Modeling Bioretention Hydrologic Performance using DRAINMOD under Current and Future Climate Scenarios

Modélisation des performances hydrologiques de biorétention avec le modèle DRAINMOD, selon des scénarios climatiques actuels et futurs

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RÉSUMÉ

Des études de terrain ont démontré que les caractéristiques de la conception des bassins versants et de biorétention ont un impact sur la performance hydrologique des cellules de biorétention. Le modèle agricole DRAINMOD largement accepté de gestion équilibrée de l'eau a été adapté pour être utilisé dans la modélisation hydrologique des cellules de biorétention. Des modèles distincts de DRAINMOD ont été calibrés et validés par rapport aux données hydrologiques recueillies sur le terrain pour trois cellules de biorétention dans le nord de l'Ohio. Les coefficients de Nash-Sutcliffe dépassaient souvent 0,8 et les différences entre les volumes mesurés et modélisés étaient inférieures à 3% pour chaque domaine de la gestion équilibrée de l'eau (ruissellement, drainage, débordement et exfiltration/ET) pour chaque cellule de biorétention. Des analyses de sensibilité ont été effectuées en utilisant ces modèles de DRAINMOD, calibrés en modifiant singulièrement les paramètres de conception. Les cellules de biorétention étaient plus sensibles au rapport entre leur surface et la zone de chalandise, la profondeur de la zone interne de stockage de l'eau, et le type de sol d'origine; la profondeur de médias, la profondeur de stockage de bol, et la profondeur d'enracinement n'ont pas eu un impact important sur l'équilibre de l'eau à long terme. Les données climatiques futures pour le milieu du XXIe siècle ont été utilisées pour observer les changements potentiels dans l'hydrologie de la biorétention. Généralement, les scénarios climatiques futurs ont suggéré des hauteurs moyennes annuelles de pluie, des périodes de sécheresse plus longues et des températures plus chaudes au nord-est de l'Ohio. Les résultats de la modélisation ont montré des réductions de volume similaires à celles des scénarios climatiques actuels, avec un changement de -7% à 8% dans les conditions climatiques futures.

ABSTRACT

Catchment and bioretention design characteristics have been shown in field studies to affect the hydrologic performance of bioretention cells. The widely-accepted agricultural water balance model, DRAINMOD, was adapted for use in hydrologic modeling of bioretention cells. Separate DRAINMOD models were calibrated and validated against field-collected hydrologic data from three bioretention cells in northeast Ohio. Nash-Sutcliffe coefficients commonly exceeded 0.8 and differences between measured and modeled volumes were within 3% for each portion of the water balance (runoff, drainage, overflow and exfiltration/ET) for each bioretention cell. Sensitivity analyses were conducted using these calibrated DRAINMOD models by singularly modifying design parameters. Bioretention cells were most sensitive to the ratio between their surface area and the catchment area, the internal water storage zone depth, and native soil type; media depth, bowl storage depth, and rooting depth did not greatly impact the long-term water balance. Future climate data for the mid-twenty-first century were used to observe potential changes in bioretention hydrology. Generally, future climate scenarios suggested lower annual average rainfall depths, longer dry periods, and hotter temperatures for northeast Ohio. Modeled results showed similar volume reductions to current climate scenarios, with a -7% to 8% change under future climate conditions.

KEYWORDS

Bioretention, Climate Change, Hydrology, Internal Water Storage, Modeling, Sensitivity Analysis

1 INTRODUCTION

Bioretention cells are planted media filters designed to capture and treat the first flush of stormwater runoff (Hathaway and Hunt, 2011). A number of field and laboratory-based research studies have focused on their hydraulics and pollutant removal processes (Hatt et al., 2009; Lucas and Greenway, 2011; Paus et al., 2014). Despite the depth and breadth of research, it is difficult to determine the expected water balance (e.g., the fraction of drainage, overflow, exfiltration, and ET) from a bioretention cell under varying site conditions and design configurations. To characterize bioretention performance under a multitude of design scenarios, an effective model is needed to determine its hydrologic and hydraulic functionality. No widely accepted long-term model exists for bioretention. Currently available bioretention models either: (1) are single-storm models, (2) use unsubstantiated estimation methodologies to calculate drainage, (3) do not account for the variations in the volumetric water content in the media, and/or (4) cannot model the internal water storage (IWS) drainage configuration. A mechanistic model such as DRAINMOD is perhaps most useful as a tool for determining bioretention function under various design scenarios.

