

An event-based hydrologic simulation model for bioretention systems

A. Roy-Poirier, Y. Filion and P. Champagne

ABSTRACT

Bioretention systems are designed to treat stormwater and provide attenuated drainage between storms. Bioretention has shown great potential at reducing the volume and improving the quality of stormwater. This study introduces the bioretention hydrologic model (BHM), a one-dimensional model that simulates the hydrologic response of a bioretention system over the duration of a storm event. BHM is based on the RECARGA model, but has been adapted for improved accuracy and integration of pollutant transport models. BHM contains four completely-mixed layers and accounts for evapotranspiration, overflow, exfiltration to native soils and underdrain discharge. Model results were evaluated against field data collected over 10 storm events. Simulated flows were particularly sensitive to antecedent water content and drainage parameters of bioretention soils, which were calibrated through an optimisation algorithm. Temporal disparity was observed between simulated and measured flows, which was attributed to preferential flow paths formed within the soil matrix of the field system. Modelling results suggest that soil water storage is the most important short-term hydrologic process in bioretention, with exfiltration having the potential to be significant in native soils with sufficient permeability.

Key words | bioretention, hydrology, low impact development, modeling, rain garden, stormwater

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INTRODUCTION

Bioretention systems are structural best management practices (BMPs) that provide at-source stormwater retention and treatment. These soil and vegetation-based systems have shown great promise at reducing runoff volumes and delaying runoff flows, thus mimicking pre-development hydrology in developed areas (Davis 2008; Roy-Poirier *et al.* 2010; DeBusk *et al.* 2011). Bioretention systems have also been found to significantly improve stormwater quality by reducing heavy metal, oil and grease, and total suspended solid concentrations (Davis *et al.* 2003; Hong *et al.* 2006; Li & Davis 2008; Roy-Poirier *et al.* 2010).

Several bioretention hydrology models exist, falling into two main categories: design storm models (Lucas 2010; He & Davis 2011) and continuous models (Aravena & Dussailant 2009; Palhegyi 2010; Brown *et al.* 2013). Watershed modelling environments such as SUSTAIN, SWMM and HEC-HMS are often used (Lucas 2010; Palhegyi 2010; Montalto & Lucas 2011), while some codes such as R2D (Aravena & Dussailant 2009) and RECARGA (Dussailant *et al.* 2005) are developed specifically for bioretention.

The aim of this work is to develop a simple hydrologic model that can be used by designers to size bioretention systems and can be integrated into pollutant modelling. Because, to date, bioretention modelling has been mostly disconnected from field performance, the research also seeks to assess the applicability of the model developed to field conditions. The structure and mathematical framework of the Bioretention Hydrologic Model (BHM) are first described. Field monitoring data are then briefly introduced and model results are evaluated against field measurements. A sensitivity analysis of the model is performed, and its applicability to bioretention systems in the field is discussed.

MODEL DEVELOPMENT

BHM is a one-dimensional finite difference model that simulates stormwater flow through a bioretention system over the duration of a storm event, consistent with design guidelines

requiring systems be sized based on a design storm (PGC 2007). The structure of BHM is based on the RECARGA model developed to simulate groundwater recharge through bioretention (Dussaillant et al. 2005). RECARGA is recommended as a bioretention design tool by the Wisconsin Department of Natural Resources (WDNR 2004), but it has not been thoroughly validated against field data. BHM was designed to facilitate pollutant transport model integration and adapted to better represent current bioretention construction. In RECARGA, a sand layer was included below the underdrain structure to encourage groundwater recharge, while BHM was designed to enable groundwater recharge or underdrain discharge simulation independently. For improved accuracy, BHM includes exfiltration from the system to surrounding native soils and a rate of overflow defined by a weir equation. In addition, bioretention soils were divided into two layers to allow pollutant vegetative uptake to be simulated strictly within the root zone depth. As for RECARGA, BHM is an independent code for bioretention designers unfamiliar with watershed modelling environments.

