies have been conducted on the modelling of urban surface flows during pluvial floods. Globally, studies can be grouped in two types of approaches. The first approach consists in the use of one-dimensional (1D) surface flow models and - where necessary - of two-dimensional (2D) ones. The second approach addresses the analysis of the interaction between the drainage at the surface and the sewer system flow, commonly known as dual drainage analysis.

With regard to the first approach, 1D models represent the main flow in a single dimension. Although 1D models require minimal input data and relatively short calculation times, they may have limitations

when flows are multi-directional (Heywood et al., 1997; Basnayaka and Sarukkalige, 2011). In contrast, 2D models discretize the catchment area using a structured grid that allows both components of the flow to be considered (Li et al., 2022). However, 2D models require high-resolution topographic data, significant computational resources, and extended calculation times (Mark et al, 2004; Oberauer and Lehmann, 2023).

Another important problem in modelling floods in urban areas is due to difficulties in providing sufficient data to build the sewer network model (Zhang and Pan, 2014; Liu et al., 2015). This is why 1D and 2D flow surface models frequently do not account for flows entering sewers (Henonin et al., 2013), reducing - *de facto* - the accuracy of the simulation results (Li et al., 2023). The analysis of the scientific literature shows some attempts to take into account sewer capacity, that consist mainly of approximated procedures based on artificially increasing infiltration in the urban soil (Wang et al., 2018), on simulating sewer inlets by assuming unlimited capacity of the sewer (Xing et al., 2022), or on reducing the net rainfall by a constant value on time representative of the sewer design capacity (Yu and Coulthard, 2015; Yin et al., 2016; Wang et al., 2018; Xing et al., 2022). However, adoption of such procedures would need preliminary validation through experimental data in order to avoid inaccuracies due to over/underestimation of the surface runoff during the flood event (Montalvo et al., 2024).

With regard to the second approach, dual drainage analysis includes use of 1D–1D and 1D–2D models, for connecting flow in the sewer system (1D) to the surface flow (1D or 2D). Great advances have been made in the recent years with the development of dual drainage models, but their use is still not a common practice outside of research environments. In fact, such models require high spatial resolution in terms of hydrological data (e.g., local infiltration capacity, soil roughness, etc.), detailed topographic information, as well as significant computational capacity. In addition, a very detailed knowledge of the characteristics of sewer networks is needed including, not only basic data (such as elevations, diameters, and lengths of pipes), but also information that is more complex to obtain (e.g., locations, types, and geometry of inlets and manholes) for modelling the bi-directional flow exchanges between sewer and surface networks (Wang et al., 2018). These requirements greatly limit the practical applicability of dual drainage models for most urban catchments for which such detailed information is not available (Kourtis, et al., 2017).

In light of above considerations, 1D approaches for surface flow modelling, if validated, always remain good alternatives to describe in a sufficiently proper way the impact of pluvial floods in urban areas without the computational limitations of 2D approaches or dual drainage models.

Building on this, the objective of this work is to present a novel methodology for modelling surface flows on urban streets during pluvial floods. The main novel aspect of the methodology lies in the definition of a simulation-based procedure to evaluate the sewer capacity that allows accounting for its variability over time during the flood event. The developed methodology includes the construction of two different models: the model of the sewer network and the model of the surface street network. The sewer network model is used to evaluate dynamically the capacity of the sewer system during the rainfall event. Such results are then used to obtain a “reduced” hyetograph, which is adopted as input for the next simulations with the surface network model. The methodology was applied to a large urban catchment in the city of Catania, Italy, in which significant pluvial flood events have occurred in recent years. The Storm Water Management Model (SWMM) of the U.S. Environmental Protection Agency (EPA) (Rossman, 2015) was used for the application of the methodology. Calibration and successive validation of the developed methodology were carried out based on available experimental data from field observations of water depth, flow velocity, and flow rate in streets of the city during flood events.

