https://doi.org/10.71573/sjczjm67

Modelling tray-based modular blue-roof systems by using EPA-SWMM

Aurora Gullotta [1,*] https://orcid.org/0000-0003-3782-8015,
Leonardo Bayas-Jiménez [1] https://orcid.org/0000-0001-8957-7604
& Alberto Campisano[1] https://orcid.org/0000-0002-8664-8996

[1]*University of Catania, Department of Civil Engineering and Architecture, Catania, Italy*
**Corresponding author email: aurora.gullotta@unict.it*

Abstract

This study proposes a model to simulate the hydraulic/hydrological behaviour of modular tray-based blue roof systems during rainfall events. The model was developed using EPA-SWMM software and it was applied to a full-scale pilot of modular blue roof installed in south Italy. The paper firstly provides a description of the pilot installation. Then, the conceptualization of the modular blue roof system in the software is outlined. Available components and tools in the software were arranged and customized to reproduce the system behaviour. Model parameters were set based on the geometrical and hydraulic characteristics of the pilot. The model was validated by simulating the system behaviour during 9 rainfall events recorded on the pilot between 2018 and 2024. Results of the model application to the pilot show a good ability of the model to reproduce the behaviour of the system during precipitation events. The model opens perspective to the analysis of the broader benefits of implementing such systems at the scale of the urban catchment, providing valuable opportunities for sustainable urban water management.

Highlights

- A modular tray-based blue roof pilot was modelled using EPA-SWMM software
- The model shows a good ability to reproduce the behaviour of the blue roof during precipitation events
- Results open perspectives for the simulation of blue roofs at the scale of the urban catchment

Introduction

Among the available Sustainable Urban Drainage Systems (SUDS), Blue Roofs (BRs) have recently been shown to provide great potential for runoff control (Gullotta et al., 2025).

BR systems allow on-site detention and delayed release of runoff from building roof catchments (Hamouz and Muthanna, 2019; Almaaitah and Joksimovic, 2022). Different BRs technologies have been proposed in the literature to obtain the desired flow attenuation effects from the roofs. Technologies include the use of flow limiters mounted on the outlet roof drains, concentric check dams/weirs placed around the roof outlets, and the use of modular trays with restricted orifices for rainwater detention (NYC DEP 2012).

Among the applied technologies, BRs based on the use of modular trays proved high performance in controlling storm water flows at low costs of installation and maintenance. Recent results of the use of this technology are available from experiments on a full-scale BR pilot mounted on the roof of a building of the campus of the University of Catania, Italy (Campisano et al., 2018; 2021). The BR installed in one catchment of the rooftop was compared with an identical catchment that was left

unmodified and used as a reference. Comparatively, the BR always outperformed the conventional roof, showing on average a 34% runoff reduction and a 60% flow peak attenuation (Campisano et al., 2021).
However, the development of BRs is still at a prototypal/pilot stage and a major research gap exists on the modelling of these systems. Campisano et al., (2022) developed a simple spreadsheet-based model to simulate the hydrological behaviour of the modular BR system installed in Catania. Results of the model application with reference to precipitation events occurred between 2018 and 2020 showed a good match between simulations and experiments. However, embedding the proposed model into common software for the simulation of SUDS within urban catchments may require a major effort. Following this, the present work aims at developing a model of modular tray-based BR systems by using the Storm Water Management Model (SWMM) developed by the U.S. Environmental Protection Agency (EPA), already used in the literature for the modelling of different types of SUDS (Hamouz et al., 2018; Jeffers et al., 2022). The developed model was applied to the pilot installed in Catania. Available components and tools in the software were arranged and customized to reproduce the system behaviour. Model parameters were set based on the geometrical and hydraulic characteristics of the pilot. The model was validated by simulating the system behaviour during 9 rainfall events recorded on the pilot between 2018 and 2024.