BHM consists of four layers that act as completely mixed reactors, such that no gradient in water content exists within any layer. This implies minimal two-dimensional horizontal flow within bioretention systems since they are designed to drain rapidly. Figure 1 shows the transport processes included in BHM, with optional processes labelled in grey. The ponding layer represents water that accumulates at the surface of the system during high-intensity rainfall. The second layer represents mulch placed at the surface of some bioretention systems. The third and fourth layers make up the bioretention soils. The soil root zone contains vegetation rhizospheres, while the deep soil zone seeps to the underdrain structure, or recharges the ground below the system.

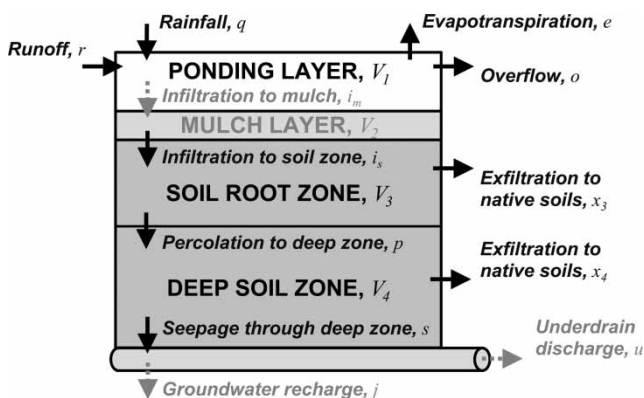


Figure 1 | BHM model schematic.

Mathematical framework

The mathematical equations describing the hydrological processes in BHM are defined below. In all equations, subscript 1 represents the ponding layer, 2 the mulch layer, 3 the soil root zone, 4 the deep soil zone, and N native soils surrounding the bioretention system. Dimensional analysis is provided for all variables, with L for length, T for time, and ‘-’ identifying unitless variables. V is the volume of water in a model layer [L^3], D is the depth of the layer [L], A is the area of the bioretention system [L^2] and P is its perimeter [L].

The rainfall inflow rate [L^3/T], q , corresponds to precipitation directly above the bioretention system, calculated based on a time series of rainfall intensities from field data or design storm conditions. The runoff inflow rate [L^3/T], r , is also provided in the form of a time series. The evapotranspiration rate [L^3/T], e , is defined by a constant for each storm event. Overflow structures are represented as weirs where, for rectangular weirs, the overflow rate [L^3/T], o , is given by:

$$o = \frac{2}{3} C_d \sqrt{2g} L \left(\frac{V_1}{A} - D_1 \right)^{\frac{3}{2}} \quad (1)$$

where C_d is the weir discharge coefficient [-] and L is the weir width [L].

The mulch layer is treated as a store above bioretention soils: water enters the layer as soon as it is available in the ponding layer until the capacity of the mulch layer [-], α_2 , is reached:

$$\alpha_2 = M_2 D_2 A \quad (2)$$

where M is the effective porosity [-].

Dussaillant et al. (2005) found good agreement between the RECHARGE and RECARGA models, which respectively rely on the Richard’s and Green–Ampt equations to simulate infiltration. In BHM, the infiltration rate to the soil root zone [L^3/T], i_s , is given by Equation (3), a modified version of the Green–Ampt equation (Mein & Larson 1973). Typically, the water ponding depth on a soil surface is considered small relative to the capillary suction head across the wetting front [L], ψ . In bioretention systems, this depth cannot generally be considered negligible and is thus included in Equation (3).

$$i_s = K_{sat3} A \left[1 + \frac{(\theta_{sat3} - \theta_{res3}) \left(\psi_3 + \frac{V_1 + V_2}{A} \right)}{W_e} \right] \quad (3)$$

where K_{sat} is the saturated hydraulic conductivity [L/T], θ_{res} and θ_{sat} are the residual and saturated water contents [-], respectively, and W_e is the effective wetting front depth [L]. In the traditional Green–Ampt equation, W_e is given by the cumulative infiltration depth. Because water in bioretention systems is allowed to exfiltrate into surrounding native soils, W_e is instead defined in BHM as:

$$W_e = \frac{\left(\frac{V_3 + V_4}{A}\right) - (\theta_{res_3} D_3 + \theta_{res_4} D_4)}{(\theta_{sat_3} - \theta_{res_3})} \quad (4)$$

In RECARGA, percolation is based on the kinematic theory of unsaturated flow, which implies fully-gravitational vertical drainage and a pressure gradient of unity (Dussailant et al. 2005). This theory was adopted in BHM to define percolation rates to the deep soil zone [L³/T], p , seepage through the deep soil zone [L³/T], s , underdrain discharge [L³/T], u , and groundwater recharge [L³/T], j , as given by Equations (5)–(7):

$$p = A K_{unsat_3} \quad (5)$$

$$s = u = A K_{unsat_4} \quad (6)$$

$$j = A K_{unsat_N} \quad (7)$$

where K_{unsat} is the unsaturated hydraulic conductivity [L/T].