Methodology

The main stages of the methodology are presented in the flowchart in Figure 1. The process requires the development and decoupled use of two different models: the model of the sewer network and the model of the surface network. Modelling requires geospatial information and field data concerning topological, geometrical and hydraulic characteristics of the networks of sewer pipes and streets. Firstly, the sewer network model is used to simulate the precipitation event using the total hyetograph as model input. Then, the results of the simulation are used to evaluate a “reduced” hyetograph, obtained by subtracting the capacity of the sewer at each time step from the total rainfall of the event. Finally, the reduced hyetograph is used as input for the surface network model in order to simulate flows in the streets. As shown in the flowchart, the methodology provides that different sets of the parameter values (e.g., sub-catchment parameters) are tested for model calibration. Calibration and successive validation are carried out through comparison of model results with experimental data derived from field observations during real flood events.

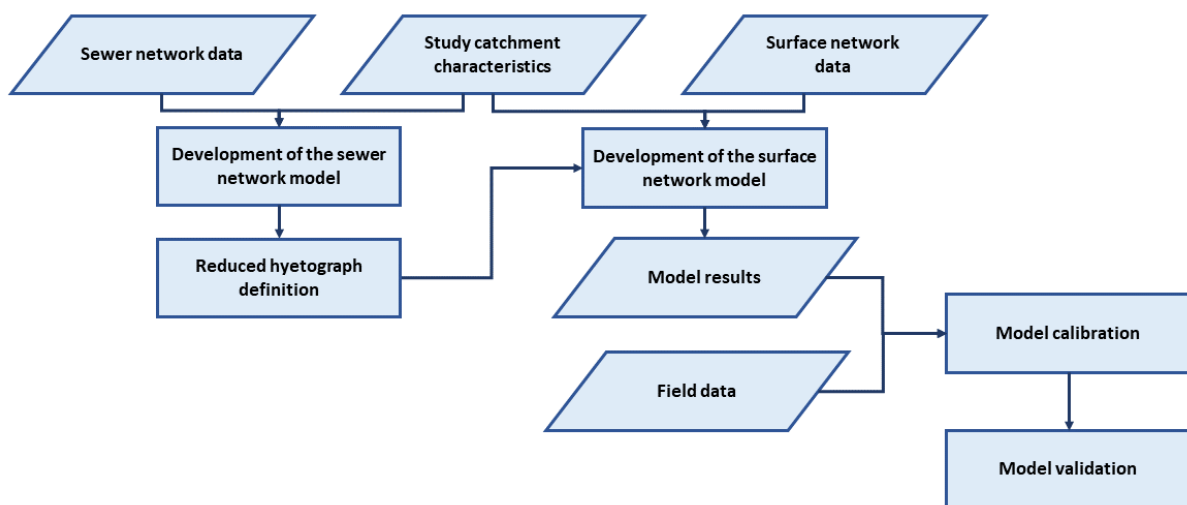


Figure 1. Framework of the proposed methodology.

Development of sewer network and surface network models

Both the sewer network model and the surface network model were developed using EPA-SWMM (release 5.2).

Construction of the sewer network model was based on basic information about the sewer infrastructure that was derived mostly from consultation of maps and reports provided by the municipality and water utility. This information includes elevation data for the nodes, and characteristics of pipes. No detailed information about locations and geometry of inlets and manholes was necessary to include.

The surface network model in the SWMM environment was constructed by representing streets as open channels, with their cross-sectional geometry reflecting the actual street transects. The intersections between streets were modelled as nodes. The characteristics of the transects and the nodes were derived from geospatial information. In particular, a geodatabase of the roadway infrastructure was used to extract the topology of the streets, while a Digital Surface Model (DSM) of the area was used to derive elevations. Wherever missing, specific field surveys were carried out to determine other important geometrical/hydraulic characteristics of the streets. Transects modelling includes both street lanes and sidewalks, thus enabling the simulation of hydraulic conditions occurring when water depth exceeds curb height and invades pedestrian areas.

An important assumption of the methodology is that both the sewer and the surface network models share the same total area of the urban catchment and the same number, positions and characteristics of sub-catchments. The whole catchment was divided into sub-catchments that were allocated to the street network nodes. The area of each subcatchment is determined proportionally to the half-sum of the lengths of the streets connected to the node. All sub-catchments comprise portions with pervious and impervious areas, respectively. The Curve Number (CN) method was used to evaluate infiltration in the pervious areas of each sub-catchment.