Methodology

The BR pilot

The pilot is a tray-based modular BR system installed on a catchment of the roof terrace of a building in the university campus of Catania, Italy (Campisano et al., 2021). The system consists of 64 tray modules arranged into four macro-strips, each comprising 16 trays (Figure 1). The total dimensions of the catchment are 5.72 m in length and 4.60 m in width, yielding a surface area of 26.31 m². Of this, the modules themselves cover 17.21 m², corresponding to approximately 65.4% of the total area, while the remaining 9.10 m² (34.6%) comprises internal corridors between the strips and perimeter drainage channels.

Figure 1. Tray-based modular BR pilot.

Each module is an open rectangular polypropylene tray with internal dimensions of 59.5 cm by 39.7 cm and a height of 11.5 cm (Campisano et al., 2018). A circular drainage hole (7 mm diameter) is located 7.5 cm from the short side, aligned with the lateral central axis. At the bottom of each tray, a non-recycled polyester geotextile sheet was installed. The trays were partially filled with lava gravel ranging from 1.5 to 3.0 cm in diameter, forming a uniform layer approximately 3 cm deep. To ensure effective drainage, the modules were elevated 1 cm above the ground using plastic spacers at the four

corners of the bottom (external side). According to the characteristics of the used trays, the BR system provides for temporary storage capacity during rainfall events close to 1500 litres.
At the base of the building, a 1000-litre tank is used to collect runoff from the catchment. A silicon piezoresistive probe is installed within the tank for the estimation of the inflow through differential water level measurements. A meteorological station is installed on the roof, recording precipitation and other weather variables at one-minute time step. A programmable logic controller (PLC) manages the collection, synchronisation, and storage of data from all sensors in the experimental setup. Further details on the pilot installation as well as on the set-up of the single module can be found in Campisano et al., (2018, 2021).

Conceptualization of the BR pilot in EPA-SWMM

SWMM is a dynamic rainfall-runoff model developed for the simulation of urban drainage systems in primarily urban area. The Release 5.1 of the software was used in this study (Rossman, 2015). The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff, after computation of water losses. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators.
The outlet of a subcatchment can be a simple junction of the drainage network or a storage unit node. The last is the only type of node in the software that can provide storage volume and possess surface area. Outflow from a storage unit node can be regulated in the software through the use of an outlet link, which is a generic type of flow regulator with a user defined rating curve that relates flow rate to effective head. It can be used in cases where the head-flow relationships that SWMM uses for other flow regulator elements (e.g., orifice or weir) do not apply.
In this context, the BR pilot is modelled by considering two representative subcatchments: one corresponding to the area occupied by the 64 trays (SC-T), and another representing the corridors and perimeter areas of the pilot (SC-C) (Figure 2). Runoff from SC-T is drained to a storage unit node (ST-T) that simulates the temporary storage of water within the trays and its release through the outlet orifices. Similarly, subcatchment ST-C drains to a storage unit node (ST-C) representing the whole roof catchment area. Node ST-C also receive the outflow from ST-T, simulated using an outlet link (O-T). Finally, the total outflow from ST-C is regulated by another outlet link (O-C) simulating the drainage process of the whole catchment through the downspout inlet.
With appropriate parameters setting, this configuration allows for a realistic representation of the hydraulic/hydrological behaviour of the pilot system during precipitation events. The conceptual model of the BR system implemented in SWMM is shown in Figure 2, while the characterization of the model elements is described in detail in the following paragraphs.

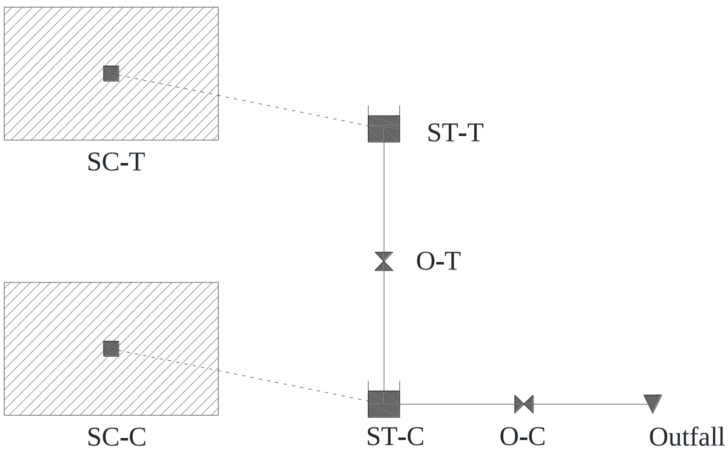

Figure 2. Conceptual model of the BR system in EPA-SWMM.