The van Genuchten drainage equation (van Genuchten 1980) is used to define the unsaturated hydraulic conductivities in Equations (5)–(7):

$$K_{unsat_i} = K_{sat_i} \Theta_i^{1/2} \left[1 - \left(1 - \Theta_i^{1/m_i} \right)^{m_i} \right]^2 \quad (8)$$

where Θ is the effective saturation [-], as defined by:

$$\Theta_i = \frac{(\theta_i - \theta_{res_i})}{(\theta_{sat_i} - \theta_{res_i})} \quad (9)$$

where θ is the water content [-] and m is:

$$m_i = 1 - 1/n_i \quad (10)$$

where n is the van Genuchten parameter [-].

Exfiltration to native soils [L³/T], x_i , is defined by a modified version of the Green–Ampt equation for sloped

soil surfaces (Chen & Young 2006):

$$x_i = K_{sat_N} \frac{\psi_N}{W_{N_i}} (P D_i) \quad (11)$$

where W_N is the wetting front depth inside native soils [L]:

$$\frac{dW_{N_i}}{dt} = \frac{x_i}{M_N P D_i} \quad (12)$$

FIELD STUDY

The field monitoring data presented here were collected by the Toronto and Region Conservation Authority (TRCA) at the King City campus of Seneca College, Ontario, Canada. A detailed project report is available online (TRCA 2008). A parking lot was divided into two equal 286 m² sections (8.8 m by 32.5 m). The first pavement section was graded to drain to a bioretention system, while the second section served as a control for the study. The bioretention area (20.2 m²) was excavated to a depth of 1 m. For monitoring purposes, the excavation was lined with an impermeable plastic membrane to prevent exfiltration from the system. An underdrain structure was installed consisting of a 150 mm (6 inches) weeping tile wrapped in a filter sock and covered with granular material. The excavation was filled with screened garden soil containing 1/3 compost (42% sand, 50% silt and 8% clay), classified as silt loam (USDA 2009b). The bioretention soils were lightly compacted and graded to provide depression storage equivalent to an 11 mm storm over the drainage area (drainage to bioretention area ratio = 14.2). The system was covered with a layer of cedar mulch and planted with drought and flood-tolerant vegetation (*Andropogon gerardii*, *Aster puniceus*, *Aster laevis*, *Penstemon digitalis*, *Liatris spicata*, and *Cornus sericea*). Excess runoff was allowed to overflow to surrounding grass swales.

Rainfall intensities were monitored at 5-min intervals using a tipping bucket rain gauge (TB3, Hydrological Services, Australia). Surface runoff flows from the control area and underdrain flows from the bioretention system were piped to an underground monitoring area where their rates were measured using electromagnetic flow meters (Promag 53W, Endress + Hauser, Canada) at 1 min intervals. Water levels at the surface of the bioretention system were measured using pressure transducers to indicate overflow occurrences during high-intensity storms.

The bioretention soil temperature was also measured 50 cm below the surface of the system. Groundwater levels remained >3 m below the base of the bioretention system throughout the study, such that native soils surrounding the system remained unsaturated. The bioretention system continued to function during winter periods and soil temperatures near the system surface remained above 0 °C.

MODEL EVALUATION

Initial input parameter selection

Ten storm events with different characteristics, representing a wide range of total rainfall depths, average and maximum rainfall intensities, storm durations, antecedent conditions and seasons were selected to evaluate the performance of BHM (Table 1). The modelling time step was set to 1 min

to match the flow rate measurement frequency. Control pavement runoff rates were used as model runoff inflow rates. Simulations times were set to exceed the period over which underdrain discharge was measured in the field. Meteorological data from the Toronto Buttonville Airport weather station (Environment Canada 2008) and the Penman-Monteith equation (Allen et al. 1998) were used to calculate an average evapotranspiration rate over the simulation time for each storm. Antecedent moisture conditions were defined as wet for interevent times under 2 days, average for 2 to 5 days and dry above 5 days.