Construction of the reduced hyetograph

The construction of the reduced hyetograph required to use first the model of the sewer network. At each simulation time t [h] of the rainfall event (of total duration T), the model provides, as output result, the volume of water that leaves the sewer system through the outfall nodes $V(t)_{outfall}$ [m³], as well as the volume in store in the sewer $V(t)_{store}$ [m³]. Based on such output, the reduced hyetograph of the rainfall event can be determined and subsequently used as the input for the surface network model. The total water volume handled by the sewer $V(t)_{sewer}$ [m³] is computed as (Equation 1):

$$\forall t \in T, V(t)_{sewer} = V(t)_{outfall} + V(t)_{store} \quad (1)$$

and is converted into sewer capacity $I(t)_{sewer}$ [mm/h] at time t by using Equation 2. Finally, the reduced rainfall intensity $I(t)_R$ [mm/h] is derived by subtracting $I(t)_{sewer}$ from the total rainfall intensity $I(t)_T$ [mm/h] (Equation 3).

$$I(t)_{sewer} = \frac{1000 \cdot V(t)_{sewer}}{A_T \cdot t} \quad (2)$$

$$I(t)_R = I(t)_T - I(t)_{sewer} \quad (3)$$

Model calibration and validation

Hydrological parameters of the sub-catchments play a crucial role in determining the partition of the rainfall in hydrological losses and surface runoff, thus directly influencing the simulation results. In SWMM these parameters include the percentage of impervious area ($\%Imperv$), the depth of the depression storage in impervious areas ($DStore-imperv$) and in pervious ones ($DStore-perv$), as well as the percentage of impervious area with no depression storage ($\%Zero-Imperv$).

For the study catchment, field data are available that include experimental observations of water depth, flow velocity and flow rate in streets during relatively recent rainfall events that caused flooding in the city. Therefore, it was possible to calibrate the model by performing simulations with different sets of the parameters listed above. In particular, the calibration was carried out by minimizing the Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{n}} \quad (4)$$

where n is the total number of observations available for the analysed flood event, x_i is the observed value for measure i and y_i is the corresponding simulated value.

As detailed in the following, field data collected during one of the flood events were used to calibrate the model parameters. Then, a validation stage was carried out by testing the calibrated methodology in the case of two other flood events for which further field data are available.

Case study

The proposed methodology was applied to an 873-hectares urban catchment located in the metropolitan area of Catania, in southern Italy. The metropolitan city exhibits a varied topography, with more flat zones in proximity to the coastal area and significant slopes in areas at the foothills of Mount Etna. In the recent past, the catchment has been prone to severe pluvial floods, due to both the topographical characteristics of the city and the progressive increase in urbanization especially in the foothill areas external to the city. Due to the topography of these external urbanised areas and the low development of the sewer system in such areas, part of the surface runoff generated upstream during rainfall events contributes with inflows to the city, thus sharpening flood problems in the city centre. Figure 2a shows the study catchment. The downstream segment of one of the main streets of the historical city centre (Via Etna) was assumed as the catchment closure section. Figure 2a shows also that six external areas – A1 to A6 – (about 627 additional hectares in total), partially belonging to suburbs of the city or to other neighbour municipalities, contribute to apport some runoff generated in such areas.

Five distinct sub-areas have been identified within the study catchment showing different levels of urbanisation and land use. Freely available aerial imagery and satellite photographs were used to identify the urbanised and the green zones for each sub-area and each external contributing area.

In addition, Figure 2 reports the total hyetographs of the rainfall events occurred on 19 October 2024 (Figure 2b) and on 21 February 2013 (Figure 2c). The first event was used for model calibration while the second is one of the two events used for model validation.