Model parameters setting

Parameters of the software elements in the conceptual model in Figure 2 were set according to the geometrical and hydraulic characteristics of the pilot.
Subcatchment SC-T in the model has a total area *A* of 17.21 m², corresponding to the area occupied by the trays. SC-T is considered 100% impervious with a depression storage depth of 4 mm, reflecting the total retention capacity of the trays (Campisano et al., 2021). On the contrary, subcatchment SC-C (Figure 2), with *A*=9.1 m² corresponding to the corridors between trays and perimeter zones, is modelled as a fully pervious subcatchment with no depression storage, the roof paving being laid regularly. Hydrological losses in SC-C are estimated using the Curve Number (CN) method, which depends on two parameters: the CN value itself and the drying time. A CN value of 98 was adopted, representative of the roof surface paving (concrete tiles) and local site conditions. The drying time was set to 4 hours, corresponding to the time needed for restoring dry condition in the corridors after a precipitation event (Campisano et al., 2021).
Values of slope *S*=1.6% and Manning's roughness coefficient *n*=0.016 were set for both SC-T and SC-C according to the characteristics of the catchment roof terrace. The width *W* (m) is estimated through the commonly used empirical equation (Krebs et al., 2014): $W = 0.5\sqrt{A}$.
Storage unit node ST-T (Figure 2) models the temporary storage of rainwater within the trays of the pilot. Outflow from the trays together with the rainfall that directly reaches the corridors (i.e., subcatchment SC-C) is then drained towards the storage unit node ST-C (Figure 2), thus representing the whole roof catchment. Both storage nodes are modelled in SWMM as reservoir with constant cross-sectional area. In particular, an area of 17.21 m^2 - which is the total area occupied by the 64 trays - is assigned to ST-T, while ST-C is modelled with the total area of the roof catchment in which the pilot is installed (26.31 m^2).
For the outlet link O-T (Figure 2), the total discharge is simulated using the Torricelli equation multiplied by the total number *n* of trays in the system (Eq. 1).

$$Q = n\, C_1\, A_o\, \sqrt{2\, g\, h} \tag{1}$$

where C_1 (-) is the discharge coefficient, A_o (m^2) is the outlet orifice area of each tray, and *g* (m^2/s) is the gravity acceleration. In the specific case, a coefficient C_1=0.6 – common value for circular bottom orifice – is used, while A_o is equal $3.85 \cdot 10^{-5}$ m^2 (area of the 7 mm circular orifice).
With regard to outlet link O-C (Figure 2), the dynamic of discharge of the whole roof catchment through the downspout inlet is considered. A particular of the roof downspout inlet is shown in Figure 3.

Figure 3. Downspout inlet of the roof terrace catchment.

For this type of drainage inlet, Da Deppo and Datei (1999) suggest using a modified version of Torricelli's equation that accounts for the geometry of the inlet opening (Eq. 2). In the equation, C_2 (-) is the discharge coefficient, and l (m) is the effective length of the drainage inlet.

$$Q = C_2\, l\, h \sqrt{2\, g\, h} \tag{2}$$

Based on the geometric characteristics of the drainage inlet, the authors recommend a discharge coefficient C_2 of 0.28. The effective length l of the inlet is estimated to be 20.42 cm, according to field measurement (Figure 3).
Finally, to simulate the discharge to the storage tanks located at the base of the building, a free-type outfall is used. This configuration allows the flow to exit the system unimpeded, replicating a free-flow condition.

