Fine Scale Hydrologic Modelling of Bioretention Using DRAINMOD

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Highlights

- DRAINMOD-Urban is tested for modeling bioretention hydrographs with focus on overflow.
- Modeling results demonstrate the effectiveness of DRAINMOD for bioretention applications.
- Drainage and overflow volumes are well-predicted using the hydrograph-calibrated model.

Introduction

Reliable hydrologic models are necessary for green infrastructures (GI) planning and management purposes. To test their reliability, models should be tested and validated before use in design and optimization (Fassman-Beck & Saleh, 2021). Bioretention practices have been of particular interest lately. Recent studies have simulated bioretention hydrology and water quality using a process-based model, DRAINMOD, that was originally used to model drainage in agricultural land. Brown et al. (2013) successfully modeled bioretention outflow for four cells in North Carolina using DRAINMOD over two years using a daily timestep. Lisenbee et al. (2020) attempted to improve DRAINMOD with a fine temporal scale up to one minute, thus, transforming DRAINMOD from a field-scale model to a catchment-scale model capable of simulating more rapid processes (DRAINMOD-Urban). DRAINMOD accounts for variable soil moisture conditions using the soil-water characteristic curve (SWCC) (Brown et al., 2013). Moreover, DRAINMOD models the internal water storage (IWS) zone in bioretention by adjusting the weir configuration in the model (Vijayaraghavan et al., 2021). Thus, DRAINMOD-Urban is a relatively comprehensive model for bioretention practices and its many design variants. However, the overflow prediction performance of DRAINMOD-Urban was not sufficiently verified in previous literature due to the lack of overflow events in the monitoring data (Lisenbee et al., 2020). Accurate overflow prediction is imperative for the application of DRAINMOD at the catchment scale, where local effects aggregate. Therefore, the aim of this study is 1) to verify the ability of DRAINMOD-Urban to simulate bioretention cell drainage across a diversity of sites 2) verify DRAINMOD-Urban's capability for predicting overflow using a larger monitoring dataset that includes more overflow events.

Methodology

Site description and monitoring methods

The study area consists of two bioretention cells constructed in an impervious asphalt parking lot of a commercial store in Nashville, NC, USA. The detailed bioretention cells characteristics are originally presented by (Brown et al., 2013) who parsed the data into two periods. The initial monitoring period revealed increased overflow frequency attributed to clogging by fine granite during construction (pre-repair), subsequently, they were repaired and monitoring continued (post-repair). Rainfall intensity and depth were collected on-site using a tipping bucket rain gauge (ISCO 674) and manual plastic rain gauge, respectively. Inflow and outflow data into the bioretention cells were collected at 1-min intervals using automated samplers (ISCO 6712) coupled with flow meters (ISCO 730) and sharp-crested weirs. The outlet pipe is equipped with a 90˚ v-notch weir and coveys combined drainage and overflow from the bioretention cell. Drainage and overflow were manually separated, the overflow is defined by a spike in outflow hydrograph.

Model description and calibration

DRAINMOD is a process-based continuous simulation model that solves two water balance equations; a soil surface water balance and a soil profile water balance (Brown et al., 2013). Briefly, the drainage rate is computed using the Kirkham equation when the soil profile is completely saturated. Hooghoudt equation is used to compute drainage through the soil when the water table recedes (Skaggs et al., 2012). Darcy's law and Dupuit-Forchheimer assumptions are used to compute seepage. The Green-Ampt equation is used to compute infiltration, the parameters used are obtained from the SWCC and account for the change in saturated hydraulic conductivity through the soil profile. Potential evapotranspiration is computed using the Thornthwaite method or input by the user.

The Nash-Sutcliffe efficiency coefficient (NSE) and Percent bias (PBIAS) were used to evaluate the goodness of fit of model output to measured data. In this study, calibration followed a similar approach to that of Brown et al. (2013) and Lisenbee et al. (2020). The final calibrated model parameters were selected using the cumulative NSE and PBIAS of drainage and overflow by balancing the model's ability to predict: 1) the complete time-series by considering a single NSE and PBIAS for the simulation period, 2) flow of each event separately, 3) the volume of each event, and 4) the peak flow of each event.

