

 <https://doi.org/10.71573/d78kf426>

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

Does Improved Site Scale Modeling of Bioretention Translate to Better Estimating Watershed Scale Benefits?

Ghada Diab¹  <https://orcid.org/0000-0002-6634-5875>, Ryan Winston²  <https://orcid.org/0000-0003-4218-877X>
& Jon Hathaway^{1,*}  <https://orcid.org/0000-0003-1666-8550>

¹University of Tennessee - Knoxville, Department of Civil and Environmental Engineering, Knoxville, TN, USA

²The Ohio State University, Department of Food, Agricultural and Biological Engineering, Columbus, OH, USA

*Corresponding author email: hathaway@utk.edu

Abstract

Large scale implementation of green infrastructure, such as bioretention, has become increasingly common. The goal of these installations moves beyond reducing downstream peak flows, also aiming to provide more natural hydrology in receiving streams. Thus, the partitioning of runoff to infiltration, drainage, and overflow; and the timing of these hydrologic pathways becomes critical to holistically evaluating implementations. In this study, DRAINMOD-Urban (a robust drainage model) is coupled with SWMM to provide a watershed scale model that can also perform fine scale modeling of bioretention (and proper hydrologic partitioning). This combined model is tested in a watershed with three bioretention areas in Columbus, Ohio, to evaluate its performance. Initial results show the combined model performs well for the test watershed (NSE = 0.66 for hydrograph representation). Further, the performance for hydrograph representation, mean flow, and volume was found to exceed that of a model representing the system using SWMM LID tools. The results suggest that the model chosen for site scale representation of green infrastructure can make a difference in modeling watershed scale performance.

Highlights

- A site scale drainage model was coupled with a watershed scale hydrologic model.
- The combined model represented hydrographs well in a test watershed.
- The combined model showed improved performance over the use of the SWMM LID tools.

Introduction

Despite recent widespread bioretention implementation, bioretention model development and testing is still an ongoing need (Lisenbee et al. 2020). Given the shortcoming of existing models, Brown et al., (2013) tested DRAINMOD, a process-based model originally used for poorly drained agricultural land, for bioretention applications with good success. After these initial studies, DRAINMOD-Urban (DM-Urban) was developed as a modified version of DRAINMOD for fine-scale hydrologic modeling of bioretention for hydrograph production by Lisenbee et al. (2020). DM-Urban offers a suite of capabilities that addresses some of the shortcomings of basic bioretention modeling specified by Lisenbee et al. (2021) and Li et al. (2017), including some present within the Storm Water Management Model (SWMM). Although modeling bioretention using SWMM is a common practice, the LID module oversimplifies some bioretention processes such as infiltration, seepage, plant uptake, and representation of the IWS zone compared to DM-Urban. Further, unlike DM-Urban, SWMM neglects unsaturated flow through bioretention media, thus, the bioretention media retains moisture until it reaches field capacity then percolation to the underlying soil layer starts to occur (Rossman, 2015a).

Despite the promising performance of DM-Urban for bioretention, DM-Urban can only model a single bioretention at a time at the field scale. The model lacks the routing capabilities to allow a better understanding of the performance of bioretention at subcatchment and catchment scales. Conversely, SWMM has strong capabilities for representing urban hydrologic processes, but the LID module could be improved. Combining the site scale performance of DM-Urban with the hydrologic and hydraulic capabilities of SWMM represents an opportunity to advance the practice of watershed-scale scenario testing and evaluation of bioretention implementation.

Methodology

Site Description

The Cooke-Glenmont (CG) sewershed is part of the Blueprint Columbus initiative by the city of Columbus, Ohio, USA, which aims to upgrade their sewer systems to prevent sanitary sewer overflows by reducing stormwater runoff. The Cooke-Glenmont sewershed is 11.5 hectares with 30.9% impervious land cover, and predominantly consists of small single-family residential lots. As part of Blueprint Columbus, three bioretention cells with a total area of 997 m² were added to the sewershed (Boening-Ulman et al., 2022).

