Modelling of green roofs’ hydrologic performance using EPA’s SWMM
E. Burszta-Adamiak and M. Mrowiec

ABSTRACT

Green roofs significantly affect the increase in water retention and thus the management of rainwater in urban areas. In Poland, as in many other European countries, excess rainwater resulting from snowmelt and heavy rainfall contributes to the development of local flooding in urban areas. Opportunities to reduce surface runoff and reduce flood risks are among the reasons why green roofs are more likely to be used also in this country. However, there are relatively few data on their in situ performance. In this study the storm water performance was simulated for the green roofs experimental plots using the Storm Water Management Model (SWMM) with Low Impact Development (LID) Controls module (version 5.0.022). The model consists of many parameters for a particular layer of green roofs but simulation results were unsatisfactory considering the hydrologic response of the green roofs. For the majority of the tested rain events, the Nash coefficient had negative values. It indicates a weak fit between observed and measured flow-rates. Therefore complexity of the LID module does not affect the increase of its accuracy. Further research at a technical scale is needed to determine the role of the green roof slope, vegetation cover and drying process during the inter-event periods.

Key words | green roof, hydrologic model, retention, runoff delay, storm water, SWMM

INTRODUCTION

The constant development of urban areas leads to an increase in the area of impermeable surfaces that create a barrier for natural retention and infiltration of storm water. It forces us to apply such solutions that would support the operation of traditional drainage systems. These solutions include green roofs, which are an element of low impact development (LID) practices. Data presented in literature show that the retention capacity of green roofs typically falls within the range of 40–80% (Bengtsson et al. 2005; Van Woert et al. 2005; Villarreal & Bengtsson 2005; Mentens et al. 2006; Berndtsson 2010; Burszta-Adamiak 2010). Peak runoff volume can be decreased even by 60–80% (Getter et al. 2007). The proven efficiency of green roofs depends on numerous factors. Thus, extrapolating test results from one region to another is unacceptable and bears a large risk of error. On the other hand, it seems impossible to conduct long-term field studies in every given region. Thus, there are still more attempts at the application of other tools that would allow us to evaluate the retention capacity of green roofs in a much quicker way and, usually, at a lower cost than is required for field study (Bertrand-Krajewski et al. 2000). One of the methods applied for that purpose is the curve number (CN) method, which was used by Carter & Rasmussen (2006) in order to determine the runoff volume from extensive green roofs. Other authors, looking for ways to obtain data related to storm water management on green roofs, undertook attempts to develop their own mathematical models (Zimmer & Geiger 1997; McCuen 2005; Villarreal & Bengtsson 2005). An alternative method of obtaining practical information on this subject is the application of computer software, including RWS (German: Regen Wasser-Speicher) developed by Optigrün (Mann 2000a, 2000b; Mann et al. 2000; Mann & Szajda 2008), HYDRUS-1D (Hilten et al. 2008), Infoworks CS/SD (Wallingford Software’s Infoworks CS/SD model), green roof water balance model (Raes et al. 2006) and MicroDrainage’s Win DAP. The growing popularity of applying various types of software results from the fact that it makes it possible to evaluate the rainfall to runoff ratio also for green roofs located in regions other than those where direct measurements are being conducted. The possibility to
use such software to predict the potential influence of green roofs on urban catchments (Graham & Kim 2003; Gutteridge 2003; Deutsch et al. 2007) is another reason for using these types of program in engineering practice. Another advantage of the software is the fact that it is often non-commercial, i.e. generally available. These include, among others, the Storm Water Management Model (SWMM) of the US Environmental Protection Agency (USEPA) (Stovin 2010; Palla et al. 2011).

The purpose of this study is to evaluate the possibilities of application of the SWMM with the LID Controls module (version 5.0.022) for the evaluation of retention properties of green roofs. In previous SWMM versions green roofs could be represented as pervious surfaces with defined parameters of the Green-Ampt infiltration model – this variant was applied by Palla et al. (2011). The LID module introduced many new parameters that describe each layer of green roof, but there is no available literature about the quality of this model. The presented paper describes the attempt to evaluate the accuracy of the SWMM LID module to reflect rainfall–runoff transformation for green roofs. The model has been verified based on the measurement results obtained from rainfall and runoff monitoring conducted in Wroclaw on experimental sites equipped with extensive green roofs.

**METHODOLOGY**

**Characteristics of the experimental site**

Experimental sites were made in the form of four roof platforms with the exterior dimensions 2.40, 1.20 and 0.35 m (length, width, height) and a slope of 7.7%. The platforms were located on the roof of the Scientific-Educational Center of the University of Environmental and Life Sciences, Wroclaw, Poland. This building is located in the city centre not far from the national road.

