Using LID Physical Properties to Predict Unsaturated Flows with SWMM

S. De-Ville[1*] and V. Stovin[1]

[1]Department of Civil & Structural Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, UK
**Corresponding author email: simon.de-ville@sheffield.ac.uk*

Highlights

- Validation of the SWMM LID module using pilot-scale bioretention systems.
- Existing transfer functions for unsaturated hydraulic conductivity do not seem applicable to engineered LID media.

Introduction

Stormwater engineers need to understand how Low Impact Development (LID) assets (e.g. bioretention cells) respond to both routine and extreme rainfall events. Considerable research effort has been invested in recent years to monitor the hydrological performance of installed bioretention devices in the field (see Skorobogatov et al. (2020) for an overview). The data derived from such studies provide useful indications of hydrological performance, but they are often limited by: (i) being locally specific in terms of both system components and climate; and (ii) monitoring periods that are often too short to provide clear evidence about performance in high return period events.

For these reasons, stormwater engineers require fit-for-purpose hydrological/hydraulic modelling tools to simulate the rainfall/runoff behaviour of these devices, including their performance in response to extreme events. SWMM (Rossman 2015) is the most well-known of the available open-source modelling tools. To obtain robust predictions of hydrological performance, each of the components of the bioretention system needs to be comprehensively characterised. These physical characteristics are the input parameters to physically-based models, like SWMM. The resultant model predictions are therefore only as robust as the techniques used to characterise the individual bioretention components.

Bioretention systems are often designed such that they will be saturated for a period no longer than 48 hours after a rainfall event. This means that flows within the bioretention system are predominantly governed by unsaturated flow conditions. Correctly representing these unsaturated flows is critical to ensuring robust long-term continuous simulations of bioretention hydrological performance. These continuous simulations are becoming increasingly important when attempting to understand the antecedent dry weather periods and initial conditions of LID systems prior to extreme events, and the impacts that initial conditions can have on flood risk.

This study aims to explore the performance of the SWMM model for predicting unsaturated flows in a bioretention system when model inputs are derived from laboratory and field assessments of system physical characteristics.

Methodology

As part of the Urban Green DaMS project (https://ugdams.sites.sheffield.ac.uk/), a set of eight 2 m^2 pilot-scale bioretention lysimeters has been constructed at the National Green Infrastructure Facility (NGIF) in Newcastle, UK, to provide data for model validation. Each lysimeter has a total depth of 1100 mm, with a 100 mm ponding zone, a 300 mm filter media layer, a 120 mm transition layer and a 180 mm drainage layer. The systems are lined and incorporate an underdrain. The filter media comprises 100% recycled components which are (by weight): 50% Quarry Waste Material; 25% Crushed Recycled

Glass; 15% Green Waste Compost; and 10% Sugar-beet Washings (topsoil). The transition layer comprises 2 to 6 mm stone aggregate, whilst the drainage layer is 4 to 40 mm stone aggregate. Each lysimeter is monitored for inflow, outflow, soil volumetric water content and soil matric potential. Climate data is also collected to create estimates of potential evapotranspiration (PET) via the FAO-56 Penman Monteith method. There are four monoculture vegetation treatments (unvegetated, amenity grass, *Iris Sibirica*, and *Deschampsia Cespitosa*) and two outflow conditions (unrestricted and greenfield runoff rate restriction). The systems have been monitored since August 1st 2020. The data presented here is from July 2021. The lysimeters are currently only receiving incident rainfall as inflow. A more complete overview is presented in Green et al. (2021).

SWMM version 5.1.015 was used to predict the performance of the pilot-scale bioretention systems. The parameters used to define the bioretention system were based on the design specification, whilst physical properties of the fill and drainage media were derived through lab characterisation or in-situ testing (De-Ville et al. 2021). Conductivity slope and suction head were both derived from physical properties using transfer functions presented in the SWMM Manual (Rossman 2015). Drain outflow was modelled as entirely unrestricted, as outflow travel times from the system to outflow measurement devices were found to be shorter than the 5-minute model timestep. Rainfall data collected at NGIF in July 2021 was applied to the simulated systems using a 5-minute timestep, whilst PET data was input at a 15-minute timestep.