Precipitation events for model validation

The SWMM model of the BR described in previous sections was validated by simulating the system behaviour during 9 rainfall events recorded on the pilot between 2018 and 2024. For each event, the total precipitation *P* (mm), the duration *d* (h), the peak rainfall intensity I_{max} (mm/h), and the observed accumulated runoff from the BR h_{BR}^{obs} (mm) at the end of the event are reported in Table 1.

Table 1. Characteristics of the precipitation events used for model validation.

Event	Date	*P* (mm)	*d* (h)	I_{max} (mm/h)	h_{BR}^{obs} (mm)
1	18/10/2018	19.80	19.80	33.50	14.54
2	31/10/2018	18.00	8.80	9.20	12.94
3	04/02/2019	42.40	30.60	21.40	33.69
4	03/11/2019	15.60	16.70	169.10	13.52
5	17/04/2022	24.20	22.10	37.70	18.40
6	13/10/2022	17.90	13.60	50.80	13.30
7	29/11/2022	20.80	15.80	9.30	18.60
8	09/01/2024	35.30	94.20	30.48	26.67
9	20/01/2024	16.00	35.90	9.12	11.53

To evaluate the ability of the model to reproduce the system behaviour, two statistical indexes were considered. First, the Relative Root Mean Square Error (RRMSE) between the observed and simulated accumulated runoff from the BR was calculated for each precipitation event:

$$\mathrm{RRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_{BR,i}^{obs} - h_{BR,i}^{sim}\right)^2}}{\overline{h_{BR}^{obs}}} \tag{3}$$

where *n* is the number of observations, $h_{BR,i}^{obs}$ (mm) represents the observed value of accumulated runoff at time *i*, $h_{BR,i}^{sim}$ (mm) is the corresponding simulated value, and $\overline{h_{BR}^{obs}}$ (mm) is the mean of the observed values of accumulated runoff for a specific event. This metric quantifies the discrepancy between the two curves.
In addition, the Nash–Sutcliffe Efficiency coefficient (NSE) was calculated, as defined in Equation 4:

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(h_{BR,i}^{obs} - h_{BR,i}^{sim}\right)^2}{\sum_{i=1}^{n}\left(h_{BR,i}^{obs} - \overline{h_{BR}^{obs}}\right)^2} \tag{4}$$

This coefficient assesses the model's ability to reproduce the temporal dynamics of the observed data. An NSE value close to 1 indicates a high predictive accuracy, whereas values near zero or negative suggest poor model performance.

Results and discussion

Values of both indicators for the nine analysed precipitation events are summarised in Table 2, while Figure 4 displays the curves for h_{BR}^{obs} and h_{BR}^{sim} for rainfall events n. 2, 3, 5 and 9.

Globally, the model proves capable of suitably reproducing the runoff process from the BR for all four events reported in Figure 4. The dashed line of the model follows rather well the continuous line of the experiments both in terms of cumulative runoff and slope of the curves during the event. Remarkably, the model is able to simulate correctly the hydrological response of the BR for all the showed events, which have different magnitudes.

Table 2. RRMSE and NSE indicators calculated for the analysed events.

Event	Date	RRMSE	NSE
1	18/10/2018	0.05	0.980
2	31/10/2018	0.05	0.991
3	04/02/2019	0.06	0.995
4	03/11/2019	0.34	0.876
5	17/04/2022	0.06	0.956
6	13/10/2022	0.07	0.992
7	29/11/2022	0.21	0.786
8	09/01/2024	0.07	0.979
9	20/01/2024	0.05	0.991