Site monitoring of the pipe leaving the sewershed was conducted from July 2016 to July 2020, with a seasonal break from late December to early March to protect equipment from freezing. This study used the post-bioretention construction monitoring data from September 2017 to May 2020, including 116 monitored rainfall events. Flow velocity and water level were recorded using Teledyne ISCO 6712 automated samplers equipped with area velocity sensors that collected data at one-minute intervals. Rainfall was recorded using a tipping bucket rain gauge equipped with HOBO pendant loggers at one-minute intervals. No baseflow occurred in the Cooke-Glenmont storm sewer between wet weather events. Monitoring data was divided into two periods for this study: 1) from September 2017 to December 2018 was used to calibrate the model, and 2) from March 2019 to June 2020 was dedicated to model validation and any further analysis within the study.

Modeling Methodology

EPA SWMM source code is written in the C programming language while DM-Urban is written in FORTRAN. To allow the coupling of the two models, the Python interface of SWMM (PySWMM) was used instead of EPA SWMM (McDonnell et al., 2020). For DM-Urban, a Python-wrapped function was created using the F2Py package by Peterson (2009) to run DM-Urban in a Python environment. The coupling approach relies on passing files between both models to import and export flow data. Briefly, PySWMM uses rainfall data, land use, and soil characteristics for each subcatchment to generate an inflow time series for the bioretention cells. DM-Urban uses this time series to model the hydrologic pathways, specifically overflow and drainage from the bioretention cells, then passes these data back to PySWMM which routes them to the rest of the watershed sewers and channels (Figure 1).

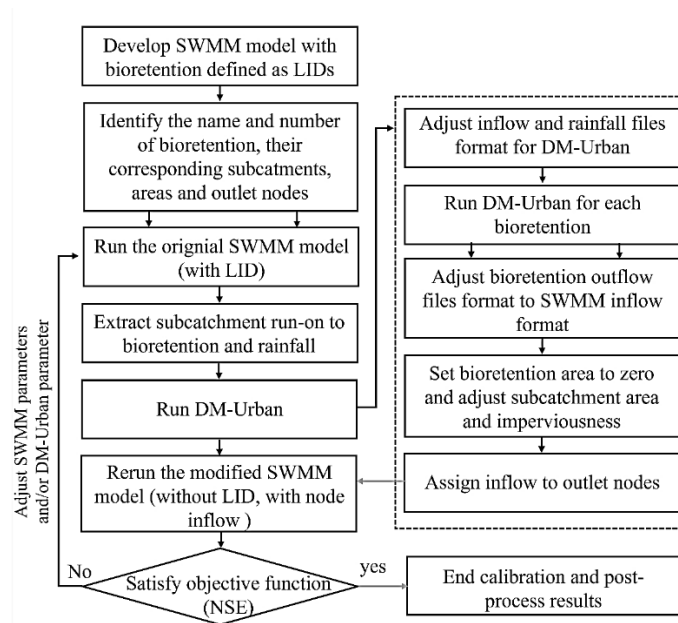


Figure 1. Coupled SWMM and DM-Urban model framework.

DM-Urban requires an extensive set of model inputs, some of which are design parameters, others can be measured through field or laboratory tests, while the remainder were estimated from previous DM-Urban studies (Diab et al., 2022; Lisenbee et al., 2020; Brown et al., 2013). Notably, the three bioretention share the same cross-section and characteristics as described by Boening-Ulman et al. (2022). Therefore, a single bioretention model was developed for all three bioretention (i.e. with the sample input parameters), however, differences did exist between each bioretention based on the inflow, drainage area, and the surface area of each bioretention.