Proven hydrologic benefits of bioretention are not assured under augmented precipitation depth and intensity, and elongated dry periods predicted under climate change. Fine temporal and spatial resolution future climate data may be used as inputs to long-term, mechanistic models to predict bioretention performance under climate change scenarios (Lucas 2010; Brown et al. 2013; Hathaway et al. 2014). Determining the ability of individual SCMs, such as bioretention, to combat the effects of climate change on urban hydrology is critical to resiliency and improved decision making in water resources management.

DRAINMOD was calibrated with and validated against hydrologic data sets from three field-monitored bioretention cells located in Northeast Ohio. These models were used to conduct sensitivity analyses to predict performance of bioretention design configurations that have not been field-tested and help identify best design methodologies for fill media depth, loading ratio (LR, i.e., catchment to surface area ratio), bowl storage (i.e., ponding) depth, and underdrain configuration over various native soil types (Davis et al., 2009; Hunt et al., 2012). Sensitivity analyses were performed using 30 years of historical climatic records. This study also aimed to build on this work by observing bioretention function under two future climate scenarios. Dynamically downscaled mid-21st century future climate predictions were coupled with long-term, continuous simulation modeling in DRAINMOD to determine how future climate might impact bioretention hydrologic performance. Simple retrofits or improvements to bioretention design were suggested to ensure bioretention cells in this region are resilient to climate change.

2 MATERIALS AND METHODS

Three bioretention cells located in Kirtland and Pepper Pike, Ohio, USA, were intensively monitored to quantify the water balance. Characteristics of the three cells - Ursuline College (UC), Holden Arboretum South (HA South) and Holden Arboretum North (HA North) – may be found in Winston et al. (2015). All three bioretention cells employed internal water storage (IWS), a design feature created using an upturned elbow in the underdrain, promoting both denitrification and exfiltration. A variety of IWS zone depths, media types, drawdown rates, surface storage depths, media saturated hydraulic conductivities (K_{sat}), vegetation types, as well as catchment compositions characterized the three cells (Winston et al. 2015). Detailed analysis of the hydrologic performance of these bioretention cells was presented in Winston, Dorsey et al. (submitted).

The agricultural drainage model DRAINMOD was adapted to model bioretention hydrology. DRAINMOD uses the Hooghoudt and Kirkham equations to explicitly determine drainage when the water table is below and above the soil surface, respectively (Hooghoudt 1940; Kirkham 1957). It is able to simulate an IWS zone, which is analogous to controlled drainage in agricultural fields. Drainage characteristics and soil attributes, such as K_{sat}, the soil water characteristic curve, and exfiltration rate are input into DRAINMOD to simulate water movement through drained soil profiles and model changes in water content with water table depth. The governing equations for DRAINMOD are based on water balances (1) in the soil profile and (2) at the soil surface. Detailed descriptions of DRAINMOD can be found in Skaggs (1980).

A separate DRAINMOD model was calibrated with and validated against the measured or estimated runoff, drainage, overflow, and exfiltration+ET from each bioretention cell. Since bioretention hydrologic performance is seasonal in nature (Emerson and Traver 2008; Muthanna et al. 2008), storm events occurring during even-numbered months (April, June, etc.) were used for model calibration. Data collected during odd-numbered months (May, July, etc.) were extracted for model validation. Field monitoring methods were consistent over the calibration and validation periods. Using DRAINMOD, the water balance [e.g. inflow (runoff), drainage, overflow, exfiltration, and ET] was quantified over the monitoring periods. DRAINMOD outputs were compared to field-collected data using Nash-Sutcliffe efficiencies and coefficients of determination (R^2). Tabulated NSE and R^2 values for the calibration and validation periods indicated the DRAINMOD models were well calibrated to the field observations (Table 1).

Table 1. Nash-Sutcliffe efficiency and coefficient of determination between measured and modeled data during calibration and validation periods.