Three of the roof platforms replicated commercial extensive green roofs with a 10 cm thick substrate layer (marked in this study as GR-2, GR-3, GR-4), and one of the roof platforms was used as a reference object, hereafter referred to as a conventional, impermeable roof (CR-1). Photos and cross-sections of roof platforms are presented in Table 1.

The rainfall and runoff from test plots was continuously and automatically recorded. Runoff was captured by Naja 0404 meters. The meters were connected to a Memory Hilogger 8430–20 data logger, manufactured by Hioki. Rain depth and intensity were monitored using a Parsivel laser precipitation sensor manufactured by OTT Messtechnik GmbH & Co. KG.

Retention for single (daily) rainfall events was determined as the percentage of the volume of water retained in the test plots in relation to the volume of rainwater falling on the model roof surface. Measured runoff delay was recorded as the time between the start of the given rainfall event and the occurrence of runoff from the green roof or from the reference roof. Peak runoff reduction was calculated as the difference between peak runoff intensity and peak rainfall intensity.

**Green roof representation in SWMM5**

The USEPA SWMM is a large, complex software package capable of simulating the movement of precipitation and pollutants from the ground surface through pipe/channel networks and storage/treatment facilities to the receiving water. The model can be used to simulate a single event or a long continuous period. SWMM is arguably the most widely utilized model in the world, and has been used and developed as freeware since 1971.

Starting from version 5.0.19, SWMM5 software is equipped with an additional calculation module that enables one to take into consideration various types of technological solutions known as LID practices, i.e. infiltration trenches, vegetative swales and bio-retention cells for the catchment model. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas.

During a simulation SWMM performs a moisture balance that keeps track of how much water moves between and is stored within each LID layer. The general scheme of LID controls in SWMM5 contains the following layers: surface layer, soil (substrate) layer, storage layer, underdrains. In order to evaluate the accuracy of the SWMM software in the aspect of modelling storm water runoff from green roofs, a series of verification tests was conducted, using the results of measurements presented in the ‘Monitoring on experimental sites’ section.

**RESULTS AND DISCUSSION**

**Monitoring on experimental sites**

The test results presented in this study refer to the rainfall and runoff recorded during the period from June to
November 2009 and 2010. From this period, rainfall events characterized by daily rain depth ranging from 4 to 23 mm were selected for analysis. During this type of rainfall events, runoff occurred each time, both from green roofs and from the reference roof (conventional roof).

Mean retention for single (daily) rainfall events fell within the range between 29.9% for the reference roof to 77.7% for green roof GR-3. For two remaining green roof test plots, the recorded average values of retention were similar, i.e. 74.2% for GR-2 and 72.9% for GR-4.

During the test period, a delay in the runoff of storm water from test plots was observed. On most measurement days the first recorded runoff from green roofs occurred after several hours from the beginning of rainfall (Table 2). This phenomenon proves that runoff from extensive green roofs usually occurs only after the substrate has been saturated and the water has been used by the plants. Some of the water is also transferred back to the atmosphere as a result of the process of evaporation and transpiration.

The slowing down of the rainfall and the retention of part of the rainwater inside the structure of green roofs contributed to a noticeable peak runoff reduction. During each of the analysed rain events, the peak runoff reduction values for the reference roof were lower than the reduction measured on green roofs (Table 2). In spite of the differences in the structure of the green roofs, the obtained results were similar and differed only by a small percentage.

**Simulations in SWMM5**

The simulations were conducted for 13 rain events characterized by the parameters presented in Table 2. Rainfall hyetographs were recorded at 2-min intervals. Roof characteristics, i.e. soil thickness, porosity, field capacity, conductivity and storage layer, as well as storage height were adopted pursuant to technological characteristics of the products provided by the manufacturer. It is worth noting that the water permeability of the substrates used for the construction of green roofs is significantly higher.
Table 2 | Presentation of the data for selected rainfall and runoff events during the test period

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A. Changing the parameters of the model in order to obtain the most precise adjustment of the water runoff volume, expressed by the parameter $R_V$:

$$R_V = \frac{\sum_{t=1}^{t_f} Q_{\text{sim}}(t) \Delta t}{\sum_{t=1}^{t_f} Q_{\text{mea}}(t) \Delta t}$$

where: $Q_{\text{sim}}(t)$ - calculated flow-rate, $Q_{\text{mea}}(t)$ - measured flow-rate, $\Delta t$ - time step.

B. Evaluation of simulated and measured hydrographs performed basing on the calculated Nash coefficient (NC):

$$\text{NC} = 1 - \frac{\sum_{t=1}^{t_f} (Q_{\text{mea}}(t) - Q_{\text{sim}}(t))^2}{\sum_{t=1}^{t_f} (Q_{\text{mea}}(t) - Q_{\text{Amea}})^2}$$

where: $Q_{\text{mea}}(t)$ and $Q_{\text{sim}}(t)$ - as above, $Q_{\text{Amea}}$ - mean observed flow-rate.