Results and discussion

Model Calibration

The calibration parameters can be classified into design parameters (drainage coefficient and ponding depth), seepage parameters (thickness of the restrictive layer, the piezometric head of the aquifer, and the vertical conductivity of the restrictive layer), and soil parameters (lateral saturated hydraulic conductivity of each soil layer). Model parameters were calibrated sequentially starting with the most sensitive parameters such as soil parameters to achieve the optimum NSE and PBIAS of the overflow and drainage hydrographs.

Drainage prediction performance

The calibrated DRAINMOD-Urban model showed overall good performance in the prediction of drainage hydrographs for all cells except for the 0.9-m media depth during the pre-repair period (see Table 1). For the post-repair time series, the NSE was 0.56 and 0.57 and PBIAS was –11.7% and -24.8% for the 0.6-m and 0.9-m cells, respectively, this is comparable to the NSE of 0.60 obtained by Lisenbee et al. (2020). However, for the pre-repair period time series, the NSE was 0.52 and 0.16 and the PBIAS was -17.4% and -21.6% for the 0.6-m and 0.9-m cells, respectively. The model also performed better for the 0.6-m cell compared to the 0.9-m cell for individual events (median event model output). DRAINMOD-Urban showed a better prediction of event volume compared to the original DRAINMOD. For the pre-repair period, cumulative event volume NSE was 0.77 and 0.52 for the 0.6-m and 0.9-m cells, respectively. For the post-repair period, the cumulative event volume NSE was 0.90 for both cells. The PBIAS of all cells ranged between -15.7% and 9.7%. Figure 1 shows the predicted versus measured drainage volume of all events. It is observed that the calibrated models systematically underpredict the volume of drainage. The hydrographs of all events during the post-repair period of the two bioretention cells showed the model capability to predict the time of peak flow correctly and the duration of each event. Figure 1a (right) presents a sample event that shows the model's ability to predict time to peak and duration of the event.

Table 1. Model performance statistics for drainage and overflow.

Model output		0.6-m media depth				0.9-m media depth			
		Pre-repair		Post-repair		Pre-repair		Post-repair	
		NSE	PBIAS (%)	NSE	PBIAS (%)	NSE	PBIAS (%)	NSE	PBIAS (%)
Drainage	Time series	0.52	-17.4	0.56	-11.7	0.16	-21.6	0.57	-24.8
	Median event	0.27	0.21	0.50	-8.1	-0.22	2.9	0.29	-14.8
	Volume	0.77	-15.7	0.90	-9.7	0.52	-12.6	0.90	-10.2
	Peak	-0.21	-41.3	0.24	-18.8	-0.30	-47.4	0.38	-12.9
Overflow	Time series	0.56	-42.6	0.41	-8.4	0.89	0.8	0.67	-22.0
	Median event	0.28	-54.84	0.12	-31.8	0.47	-11.1	0.57	-8.6
	Volume	0.78	43.4	0.59	18.3	0.96	1.4	0.83	10.4
	Peak	0.76	-40.50	0.46	24.1	0.96	-3.4	0.77	22.5

Overflow prediction performance

The pre-repair bioretention cells experienced around 34 overflow events over one year while the post-repair period experienced around 15 overflow events, this allowed for better calibration of overflow hydrographs compared to Lisenbee et al. (2019) that observed NSE of -0.1 due to limited overflow data. The cumulative NSEs of events were 0.54 and 0.90 for the 0.6-m and 0.9-m cells (pre-repair), respectively, and 0.63 and 0.73