Results and discussion

Figure 1A presents the inflow and outflow data for a single pilot-scale bioretention system for the month of July 2021. A total of 116 l of inflow was recorded, with 54.5 l of recorded underdrain outflow. This high level of retention for a bioretention system is due to the system only receiving incident rainfall. SWMM predictions of outflow (also shown in Figure 1A) are clearly not coincident with the observed outflow, although overall volumetric performance is within 16% of observed data. This discrepancy could be a function of uncertainty in characterised parameter values arising from the highly heterogenous fill media and/or simplifications of hydrological process within the SWMM model.

Figure 1B focuses on one week of inflow and outflow data from the 4th of July to show the dynamic outflow response. It is clearly demonstrated that SWMM overpredicts outflow rates most of the time whilst underpredicting peak flows. There is also an apparent minimum drainage rate of the system imposed by the SWMM model (0.0502 l/5 min) which is much greater than the lowest observed flow rates. This minimum rate is dictated by the value of unsaturated hydraulic conductivity (K) at the fill media's field capacity (Figure 1C). Below field capacity drainage is assumed to not occur, hence the sharp reduction in outflow from 0.05 to 0 l/5 min in Figure 1B. Existing transfer functions in SWMM use saturated hydraulic conductivity (K_{sat}) and particle size data to predict the unsaturated hydraulic conductivity function. The high saturated conductivity value of the bioretention fill media compared with conventional soils (from which much of the theory utilised in SWMM was derived) and the relatively shallow gradient of the conductivity function result in an elevated minimum drainage rate.

A reworked approach to the existing conductivity function is required to replicate the exponential drainage tails seen in the observed outflow data. Other forms of hydraulic conductivity function have been explored by Peng et al. (2020) for LID media and these formulations could be applied within SWMM to better predict unsaturated flows.

Conclusions and future work

Without extensive validation datasets, stormwater engineers have to trust that modelling tools available to them provide robust predictions of LID performance based on available system data. This study has introduced an experimental facility which is designed to generate validation datasets for bioretention