Table 2 lists initial model input parameters for the Seneca College bioretention facility. Root depth requirements reported in the USDA PLANTS database (USDA 2009a) were used to estimate the soil root zone depth. An average discharge coefficient for the overflow weir was calculated using an empirical equation (Crowe et al. 2005) assuming a water head above the weir of 25 mm. Bioretention soil hydraulic

Table 1 | Characteristics of storm events selected for modelling

Date	Total rainfall duration (h)	Total rainfall depth (mm)	Average rainfall intensity (mm/h)	Peak 5 min rainfall intensity (mm/h)	Antecedent moisture condition	Peak runoff rate from control area (L/s)	Total runoff volume from control area (m ³)	Overflow from bioretention system	Simulation time (min)	Evapo-transpiration rate (mm/d)
10/07/2006	12.4	73.0	5.9	40.8	Dry	4.307	14.97	Yes	3,120	1.5
12/07/2006	9.4	15.8	1.7	36.0	Wet	0.496	1.29	Unknown	4,020	2.0
22/09/2006	46.2	16.8	0.4	19.2	Average	2.029	1.09	No	3,900	1.4
27/09/2006	3.9	13.2	3.4	26.4	Average	3.518	2.03	No	3,120	1.2
07/11/2006	24.5	11.6	0.5	4.8	Dry	0.138	0.41	No	2,340	0.3
30/11/2006	36.8	64.4	1.8	14.4	Dry	0.958	10.20	Yes	4,500	0.8
04/01/2007	42.7	17.6	0.4	7.2	Average	0.246	3.13	No	3,180	0.4
23/04/2007	0.8	9.8	13.1	43.2	Dry	3.017	2.26	Yes	2,700	3.1
03/06/2007	14.3	24.6	1.7	60.0	Average	3.892	6.13	Yes	2,000	1.6
25/09/2007	16.1	18.6	1.2	74.4	Dry	4.162	4.38	No	3,300	1.7

Table 2 | BHM parameters selected for the Seneca College bioretention facility

Input parameter	Value	Unit	Source	Input parameter	Value	Unit	Source
A	20.2	m ²	Measured	C_d	0.61	–	Crowe et al. (2005)
D_1	106	mm	Measured	D_3	0.51	m	USDA (2009a)
D_2	50	mm	Measured	D_4	0.49	m	Calculated from D_3
M_2	0.76	–	Huang et al. (2006)	n_3, n_4	1.578	–	Rosetta (Schaap et al. 2001)
L	200	mm	Visual observation	$\theta_{res_3}, \theta_{res_4}$	0.246	–	Aravena & Dussailant (2009)
ψ_3	180	mm	Rawls et al. (1990)	$\theta_{sat_3}, \theta_{sat_4}$	0.407	–	Rosetta (Schaap et al. 2001)
				K_{sat_3}, K_{sat_4}	17.1	mm/h	Measured

properties were obtained with the Rosetta model based on soil texture (Schaap *et al.* 2001). The saturated hydraulic conductivity was estimated based on underdrain flows measured on site under saturated soil conditions and agreed well with Rosetta ($\pm 6\%$). The residual water content for a rain garden organic soil (50% sand and 50% compost) was adopted (Ara-vena & Dussailant 2009). Native soil hydraulic properties were set to zero since exfiltration from the bioretention system was prevented by an impermeable membrane.

Bioretention soil antecedent moisture content, θ_{ini} , was defined based on the antecedent condition category reported in Table 1. Ponding and mulch layers were assumed to contain no water at the start of a storm. As an initial estimate, dry, average and wet bioretention soils were set to 20%, 50% and 70% saturation, respectively.

Sensitivity analysis

A deterministic sensitivity analysis was performed on the 12/07/2006 storm event (Figure 2(a)) to identify input parameters requiring calibration based on their impact on simulated underdrain volumes (Figure 2(b)). This event was selected because it yielded good agreement between measured and simulated underdrain discharge volumes using initial input parameters. Further, overflow is not believed to have occurred based on the storm characteristics and no overflow was simulated by BHM.