Results and discussion

To achieve the most robust calibration, both SWMM and DM-Urban were calibrated. The calibration followed a sequential order; first, DM-Urban was calibrated while all SWMM parameters were kept constant, then SWMM was calibrated while all DM-Urban parameters were kept constant. The objective function during calibration was matching of the monitored hydrographs. The calibrated model assessment showed an acceptable performance (NSE = 0.42), according to Skaggs et al. (2012) for a daily timestep. Further assessment of the rainfall, measured flow, and simulated flow indicated a time shift of 10 minutes between rainfall and measured flow. Using PCSWMM, a 10-minute shift was applied to observed flow to evaluate the model performance regardless of the time shift. This shift indicated a better model performance for hydrograph representation (NSE = 0.55). Model validation for the monitoring period from April 2019 to May 2020 indicated even better model performance (NSE = 0.67) for the validation period despite higher BIAS (47.2% compared to 6.7%).

While performance metrics provide a quantitative assessment of results, visual inspection of hydrograph peak, timing, and duration provides a better understanding of the model performance (Moriassi et al., 2007). Figure 2 shows three simulated versus measured storm event hydrographs from the calibration period with variable peaks and duration. Overall, the SWMM-DMU model demonstrated good performance in capturing the timing of the flow and peaks of the hydrographs with no large difference in performance between calibration events (1, 2, and 3) and validation events. For example, event 2 has a small NSE, however, with further investigation, a slight time mismatch (10 minutes) in the hydrographs reduced the NSE from 0.75 to 0.32. Therefore, assessing performance solely based on the NSE is not recommended. Another observation is the discrepancy in depicting the receding limb of the hydrograph, this is potentially attributed to how the NSE emphasizes peaks over

smaller flows as noted previously for DM-Urban (Diab et al., 2022; Lisenbee et al., 2022). In addition to hydrograph accuracy, the peak flow, mean flow, and volumes for all events used for model calibration and validation were evaluated against field data (Table 1).

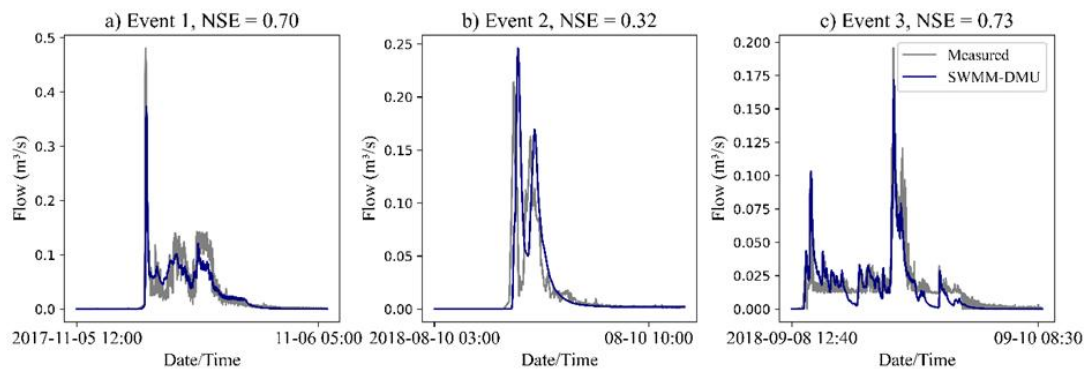


Figure 2. Examples of predicted versus measured hydrographs from calibration (a, b, and c)

Table 1. SWMM-DMU model goodness of fit (NSE and PBIAS) evaluation for calibration and validation for different model outputs.

Model	Hydrograph		Peak Flow		Mean Flow		Volumes	
	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
SWMM-DMU Calibration	0.55**	6.7	0.26	10.2	0.19	-7.3	0.66	-2.3
SWMM-DMU Validation	0.67	47.2	0.52	1.6	0.74	26.8	0.92	20.6

**after 10-minute time shift

Conclusions and future work

This study extended the application of DM-Urban from modeling bioretention at the field scale to modeling bioretention at the catchment-scale by coupling DM-Urban with the SWMM model to leverage the unique hydrologic and hydraulic capabilities of each model. A Python interface was developed for the DM-Urban model and the soil utility program to enable the coupling of DM-Urban model with PySWMM. To evaluate the performance of the coupled model, monitoring data from a bioretention site in Columbus, Ohio, was used to calibrate and validate the coupled SWMM-DMU model. Overall, the SWMM-DMU model showed good performance with respect to hydrograph prediction during model calibration (NSE = 0.55) and model validation (NSE = 0.67). During the validation time, the model showed accurate peak prediction (NSE = 0.52) and volume prediction (NSE = 0.97).