A total of 13 direct measurements of water depth h [m] and two sets of estimated (from video-clips) measurements of h , flow velocity V (m/s) and flow rate Q [m³/s] in various street sections of the city were available for the event of 19 October 2024. Video footages were used to evaluate average water depths, as well as for the estimation of average values of flow velocity in the transects. The procedure to estimate the flow velocity is based on the identification, in the video frames, of objects transported by the flow (e.g. floatables, etc.) and on the evaluation of their velocity. It is worth noting that the positions of the object (and therefore the travelled distance by the object) were determined in two successive frames, by projecting such positions with respect to fixed points of the surrounding environment (e.g., on walls of buildings, curb edges, etc.); the velocity of the object is then estimated according to the time of travel, based on the lag time between the frames. Finally, based on the street transect geometry, an approximate estimation of flow rate was carried out.

For the event in Figure 2c, a set of estimated (from video-clips) measurements of h , V and Q in a street section were available.

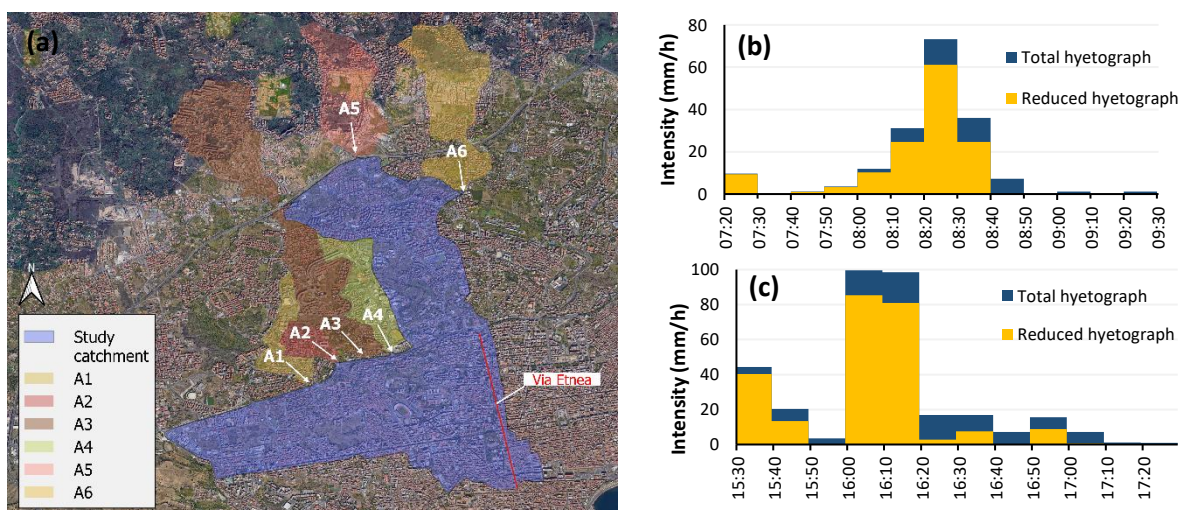


Figure 2. (a) Study catchment and external contributing areas (A1-A6). Total and reduced hyetographs of (b) event of 19 October 2024 and of (c) event of 21 February 2013.

Results and discussion

For model calibration, fifteen different parameter configurations were tested (Table 1). In particular, based on the analysis of the characteristics of the catchment, simulations were performed with values of impervious areas in urbanised zones ranging from 60-90% (see Table 1). This was translated into values of model parameter *%Imperv* that are different for each sub-area and external area of the catchment. Also, values of *%Zero-Imperv* between 5-25%, of *DStore-imperv* between 2-3 mm, and of *DStore-perv* between 4-6 mm were tested in the simulations. The results indicate that configuration n. 14 demonstrated the best predictive performance – that is the lowest values of the RMSE for 2 out 3 hydraulic variables.

For such a configuration, Figure 2 reports the reduced hyetographs for the event of 19 October 2024 (Figure 2b) and of 21 February 2013 (Figure 2c), obtained according to the procedure described in the methodological section.

Figure 3 reports the comparison of the results of the calibrated model with observed values of *h*, *V*, and *Q* at the specific measurement street section for the event used for model validation (21 February 2013).