The value of each model parameter (Table 2) was perturbed individually by $\pm 5\%$ and $\pm 20\%$. The corresponding BHM simulation sensitivities are reported in Table 3. The difference in simulated underdrain discharge, $\%_{diff}$, was

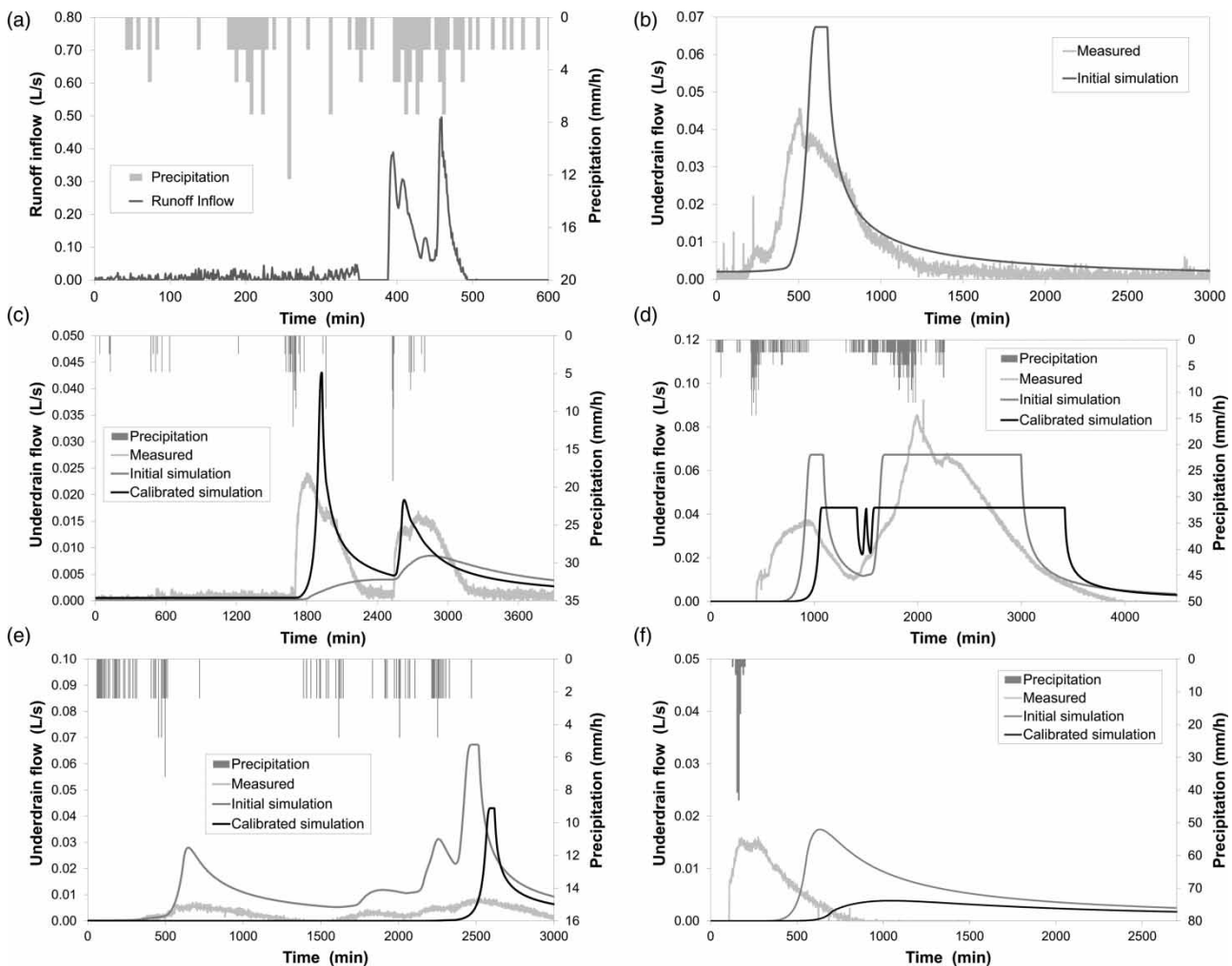


Figure 2 | Measured and simulated underdrain discharge rates with storm characteristics for selected events. (a) Rainfall and runoff on 12/07/2006; (b) initial underdrain discharge for 12/07/2006; (c) 22/09/2006; (d) 30/11/2006; (e) 04/01/2007; (f) 23/04/2007.