	Nash-Sutcliffe efficiency				
Site	Period	Runoff	Drainage	Overflow	Exfiltration/ET
UC	Calibration (June, August, October 2014)	0.99	0.94	0.97	0.95
	Validation (May, July, September 2014)	0.99	0.98	0.73	0.95
HA South	Calibration (October 2013, April, June, August, October 2014)	0.99	0.96	0.87	0.76
	Validation (November 2013, May, July, September, November 2014)	0.96	0.95	0.71	0.75
HA North	Calibration (October 2013, April, June, August, October 2014)	0.99	0.97	0.87	0.81
	Validation (November 2013, May, July, September, November 2014)	0.96	0.98	0.74	0.76

	Coefficient of determination (R^2)				
Site	Period	Runoff	Drainage	Overflow	Exfiltration/ET
UC	Calibration (June, August, October 2014)	0.99	0.95	0.99	0.95
	Validation (May, July, September 2014)	1.00	0.99	0.89	0.96
HA South	Calibration (October 2013, April, June, August, October 2014)	0.99	0.96	1.00	0.80
	Validation (November 2013, May, July, September, November 2014)	0.97	0.96	1.00	0.76
HA North	Calibration (October 2013, April, June, August, October 2014)	0.99	0.97	0.94	0.82
	Validation (November 2013, May, July, September, November 2014)	0.97	0.98	0.96	0.77

Site specific climate change predictions were gleaned from Gao et al. (2012), who generated high resolution projected future climate data for the eastern United States. Dynamic downscaling provided high spatial resolution, allowing analysis of changes in precipitation and temperature at two different locations (UC and HA) within the Chagrin River Watershed. Three modeled climate scenarios were utilized for this work, one current base and two future climate data sets, each containing 4 or 5 years of data. These scenarios were derived as the average of nine grid cells within the climate model (i.e., the cell containing the site and the eight surrounding it) to provide representative data. The base model case was for 2001-2004 climate data. For future climate scenarios, data from the IPCC Representative Concentration Pathways (RCP) were utilized. Bioretention performance was analyzed under two greenhouse gas scenarios, one where emissions moderate by 2100 (RCP 4.5) and another where emissions continue to rise on the current trajectory (RCP 8.5). Modeled precipitation and temperature data from 2055 to 2059 (5 years) were used for both climate change scenarios.

3 RESULTS AND DISCUSSION

3.1 Sensitivity Analysis

Calibrated models for UC and HA South were used as the basis for a sensitivity analysis. Base models were not modified from the design parameters determined from as-built surveys and laboratory measurements. The one exception was the underlying soil K_{sat}, which was set at four values (1.27, 0.51, 0.13, and 0.05 cm/hr) to create four base models. For each modeled case, the total volume and percentage of runoff, drainage, overflow, exfiltration, and ET over the 30-yr weather record were quantified.

Of bioretention design factors, volume reduction was most affected by IWS depth and HLR. As an example, Figure 1 (left) shows exfiltration for a bioretention cell constructed in a soil with K_{sat} of 0.13 cm/hr. Each incremental 15-cm increase in IWS depth increased exfiltration, with correlative runoff volume reduction. From the no IWS configuration (i.e., drain at the bottom of the excavated cell), increasing the IWS depth to 15 cm, 30 cm and 45 cm resulted in 69%, 130% and 183% increases in exfiltration. Increasing the IWS depth to 60 cm provided no meaningful increase in volume reduction. There may be other reasons, such as enhancement of denitrification and provision of water for plants during droughts (Hunt et al. 2006; Davis 2008; Winston, Smolek et al. submitted), to consider additional IWS depth, however.

As might be expected, the amount of overflow was most affected by the HLR and bowl depth. As an example, from the monitored condition at UC (HLR of 15:1), increasing the HLR to 20:1, 35:1 and 50:1 resulted in 72%, 323% and 556% more overflow bypassing treatment through the filter media (Figure 1, right). When a bioretention cell is sized to be 10% of its contributing catchment, overflow is nearly eliminated. Sizing the bioretention cell becomes a balance amongst economics, water quality goals, and maintenance realities, as decreasing the bioretention surface area increases the rate of surface clogging (Wardynski and Hunt 2012).