At 16:25 (time of the available measurements), the model overestimates the water depth of about 0.05 m (error of 16.1%) (Figure 3a), and the flow rate of about 1.28 m³/s (error of 6.9%) (Figure 3c). Conversely, Figure 3b shows that the simulated value of the flow velocity (4.15 m/s) is 6.3% lower than the value estimated from the field (4.43 m/s).

Both Table 1 and Figure 2 shows that a good match between simulated and experimental data was obtained across the two analysed events.

Table 1. Sets of model parameters used for model calibration (event of 19 October 2024).

Configuration	Impervious area in urbanized zones (%)	<i>%Zero- Imperv</i> (%)	<i>Dstore- imperv</i> (mm)	<i>Dstore- perv</i> (mm)	RMSE <i>h</i> (m)	RMSE <i>V</i> (m/s)	RMSE <i>Q</i> (m ³ /s)
1	60	10	3	6	0.0324	0.2601	1.9863
2	70	10	3	6	0.0314	0.2508	1.5991
3	80	10	3	6	0.0318	0.1752	1.1986
4	65	10	3	6	1.0601	0.2626	1.7604
5	75	10	3	6	0.0314	0.2095	1.3939
6	70	5	3	6	0.0314	0.2524	1.6027
7	75	5	3	6	0.0314	0.2052	1.3797
8	70	10	2	6	0.0318	0.2394	1.5500
9	75	10	2	6	0.0320	0.1836	1.3676
10	70	10	3	4	0.0314	0.2508	1.5991
11	75	10	3	4	0.0314	0.2096	1.3944
12	85	10	3	6	0.0325	0.1416	1.0119
13	90	10	3	6	0.0334	0.1162	0.8485
14	90	25	3	6	0.0335	0.1096	0.8186
15	90	25	2	6	0.0340	0.1152	0.8375

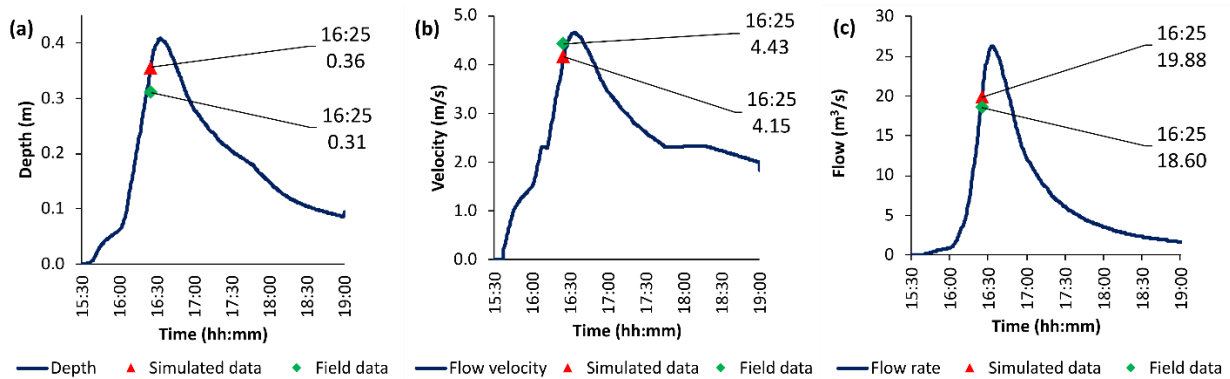


Figure 3. Simulated and observed (a) water depth (b), flow velocity, and (c) flow rate at the measurement street section for the event of 21 February 2013 (configuration n. 14).

Conclusions and future work

This work presents novel methodology for the simulation of surface flows on urban streets during pluvial floods. Differently from previous methodologies from the literature, the flow intercepted by the sewer system is determined dynamically on the basis of simulations, thus account for its variability on time during the flood event.

The proposed methodology is based on the development and decoupled use of a model of the sewer network and a model of the surface network of the urban catchment. The initial simulation with the sewer network model allows to evaluate the capacity of the sewer system on time and to construct the reduced hyetograph to be used for the simulation with the surface network model. The methodology was tested on an urban catchment in southern Italy that has shown frequent problems of pluvial flooding in the past. Field data including water depth, flow velocity, and flow rate along streets obtained by direct measurements in the field and by extraction from video-clips during real flood events in the catchment were used for model calibration and validation. The outcomes demonstrate good agreement between simulated and observed data with relatively small values of the RMSE for water depth, flow velocity, and flow rate.