Table 3 | BHM sensitivity to perturbations in model parameters

Input parameter perturbation	Difference in total underdrain discharge volume simulated (%)																
	<i>e</i>	<i>A</i>	<i>D</i> ₂	<i>D</i> ₃	<i>D</i> ₄	<i>M</i> ₂	<i>K</i> _{sat3}	<i>ψ</i> ₃	<i>n</i> ₃	<i>θ</i> _{res3}	<i>θ</i> _{sat3}	<i>K</i> _{sat4}	<i>n</i> ₄	<i>θ</i> _{res4}	<i>θ</i> _{sat4}	<i>θ</i> _{ini3}	<i>θ</i> _{ini4}
+5%	-0.1	-1.7	0.0	-1.8	-1.6	0.0	0.6	0.0	2.4	1.5	-9.4	0.5	2.5	1.3	-8.1	4.7	4.6
-5%	0.1	1.7	0.0	1.6	1.5	0.0	-1.0	0.0	-2.8	-1.7	8.6	-1.0	-3.0	-1.5	8.0	-5.2	-5.1
+20%	-0.2	-6.9	0.0	-7.6	-6.2	0.0	1.7	0.0	8.9	6.1	-29.6	1.5	9.1	5.2	-26.8	N/A	N/A
-20%	0.2	6.0	0.0	6.9	6.0	0.0	-2.2	0.0	-15.1	-7.7	N/A	-2.0	-16.3	-5.8	N/A	-18.9	-18.3

taken as:

$$\%diff = \frac{(V_{perturbed} - V_{simulated})}{V_{simulated}} \quad (13)$$

N/A is indicated where perturbed parameters fell outside the range of physically-based values. As overflow was not simulated for the 12/07/2006 storm event, D_1 , L and C_d were not included in the sensitivity analysis. Similarly, exfiltration parameters were excluded from the analysis since exfiltration was inhibited in the field.

BHM was found to be highly sensitive to bioretention soil drainage parameters in the root and deep zones, and particularly sensitive to bioretention soil saturated water content. Important changes in underdrain discharge volumes were also associated with perturbations of the van Genuchten parameters and bioretention soil antecedent water contents. This suggests that flow through the system is limited by the rates of percolation to and seepage through the deep soil zone.

To assess the importance of exfiltration, a separate sensitivity analysis was conducted ignoring the impermeable liner around the bioretention soils. Exfiltration parameters were defined based on the native clay loam at the Seneca College site (Table 4). With unperturbed parameters, exfiltration decreased the total underdrain discharge volume simulated by 36%.

Unsurprisingly, exfiltration parameters had a significant influence on simulation results, since exfiltration decreases the volume of water stored in bioretention soils, which reduces both the volume of water available for underdrain discharge and the rate of seepage through bioretention soils (given that hydraulic conductivity decreases with water content).

Input parameter calibration

Based on the sensitivity analysis, a set of critical input parameters (parameters that produced differences in simulated underdrain discharge volumes $>|2\%|$ and $>|8\%|$ when perturbed by $\pm 5\%$ and $\pm 20\%$, respectively) was selected for optimisation: θ_{sat3} , θ_{sat4} , n_3 , n_4 , θ_{ini3} and θ_{ini4} . Given that the root and deep zones contain the same soil mixture, a single optimised value of θ_{sat} , n and θ_{ini} was sought for both layers. Since θ_{ini} describes antecedent soil conditions, it was optimised individually for each storm, while θ_{sat} and n remained constant across all storms. A simple search algorithm was devised for calibration and 25