for the 0.6-m and 0.9-m cells (post-repair), respectively. Overall, the model performed better for the 0.9-m cell compared to the 0.6-m cell. The modeled overflow volume of each event was also compared to the measured overflow volume shown in Figure 1b (middle). For the pre-repair period, cumulative event volume NSE was 0.78 and 0.96 for the 0.6-m and 0.9-m cells, respectively. For the post-repair period, the cumulative event volume NSE was 0.59 and 0.83 for the 0.6-m and 0.9-m cells, respectively. The model predicted the volume of overflow better in pre-repair conditions compared to post-repair in contrast to the drainage volume results. Visual inspection of the overflow hydrographs showed good agreement between the predicted and actual event duration and time to peak for most overflow events. For the pre-repair period, the overflow peak had NSEs of 0.76 and 0.96 for the 0.6-m and 0.9-m cells, respectively. For the post-repair period, the overflow peak had NSEs of 0.44 and 0.77 for the 0.6-m and 0.9-m cells, respectively. The model underestimated the peak of overflow events during the pre-repair period and overestimated the overflow events peak during the post-repair period. This is explained by the ponding depth used in calibration during the post-repair models, which were less than the actual design depth resulting in a higher estimated overflow. Unlike the drainage peak flow prediction, the model was capable of predicting the variability of overflow peaks of different events without being constrained by any parameter.

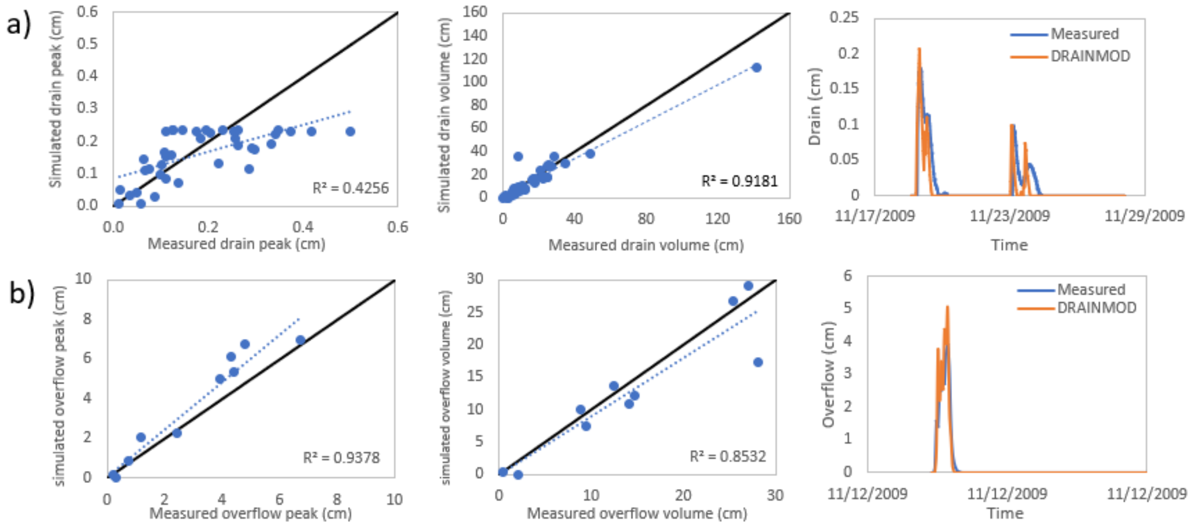

Figure 1. DRAINMOD-Urban performance in the post-repair 0.9-m media depth cell. a) measured versus simulated drain event peak (left), volume (middle), and hydrograph (right). b) measured versus simulated overflow event peak (left), volume (middle), and hydrograph (right)

Conclusions and future work

This study aimed to verify DRAINMOD-Urban's capability of simulating bioretention hydrology by calibrating the model output against two bioretention cells under different design conditions. The model successfully predicted drainage with an NSE up to 0.57 which is considered good for a timescale of one minute. The model also showed good performance for simulating the overflow of more than 44 events across two bioretention cells under different conditions. The simulated overflow showed good agreement with measured data with NSEs ranging from 0.41 to 0.89. In conclusion, DRAINMOD-Urban is capable of simulating fine temporal scale bioretention outflow hydrographs and cumulative volumes. Future work should focus on integrating and testing DRAINMOD-Urban at the watershed scale.

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