The Nash coefficient is a widely accepted method to calculate the accuracy of simulation models. This coefficient has a range from negative infinity to 1.0, with values less than 0.0 indicating that the observed mean is a better predictor than the model, while a value of 1.0 shows a perfect fit for the model (Legates & McCabe 1999).

C. Additionally the ratio of maximum flow-rate ($R_{QM}$) has been calculated:

$$R_{QM} = \frac{Q_{\text{Msim}}}{Q_{\text{Mmea}}}$$

where: $Q_{\text{Msim}}$ - maximum calculated flow-rate, $Q_{\text{Mmea}}$ - maximum measured flow-rate.

Initial simulations showed that the initial water content in the green roof layers at the beginning of rainfall has a decisive influence on the obtained results. Water is stored in the substrate layer and in the storage layer (designed to maintain proper media moisture content during dry periods). Because the initial depth in the storage layer cannot be set (SWMM manual (Rossman 2010): ‘the storage zone beneath the soil zone is assumed to be completely dry when the simulation starts’), simulations were started 2–3 days before the exact rainfall. Rainfall occurring during the antecedent period was not taken into account to calculate $R_V$, NC or $R_{QM}$ parameters as the sole aim was to determine the depth in the storage layer. Consequently, the main parameter influencing the simulation results is % Initially saturated (specified in LID Usage Editor). This is the degree to which the unit’s substrate is initially filled with water: 0% saturation corresponds to the wilting-point moisture content, 100% saturation has the moisture content equal to the porosity. The calibration procedure was conducted by changing the value of initial saturation by 1% for each rainfall event and for each roof separately.

As the simulations were conducted for each of the events separately (single event simulations), evaporation was not taken into account. This parameter is very significant during continuous simulations, as it is the only method to lower the moisture content of the media and of the volume of water filling the retention layer.

As Table 3 shows, when the model was well adjusted in the aspect of runoff volume, the values of NC were negative in more than half of the cases. This means that the results rendered by the model were worse than the calculated mean value of runoff intensity, which proves the accuracy of the model is quite unsatisfactory. Even for rainfall events with positive NC, the values have never exceeded 0.5. The lack of fitting of hydrographs was also reflected in the $R_{QM}$ values. For a significant majority of the cases, peak runoff intensity values were several times higher than those actually measured.

Runoff hydrographs obtained with use of the SWMM model were of a similar nature regardless of the type of roof (see example hydrographs in Figures 1 and 2). Highest compliance was obtained for roof GR-4 as the NC value was positive for four rainfall events (although even for this roof the average NC value was negative). Slightly poorer values were noted for roof GR-2 whereas the worst simulation results were obtained for roof GR-3, which was not equipped with a separate layer of drainage elements. Such results may suggest the existence of the following correlation: the higher the retention capacity of a green roof, the better the SWMM model will be able to simulate its hydrological operation.
The analysis of the hydrographs obtained from the model shows that a better adjustment of the R\textsubscript{QM} parameter would lead to a significant underestimation of the runoff volume (in most cases R\textsubscript{V} <0.2) and even worse values of NC.

**CONCLUSIONS**

Green roofs provide an opportunity to delay and attenuate storm runoff at the source, therefore reducing volumes of combined sewer overflow (CSO) discharges and flooding problems in urban areas. Tests conducted for a period between June and November 2009 and 2010 for three different types of green roofs have confirmed their positive influence on the reduction of volume, peak intensity values and on the delay of the occurrence of runoff. Slight differences in the results obtained for various structures may suggest that the objects of the simplest structure (i.e. GR-3) might be the optimal solution in the terms of relieving a drainage system.
The comparison of the results obtained on three experimental green roofs and the SWMM5 simulation results prove that the suggested model has limited capabilities in correctly simulating the hydrograph of storm water runoff from green roofs. The proof of this is the negative values of NC for more than a half of the analysed rainfall events.

Minimization of differences between measured and simulated runoff volumes \( R_v \) tends to create significant overestimation of maximum flow rates, while attempts to adjust the model to maximum flow rates lead to a significant underestimation of the generated volume of storm water runoff. The main reason for the above mentioned discrepancies are:

- minimization of parameters characterizing surface layer (slope and type of vegetation cover are ignored);
- drying process of substrate and storage layers is complicated and depends on many external factors (temperature, insolation, wind) that are not included in the model;
- substrate is characterized by a high value of hydraulic conductivity (0.1 m/s); thus a transport phase through this layer has no influence on runoff rate.

Further research at technical scale is needed to determine the role of the green roof slope, vegetation cover and drying process during the inter-event periods.

REFERENCES


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