Table 4 | BHM sensitivity to perturbations in exfiltration parameters

Input parameter	Value	Unit	Source	Difference in total underdrain discharge volume simulated (%)			
				Input parameter perturbation			
				+ 5%	- 5%	+ 20%	- 20%
P	22.8	m	Measured on site	-2.6	5.3	-12.4	22.9
K_{satN}	1.8	mm/h	TRCA (2008)	-1.3	2.6	-6.2	11.0
ψ_N	20.9	mm	Rawls et al. (1993)	-1.3	2.6	-6.2	11.0
M_N	0.315	-	Rawls et al. (1982)	-2.6	5.3	-12.4	22.9

values were evaluated for each parameter within the ranges reported in Table 5. The objective function used to select optimal parameters, F , is given by Barco et al. (2008):

$$F = w_1 \left(\frac{Q_{measured} - Q_{simulated}}{Q_{measured}} \right)^2 + w_2 \left(\frac{P_{simulated} - P_{measured}}{P_{measured}} \right)^2 + w_3 \sum_{t=0}^n \left(\frac{f_{simulated} - f_{measured}}{f_{measured}} \right)^2 \tag{14}$$

where Q is the total underdrain discharge volume, P is the peak underdrain discharge rate, f is the instantaneous underdrain discharge rate at time t and w_1 , w_2 and w_3 are weighing factors, set to 1, 1 and 0 herein because instantaneous rate differences interfered with the calibration as a result of temporal disparities between measured and simulated discharge flows (Barco et al. 2008). The optimised parameters are listed in Table 5.

Simulation results

The performance of BHM was evaluated by comparing simulated underdrain flows to those measured at the Seneca College bioretention site (Table 6). The Nash–Sutcliffe efficiency coefficient, E , was used to compare instantaneous

underdrain flows:

$$E = 1 - \frac{\sum_{i=1}^n (f_{measured} - f_{simulated})^2}{\sum_{i=1}^n (f_{measured} - \overline{f_{measured}})^2} \tag{15}$$

E ranges from 1 for perfect model fit to $-\infty$, with positive values when instantaneous flows are better represented by the model than the average of measured flows.

Modelling results for selected storms are illustrated in Figure 2(c)–2(f). In general, underdrain flow rates and volumes are of primary concern, as they contribute the largest portion of outflows from bioretention systems for most storms. However, overflows can become significant during large storm events and should be considered in those cases. The total volume of overflow simulated by BHM after calibration is reported in Table 6 and can be compared with the occurrence of overflows in the field reported in Table 1 (overflow volumes were not measured in the field).

Initial underdrain discharge flows deviated significantly from field measurements. Following model calibration, simulated underdrain discharge volumes closely matched observed volumes. However, instantaneous flow predictions were still poor, as shown by the low E values and high

Table 5 | Calibrated input parameters for the Seneca College bioretention facility

Input parameter	Optimisation range	Optimised value									
		10/07/2006	12/07/2006	22/09/2006	27/09/2006	07/11/2006	30/11/2006	04/01/2007	23/04/2007	03/06/2007	25/09/2007
$\theta_{sat_3}, \theta_{sat_4}$	0.35–0.65	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.425
n_3, n_4	1.2–1.7	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283
$\theta_{ini_3}, \theta_{ini_4}$	$\theta_{res} - \theta_{sat}$	0.248	0.378	0.385	0.327	0.392	0.306	0.263	0.292	0.342	0.284

Table 6 | Measured and simulated underdrain discharge from the Seneca College bioretention facility. Differences and *E* are between calibrated simulation results and field measurements

Storm date	Total underdrain discharge volume				Total overflow volume in calibrated simulation (m ³)	Peak underdrain discharge rate				Nash–Sutcliffe efficiency coefficient, <i>E</i>
	Measured (m ³)	Initial simulation (m ³)	Calibrated simulation (m ³)	Difference (%)		Measured (m ³)	Initial simulation (L/s)	Calibrated simulation (L/s)	Difference (%)	
10/07/2006	1.43	2.98	1.73	21%	11.57	0.069	0.067	0.043	–38%	–1.45
12/07/2006	1.36	1.79	1.34	–1%	0.00	0.046	0.067	0.043	–7%	0.31
22/09/2006	1.02	0.66	1.10	8%	0.00	0.024	0.008	0.043	79%	0.37
27/09/2006	1.00	1.74	0.94	–6%	0.00	0.035	0.067	0.043	23%	–0.66
07/11/2006	0.40	0.00	0.47	18%	0.00	0.010	0.000	0.008	–20%	0.77
30/11/2006	6.47	7.86	6.52	1%	3.01	0.092	0.067	0.043	–53%	0.34
04/01/2007	0.51	2.51	0.55	8%	0.00	0.009	0.067	0.043	378%	–6.98
23/04/2007	0.32	0.86	0.34	6%	0.00	0.016	0.018	0.003	–81%	–0.55
03/06/2007	0.59	0.98	0.67	14%	0.00	0.014	0.028	0.040	186%	–2.97
25/09/2007	1.73	2.38	1.70	–2%	0.70	0.096	0.067	0.043	–55%	–0.77