Future research may include, for instance, the use of multiple reduced hyetographs for the simulations, differentiating them by the sewer network characteristics of the various sub-areas of the catchment.

References

- Basnayaka, A., & Sarukkalige, P. R. (2011). Comparing hydrology and hydraulics surface routing approaches in modeling an urban catchment. In *Proceedings of the 2nd International Conference on Environmental Engineering and Applications* (pp. 123–127). IACSIT Press.
- Cea, L., & Costabile, P. (2022). Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A Review. *Hydrology*, 9(3).
- Henonin, J., Russo, B., Mark, O., & Gourbesville, P. (2013). Real-time urban flood forecasting and modelling – a state of the art. *Journal of Hydroinformatics*, 15(3), 717–736.
- Heywood, G. M., Kolsky, P. J., & Butler, D. (1997). Modelling Drainage Performance in an Indian Catchment. *Water and Environment Journal*, 11(1), 31–38.
- Hu, S., Fan, Y., & Zhang, T. (2020). Assessing the effect of land use change on surface runoff in a rapidly urbanized city: a case study of the central area of Beijing. *Land*, 9(1), 17.
- Kourtis, I. M., Bellos, V., & Tsihrintzis, V. A. (2017). Comparison of 1D-1D and 1D-2D urban flood models. In *Proceedings of the 15th International Conference on Environmental Science and Technology (CEST 2017)*, Rhodes, Greece (Vol. 31).
- Li, D., Hou, J., Shen, R., Li, B., Tong, Y., & Wang, T. (2023). Approximation method for the sewer drainage effect for urban flood modeling in areas without drainage-pipe data. *Frontiers in Environmental Science*, 11, 1134985.
- Li, D., Hou, J., Zhang, Y., Guo, M., & Zhang, D. (2022). Influence of time step synchronization on urban rainfall-runoff simulation in a hybrid CPU/GPU 1D-2D coupled model. *Water Resources Management*, 36(10), 3417–3433.
- Liu, L., Liu, Y., Wang, X., Yu, D., Liu, K., Huang, H., & Hu, G. (2015). Developing an effective 2-D urban flood inundation model for city emergency management based on cellular automata. *Natural Hazards and Earth System Sciences*, 15(3), 381–391.

- Mark, O., Weesakul, S., Apirumanekul, C., Aroonnet, S. B., & Djordjević, S. (2004). Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology*, 299(3), 284–299.
- 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.
- Oberauer, M., & Lehmann, B. (2023). Modifying 2D surface models in urban flood analysis. *Journal of Hydrology*, 625, 130063.
- Rossman, L. A. (2015). *Storm water management model (SWMM) user's manual version 5.1*. Cincinnati, OH, 45268.
- Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports* 2020 10:1, 10(1), 1–10.
- Wang, Y., Chen, A. S., Fu, G., Djordjević, S., Zhang, C., & Savić, D. A. (2018). An integrated framework for high-resolution urban flood modelling considering multiple information sources and urban features. *Environmental Modelling & Software*, 107, 85–95.
- Xing, Y., Shao, D., Liang, Q., Chen, H., Ma, X., & Ullah, I. (2022). Investigation of the drainage loss effects with a street view based drainage calculation method in hydrodynamic modelling of pluvial floods in urbanized area. *Journal of Hydrology*, 605, 127365.
- Yin, J., Yu, D., Yin, Z., Liu, M., & He, Q. (2016). Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China. *Journal of Hydrology*, 537, 138–145.
- Yu, D., & Coulthard, T. J. (2015). Evaluating the importance of catchment hydrological parameters for urban surface water flood modelling using a simple hydro-inundation model. *Journal of Hydrology*, 524, 385–400.
- Zhang, S., & Pan, B. (2014). An urban storm-inundation simulation method based on GIS. *Journal of Hydrology*, 517, 260–268.