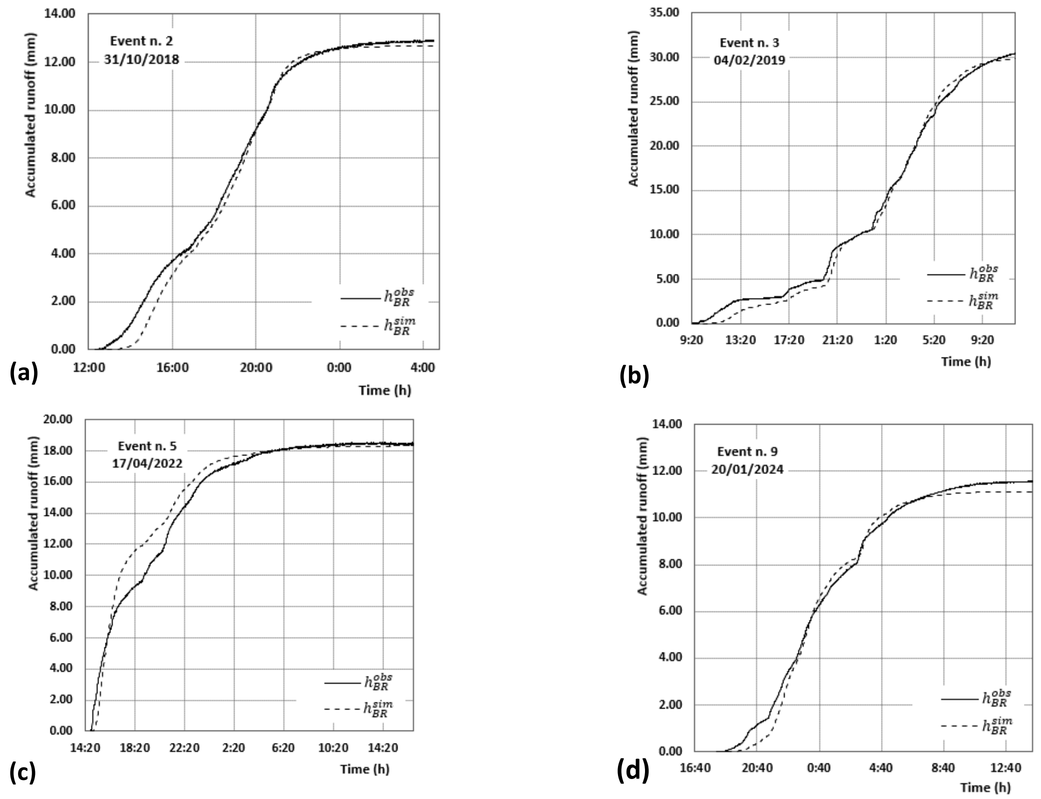

Figure 4. Observed VS simulated accumulated runoff from the BR for events of (a) 31/10/2018, (b) 04/02/2019, (c) 17/04/2022 and (d) 20/01/2024.

The good fit of the model to the experimental data is confirmed by the values of the indicators in Table 2. Specifically, across the nine events analysed, the maximum RRMSE value was 0.34 (event n. 4), the minimum was 0.05 (events n. 1, 2, 9), and the mean RRMSE was 0.11. These results indicate a good predictive capacity of the model in representing the hydrological response of the BR system. This finding is further supported by the NSE values, which remained consistently close to 1. The lowest NSE value was 0.786 (event n. 7), while the highest reached 0.995 (event n. 3), with a mean of 0.950. These values are well above the commonly accepted threshold of 0.50 for adequate performance in rainfall–runoff modelling using SWMM (Dongquan et al., 2009; Rosa et al., 2015; Johannessen et al., 2019) confirming the appropriateness of the adopted model configuration.

It is worth noting that the events n. 4 and n. 7 exhibit slightly higher deviations in both RRMSE and NSE. A plausible explanation is that the current model configuration does not account for evaporation losses that may occur in the pilot in the dry period between two successive rain showers, potentially affecting accuracy in certain conditions. This limitation highlights a possible direction for future improvements to the model.

Conclusions and future work

This paper describes a model to simulate the hydraulic/hydrological behaviour of modular tray-based blue roof systems during rainfall events. The model was developed using the free open-source EPA-SWMM software. Available components and tools in the software were arranged and customized to reproduce the system behaviour. The model was applied to a pilot of tray-based modular BR system installed on the roof terrace of a building in Catania, southern Italy. The application of the developed model to precipitation events recorded by the on-site monitoring system showed promising ability of the model to reproduce the hydrological behaviour of the BR system.