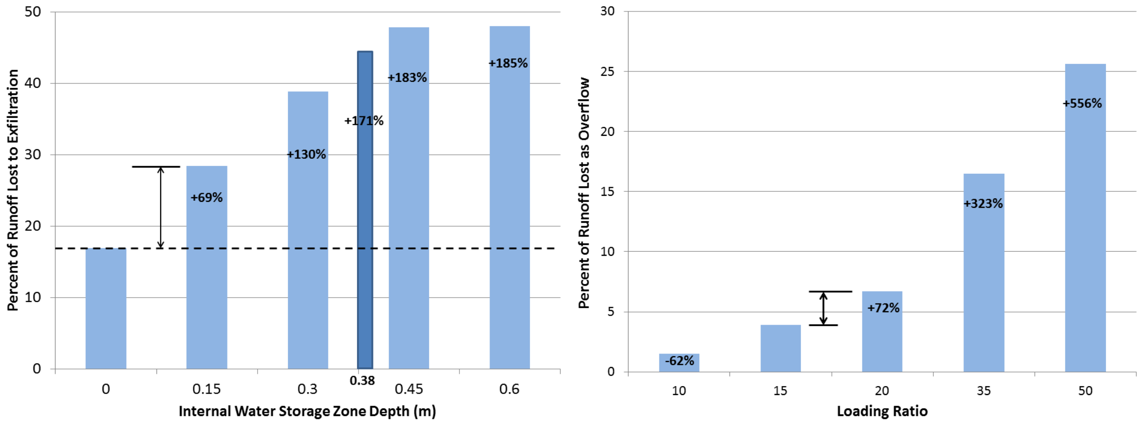

Figure 1. Percent increase in exfiltration as a function of IWS zone depth for an underlying soil K_{sat} of 0.13 cm/hr (left) and Percent increase or decrease in exfiltration as a function of loading ratio for an underlying soil K_{sat} of 0.13 cm/hr (right).

3.2 Climate Change Modeling Results

Because of predicted decreases in future annual rainfall totals, the runoff entering the HA bioretention cells was less under the future climate scenarios than under the current climate (Table 2). While average and extreme event rainfall depth tended to decrease under future climate scenarios at HA, overflow depth increased in one future climate scenario and its percentage of the water balance increased by 1-3% under RCP 4.5 and RCP 8.5. This is probably related to either (1) the increase in antecedent dry period, creating shorter duration, higher average intensity rain events under future climate conditions or (2) predicted increases in back-to-back, high intensity storm events. Drainage depth was 28-33% less in future climate scenarios, representing 5-8% less of the overall water balance. Exfiltration depth was 15-18% less under future climate scenarios based on depth, but modestly increased (by 1-2%) as a fraction of the overall water balance due to the aforementioned decrease in runoff entering the bioretention cells under future climate scenarios. Due to the warmer air temperatures and longer dry periods, coupled with low exfiltration rates that result in long-term storage of water in the IWS zone, depth of ET increased by 16-23% under future climate, resulting in a 2-3% increase in ET as a fraction of the overall water balance. For the HA bioretention cells, the percentage of runoff volume abstracted (i.e. the sum of exfiltration and ET) increased by 4-5%; however, increases in untreated overflow (1-3%) were also observed. The future performance of the HA cells was expected to improve with respect to volume reduction, but the depth of overflow was predicted to increase by up to 24%.

Because of changes in rainfall patterns at UC, DRAINMOD predicted a modest decrease (RCP 4.5) or slight increase (RCP 8.5) in surface runoff (Table 2). This factor combined with higher average and extreme rainfall depths under future climate scenarios resulted in a 2-6% greater drainage fraction of the water balance under future climate. Drainage depth was either unchanged (RCP 4.5) or increased by 30% (RCP 8.5) from the base scenario. Overflow depth increased by 23-66% under future climate scenarios, representing a 1-2% increase in the overall water balance under RCP 4.5 and 8.5, respectively. Exfiltration depth decreased by 11-18% from the base, representing 5-9% of the water balance; this decrease was partially offset by increases in ET, 1-2% of the water balance and 12-19% in depth. Overall, volume reduction as a percentage of inflow was 73% under the base climate scenario; this decreased to 68% and 64% under RCP 4.5 and 8.5, respectively. Thus, performance of the bioretention cell at UC is expected to deteriorate with respect to volume reduction and overflow under future climate conditions.