The coupled SWMM-DMU model showed promising performance in modeling bioretention at watershed-scale, with or without calibration. Further research is needed to evaluate the coupled SWMM-DMU model for sites with additional bioretention cells, in particular where data are available for the bioretention cells to allow more detailed calibration at the site and watershed scales. Further, a sensitivity analysis of the coupled SWMM-DMU would be useful in determining the most influential model parameters at the catchment scale.

Acknowledgement

Funding for this research was provided by the National Science Foundation grant no. 1553475 and Institute for a Secure and Sustainable Environment.

References

- Boening-Ulman, K.M., Winston, R.J., Wituszynski, D.M., Smith, J.S., Andrew Tirpak, R., Martin, J.F., 2022. Hydrologic impacts of sewershed-scale green infrastructure retrofits: Outcomes of a four-year paired watershed monitoring study. *Journal of Hydrology* 611, 128014. <https://doi.org/10.1016/j.jhydrol.2022.128014>
- Brown, R.A., Skaggs, R.W., Hunt, W.F., 2013. Calibration and validation of DRAINMOD to model bioretention hydrology. *Journal of Hydrology* 486, 430–442. <https://doi.org/10.1016/j.jhydrol.2013.02.017>
- Diab, G., Hathaway, J.M., Lisenbee, W.A., Brown, R.A., Hunt, W.F., 2022. Fine scale hydrologic modelling of bioretention using DRAINMOD-urban: Verifying performance across multiple systems. *Journal of Hydrology* 614, 128571. <https://doi.org/10.1016/j.jhydrol.2022.128571>
- Li, C., Fletcher, T.D., Duncan, H.P., Burns, M.J., 2017. Can stormwater control measures restore altered urban flow regimes at the catchment scale? *Journal of Hydrology* 549, 631–653. <https://doi.org/10.1016/j.jhydrol.2017.03.037>
- Lisenbee, W., Hathaway, J., Negm, L., Youssef, M., Winston, R., 2020. Enhanced bioretention cell modeling with DRAINMOD-Urban: Moving from water balances to hydrograph production. *Journal of Hydrology* 582, 124491. <https://doi.org/10.1016/j.jhydrol.2019.124491>
- Lisenbee, W.A., Hathaway, J.M., Burns, M.J., Fletcher, T.D., 2021. Modeling bioretention stormwater systems: Current models and future research needs. *Environmental Modelling & Software* 144, 105146. <https://doi.org/10.1016/j.envsoft.2021.105146>
- Lisenbee, W.A., Hathaway, J.M., Winston, R.J., 2022. Modeling bioretention hydrology: Quantifying the performance of DRAINMOD-Urban and the SWMM LID module. *Journal of Hydrology* 612, 128179. <https://doi.org/10.1016/j.jhydrol.2022.128179>
- McDonnell, B., Ratliff, K., Tryby, M., Wu, J., Mullaipudi, A., 2020. PySWMM: The Python Interface to Stormwater Management Model (SWMM). *JOSS* 5, 2292. <https://doi.org/10.21105/joss.02292>
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* 50, 885–900.
- Peterson, P., 2009. F2PY: a tool for connecting Fortran and Python programs. *Int. J. Comput. Sci. Eng.* 4, 296–305. <https://doi.org/10.1504/IJCE.2009.029165>
- Rossman, L.A., 2015. Storm Water Management Model User's Manual Version 5.1.
- Rossman, L.A., Huber, W., 2016. Storm Water Management Model Reference Manual Volume III – Water Quality [WWW Document]. URL https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRML&dirEntryId=327450 (accessed 10.22.23).