Overall, the obtained results open perspectives for the improvement of the developed model for the simulation of BR systems in roof cover terraces. Although the model parameters have to be set based on the site-specific geometry and characteristics of the installation, the methodology used in the work can be useful as a base for the development of more complex models for the simulation of BR systems at the scale of the urban catchment. The use of EPA-SWMM that is a well-know and widely adopted software in the field of stormwater management in urban environment facilitates the transferability of the developed model from the scale of the pilot installation to that of the urban catchment.

Acknowledgement

This work was supported (1) by the Italian Ministry of University and Research within the national projects “PRIN 2020 – URCA!” and (2) by the Project Multi-Risk sciEnce for resilient commUnities undeR a changiNg climate” (RETURN) funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3.

References

Almaaitah, T., & Joksimovic, D. (2022). Hydrologic and thermal performance of a full-scale farmed blue–green roof. Water, 14(11).

Brater E., King, H., Lindell, J., & Wie, C. (1996). Handbook of Hydraulics. Seventh Edition. McGraw Hill Book Company, Inc, New York. ISBN: 0-07-007247-7

Campisano, A., Creaco, E., Gullotta, A., Modica, C., & Musmeci, F. (2022). Modelling hydrological response of modular blue roofs for storm water control in a Mediterranean site. Urban Water Journal, 19(10), 1015–1024.

Campisano, A., Gullotta, A., & Modica, C. (2018). Laboratory analysis of the outflow and detention processes from modular tray-based blue roofs. Urban Water Journal, 15(10), 934–942.

Campisano, A., Modica, C., & Gullotta, A. (2021). Long-term experiments for the evaluation of the potential for storm water control of modular blue roofs in Mediterranean climate. Urban Water Journal, 18(1), 33–42.

Da Deppo, L., Datei, C. (1999). Le opere idrauliche nelle costruzioni stradali. Seconda Edizione. Editoriale Bios, Cosenza, Italia. ISBN: 88-7740-269-5

Dongquan, Z., Jining, C., Haozheng, W., Qingyuan, T., Shangbing, C., & Zheng, S. (2009). GIS-based urban rainfall-runoff modeling using an automatic catchment-discretization approach: a case study in Macau. Environmental Earth Sciences, 59(2), 465–472.

Gullotta, A., Musmeci, F., Cancelliere, A., & Campisano, A. (2025). Comparing potential for storm water control of different full-scale blue roofs by field experiments. Urban Water Journal, 22(2), 200–209.

Hamouz, V., & Muthanna, T. (2019). Modelling of Green and Grey Roofs in Cold Climates Using EPA's Storm Water Management Model. In: Mannina, G., Ed., UDM 2018: New Trends in Urban Drainage Modelling, Springer, Cham, 385-391.

Hamouz, V., Lohne, J., Wood, J. R., & Muthanna, T. M. (2018). Hydrological performance of LECA-based roofs in cold climates. Water, 10(3).

Jeffers, S., Garner, B., Hidalgo, D., Daoularis, D., & Warmerdam O. (2022). Insights into green roof modeling using SWMM LID controls for detention-based designs. Journal of Water Management Modeling 30: C484.

Johannessen, B. G., Hamouz, V., Gragne, A. S., & Muthanna, T. M. (2019). The transferability of SWMM model parameters between green roofs with similar build-up. Journal of Hydrology, 569, 816–828.

NYC DEP. (2012). New York City Green Infrastructure Plan. Green Infrastructure Pilot Monitoring Report. Retrieved from https://www.nyc.gov/assets/dep/downloads/pdf/water/stormwater/green-infrastructure/2012-green-infrastructure-pilot-monitoring-report.pdf (accessed 22/01/2025)

Rosa, D. J., Clausen, J. C., & Dietz, M. E. (2015). Calibration and Verification of SWMM for Low Impact Development. JAWRA Journal of the American Water Resources Association, 51(3), 746–757.

Rossman, L. A. (2015). Storm water management model (SWMM) user's manual version 5.1. Cincinnati, OH, 45268.