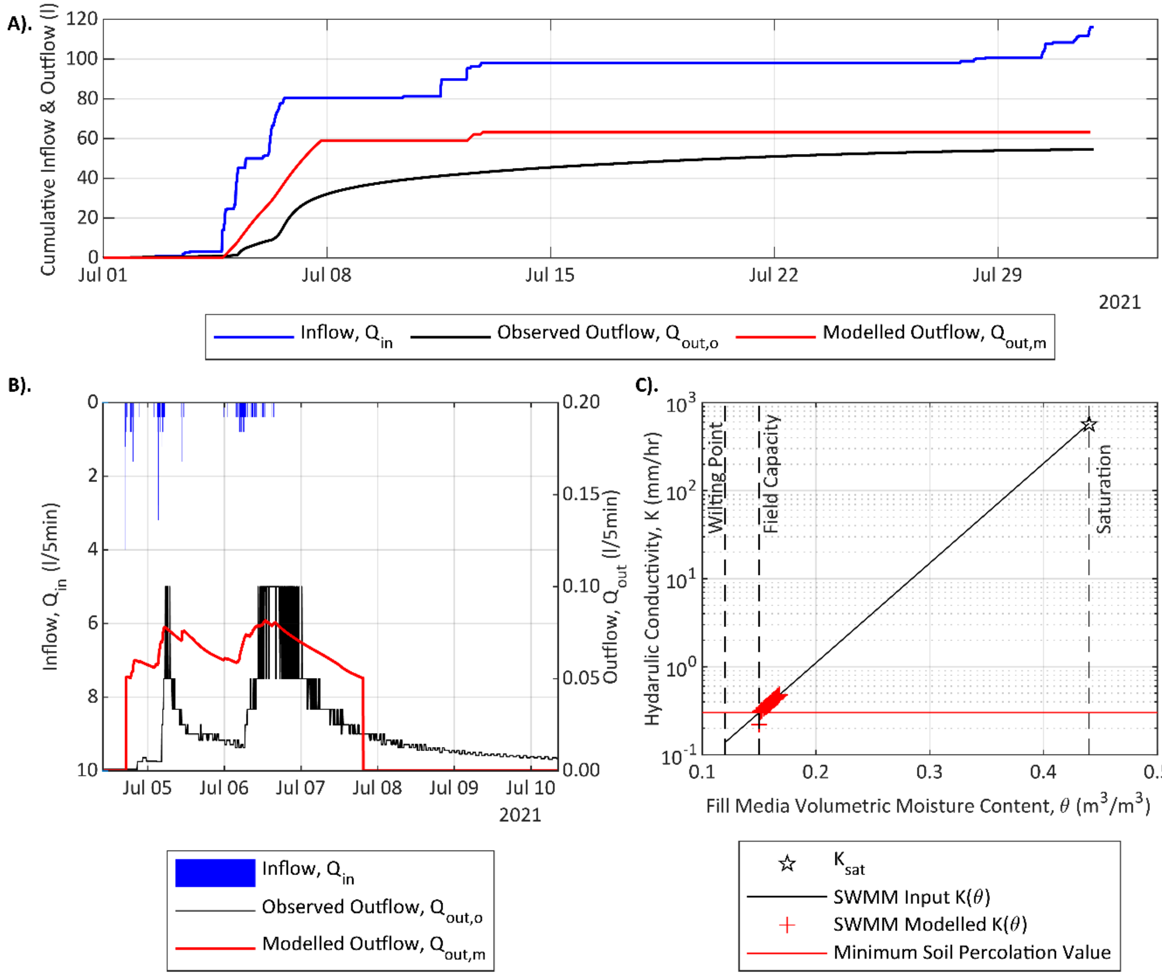

Figure 1. A). Cumulative Inflow and Outflow for Lysimeter 7b for July 2021. **B).** Inflow and Outflow for Lysimeter 7b from July 4th to 11th. **C).** Hydraulic Conductivity Function used in the SWMM model

devices such that the reliability and confidence in hydrological/hydraulic modelling of LID assets is increased. Additionally, it has been shown that the existing modelling approach within SWMM for unsaturated flow does not capture behaviours observed in a pilot-scale bioretention system. Future work will explore alternative hydraulic conductivity functions and model interactions to better predict unsaturated flows in LID assets.

References

De-Ville, Simon, Daniel Green, Jill Edmondson, Ross Stirling, Richard Dawson, and Virginia Stovin. 2021. "Evaluating the Potential Hydrological Performance of a Bioretention Media with 100% Recycled Waste Components." *Water 2021, Vol. 13, Page 2014* 13 (15): 2014. https://doi.org/10.3390/W13152014.

Green, Daniel, Ross Stirling, Simon De Ville, Virginia Stovin, and Richard Dawson. 2021. "Investigating Bioretention Cell Performance: A Large-Scale Lysimeter Study." In *EGU General Assembly Conference Abstracts*, EGU21-10259.

Peng, Zhangjie, Colin Smith, and Virginia Stovin. 2020. "The Importance of Unsaturated Hydraulic Conductivity Measurements for Green Roof Detention Modelling." *Journal of Hydrology* 590 (November): 125273. https://doi.org/10.1016/J.JHYDROL.2020.125273.

Rossman, L. 2015. "Storm Water Management Model User's Manual Version 5.1 - Manual." 5.1. Washington, DC: EPA Office of Research and Development.

Skorobogatov, Anton, Jianxun He, Angus Chu, Caterina Valeo, and Bert van Duin. 2020. "The Impact of Media, Plants and Their Interactions on Bioretention Performance: A Review." *Science of the Total Environment* 715 (May): 136918. https://doi.org/10.1016/j.scitotenv.2020.136918.