Taken together, the future climate modeling suggests volume mitigation provided by bioretention SCMs in Northeast Ohio will in some cases be slightly better than current performance (by 4-5% at HA) and in some cases suffer (by 5-9% at UC). This is due to the spatially disparate rainfall and temperature data under future climate scenarios, and suggests the need for additional resolution both spatially and temporally to effectively model site scale, small watershed hydrology. Overflow as a percentage of total inflow to the bioretention cells increased by 1-3% under all future climate scenarios. ET increased in all modeled future climate scenarios due to elevated temperatures, elongated dry periods, and available water stored in the IWS zones.

Table 2. Annual average water balances for each site and climate profile. Depths are in terms of cm per bioretention surface area.

Site	Climate Scenario	**Runoff**	**Drainage**				**Overflow**				**Exfiltration**				**Evapotranspiration**			
		Depth (cm)	Depth (cm)	% Diff Depth[1]	% of Runoff	% Diff WB[2]	Depth (cm)	% Diff Depth	% of Runoff	% Diff WB	Depth (cm)	% Diff Depth	% of Runoff	% Diff WB	Depth (cm)	% Diff Depth	% of Runoff	% Diff WB
UC	Base	1395	328	-	23	-	50	-	4	-	928	-	67	-	81	-	6	-
	RCP 4.5	1238	321	-2	26	2	61	23	5	1	758	-18	61	-5	91	12	7	2
	RCP 8.5	1439	429	31	30	6	82	66	6	2	825	-11	57	-9	96	19	7	1
HA South	Base	1368	706	-	52	-	72	-	5	-	517	-	38	-	69	-	5	-
	RCP 4.5	1070	470	-33	44	-8	90	24	8	3	424	-18	40	2	86	23	8	3
	RCP 8.5	1099	510	-28	46	-5	72	0	7	1	429	-17	39	1	84	22	8	3
HA North	Base	1366	745	-	55	-	84	-	6	-	467	-	34	-	67	-	5	-
	RCP 4.5	1070	499	-33	47	-8	98	17	9	3	391	-16	37	2	82	22	8	3
	RCP 8.5	1099	540	-28	49	-5	84	0	8	1	395	-15	36	2	77	16	7	2

% Diff Depth (% difference in depth) = $(Depth_{RCP}-Depth_{Base})/Depth_{Base}$

% Diff WB (% difference in water balance) = $\%Drain_{RCP}-\%Drain_{Base}$

4 CONCLUSIONS

A sensitivity analysis was performed using two of the calibrated DRAINMOD models to determine bioretention cell performance over a range of underlying soil K_{sat}. The models were most sensitive to loading ratio and IWS zone depth, which modified the fraction of drainage and exfiltration by 20% or more across the values of each of these design variables, regardless of underlying soil type. The simple inclusion of a 0.15-m IWS zone improved volume reduction from exfiltration by 7-13% over the no IWS configuration. IWS zone depths were optimized at 0.38 and 0.45 meters for the two modeled bioretention cells. Optimal IWS zone depth should decrease with increasing native soil K_{sat}. Undersized bioretention cells, common in retrofit situations, may still serve to ameliorate urban watershed hydrology as long as clogging does not affect their performance. The models were also highly sensitive to underlying soil K_{sat}, suggesting bioretention cells should be prioritized in areas of a development with better soils. Modeled data were moderately sensitive to bowl storage and media depths, especially with respect to overflow. The model was least sensitive to rooting depth. The results of these sensitivity analyses will aid designers in understanding how changes to design variables affect the hydrologic performance of bioretention cells.

Future climate scenarios suggested lower annual average rainfall depths, longer dry periods, and hotter temperatures for Northeast Ohio. Due to decreases in annual average rainfall depth, runoff entering each bioretention cell moderated or did not change appreciably under future climate conditions. Results indicate the bioretention water balance was little changed under RCP 4.5 and RCP 8.5, with at most 10% change in any portion of the water balance. Due to warmer temperatures and longer dry periods, ET depth increased by 12-23%, representing an increase of 1-3% with respect to the overall water balance. Because of larger extreme storms and an increase in back-to-back precipitation events, overflow increased by 1-3% of the overall water balance and increased in depth by 0-66%. Analysis of overflow events indicated bowl storage volume would need to be increased by 0-51% to observe no net increase in overflow under predicted mid-21st century climate.

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