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

Modélisation de systèmes modulaires de toitures bleues à plateaux à l'aide d'EPA-SWMM

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RÉSUMÉ

Cette étude propose un modèle permettant de simuler le comportement hydraulique et hydrologique de systèmes de toitures bleues modulaires à plateaux durant des épisodes pluvieux. Le modèle a été développé à l'aide du logiciel EPA-SWMM et appliqué à un pilote à l'échelle réelle d'une toiture bleue modulaire installé dans le sud de l'Italie. L'article présente d'abord une description de l'installation pilote. Ensuite, la conceptualisation du système de toiture bleue modulaire dans le logiciel est exposée. Les composants et outils disponibles dans le logiciel ont été organisés et personnalisés afin de reproduire le fonctionnement du système. Les paramètres du modèle ont été définis sur la base des caractéristiques géométriques et hydrauliques du pilote. Le modèle a été validé en simulant le comportement du système durant 9 événements pluvieux enregistrés sur le pilote entre 2018 et 2024. Les résultats de l'application du modèle au pilote montrent une bonne capacité du modèle à reproduire le comportement du système lors des précipitations. Le modèle ouvre des perspectives pour l'analyse des bénéfices plus larges liés à la mise en œuvre de tels systèmes à l'échelle du bassin urbain, offrant des opportunités utiles pour une gestion durable de l'eau en milieu urbain.

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.

KEYWORDS

Blue-Roof, detention, EPA-SWMM, Modelling, SUDS.

1 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). 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.

2 METHODOLOGY

2.1 The BR pilot

The pilot is a tray-based modular BR system installed on a catchment (5.72 m x 4.60 m = 26.31 m²) 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 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 (59.5 cm x 39.7 x 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. 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).

2.2 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 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.

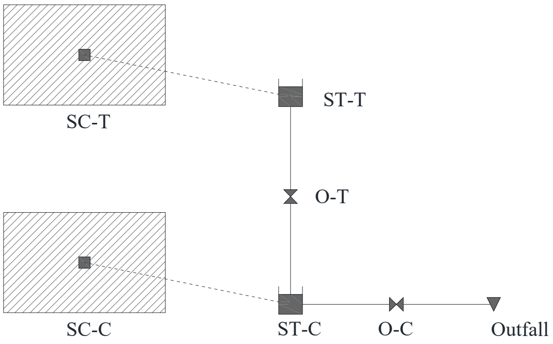

Figure 2. Conceptual model of the BR system in EPA-SWMM.

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 (total area A of 17.21 m²) 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 (A=9.1 m²) is modelled as a fully pervious subcatchment with no depression storage. Hydrological losses in SC-C are estimated using the Curve Number (CN) method, setting CN=98 and drying time of 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: $W=0.5 \cdot A^{1/2}$. Both storage nodes are modelled in SWMM as reservoir with constant cross-sectional area (ST-T 17.21 m² and ST-C 26.31 m²). For the outlet link O-T, the total discharge is simulated using the Torricelli equation multiplied by the total number n of trays in the system:

$$Q = n\, C_1\, A_o \sqrt{2\, g\, h} \qquad (1)$$

where C_1=0.6 is the discharge coefficient, $A_o=3.85 \cdot 10^{-5}$ m² is the outlet orifice area of each tray, and g (m/s²) is the gravitational acceleration. With regard to outlet link O-C, the dynamic of discharge of the whole roof catchment through the downspout inlet is considered. A modified version of Torricelli's equation that accounts for the geometry of the inlet opening is used:

$$Q = C_2\, l\, h \sqrt{2\, g\, h} \qquad (2)$$

where C_2=0.28 is the discharge coefficient, and l=0.20 m is the effective length of the drainage inlet according to field measurement. Finally, to simulate the discharge to the storage tanks located at the base of the building, a free-type outfall is used.

3 RESULTS AND DISCUSSION

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. 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 h_{BR}^{obs} (mm) and simulated h_{BR}^{sim} (mm) accumulated runoff from the BR was calculated for each precipitation event. In addition, the Nash–Sutcliffe Efficiency coefficient (NSE) was calculated. Values of both indicators for the nine analysed precipitation events are summarised in Table 1, while Figure 3 displays the curves for h_{BR}^{obs} and h_{BR}^{sim} for two of the analysed rainfall events. Globally, the model proves capable of suitably reproducing the runoff process from the BR for both events reported in Figure 3. 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 the two events which have different magnitudes. The good fit of the model to the experimental data is confirmed by the values of the indicators in Table 1. 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. 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 confirming the appropriateness of the adopted model configuration.

Table 1. 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

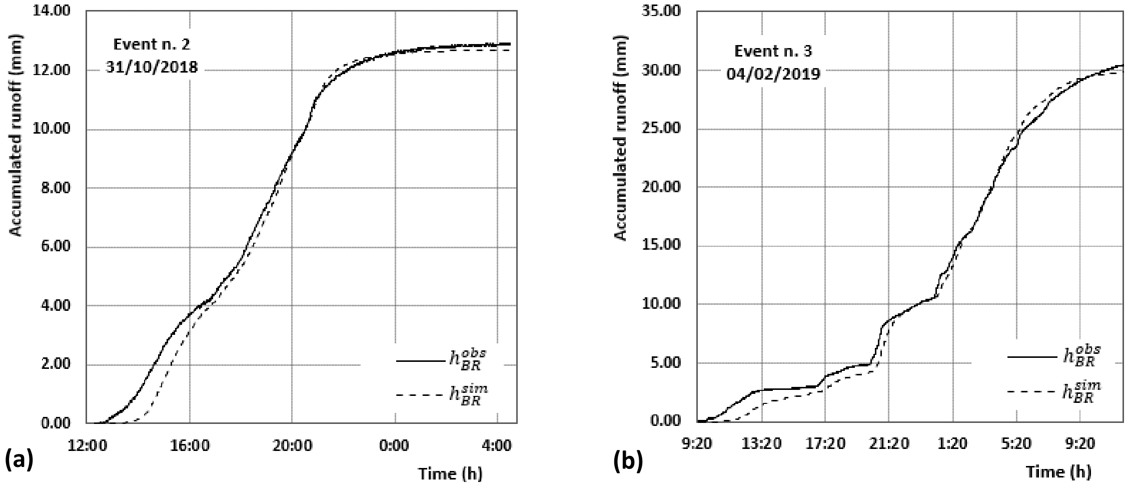

Figure 3. Observed VS simulated accumulated runoff from the BR for events of (a) 31/10/2018, (b) 04/02/2019.

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