differences in peak underdrain discharge rates. Simulated underdrain discharge rates are restricted by bioretention soil drainage properties, as highlighted by the repetitive simulated peak rates reported in Table 6. Simulated and observed overflow occurrences do not match for all storm events, but field observations are limited to water level measurements at 5 min intervals.

Underdrain flows simulated by BHM were delayed compared to measured flows for most of the events modelled (Figure 2(c)–2(f)). This temporal disparity suggests that a fraction of the influent runoff travelled through preferential flow paths in the field system, experiencing limited interaction with the soil matrix. Such short-circuiting may be due to uneven soil compaction. Carpenter & Hallam (2010) reported issues with preferential flow path development in bioretention media resulting from poor construction techniques. The time lag observed could also be due to the model structure, which assumes that water infiltrates uniformly across the bioretention area. This assumption may not accurately represent bioretention flow behaviour, particularly when no ponding occurs at the system surface to distribute the influent runoff. In these cases, influent water tends to infiltrate near the system inlet. In addition, the assumption that soil water content is uniform within the depth of a layer may not be applicable during high-intensity, short duration storm events (e.g. Figure 2(f)). Improved modelling accuracy could be achieved by integrating a horizontal flow component into BHM, or by increasing the number of model layers and reducing their individual depth.

A significantly lower *E* value was obtained for the 04/01/2007 storm than for other events. For this storm, BHM greatly overestimated underdrain flow rates (Figure 2(e)), suggesting that, currently, BHM cannot adequately predict hydrologic processes during the winter season. This may be due to a decrease in bioretention soil infiltration capacity in cold weather, which could be linked to the effect of road salts (Agassi *et al.* 1981) and/or to a decrease in water viscosity (Constantz & Murphy 1991). The average air temperature during this storm event was 6.4 °C.

The sensitivity analysis and modelling results suggest that soil water storage is the most important process for stormwater retention in bioretention systems. Actual field evapotranspiration rates may be greater than those predicted, since evapotranspiration only occurs in BHM when water is available in the ponding layer. However, evapotranspiration is a slow process relative to infiltration and seepage or overflow, which limits its impact on short-term bioretention performance.

Exfiltration was excluded from the model evaluation since it was inhibited in the field by an impermeable liner. As such, the field data collected resembles the behaviour of systems surrounded by expansive clays or similar low permeability soils. However, the separate sensitivity analysis performed on exfiltration showed it could play an important role in bioretention hydrology when native soils are permeable. BHM should be evaluated against an unlined bioretention system to ensure that the temporal disparity observed with instantaneous flows does not significantly affect total exfiltration volumes.

The behaviour of full-scale bioretention systems subjected to real storm events can deviate significantly from model simulations and, hence, predicted performance. Preferential flow paths and saturated zones may develop within the soil matrix, considerably altering hydrologic transport within the system. Poor construction and maintenance practices can compound these issues. At the Seneca College site, miscommunication between designers and contractors led to screened garden soil being placed as bioretention media instead of the specified permeable sandy soil. Additionally, snow removed from the parking lot area was at times ploughed onto the bioretention system, thereby reducing its infiltration capacity. These deviations from expected practice and operational conditions of field systems, combined with modelling limitations and input parameter uncertainties, could limit the applicability of modelling results to field systems.

CONCLUSIONS

BHM, a one-dimensional event-based model, was developed to simulate hydrologic transport in a bioretention system. The model structure was adapted from the RECARGA model. To improve accuracy, overflow was defined by a weir equation, exfiltration to native soils was added as a process, and groundwater recharge was made independent from underdrain discharge. In addition, to facilitate integration into pollutant transport models, the bioretention soils in BHM were divided into two layers that allow vegetative uptake to occur only within the depth of plant roots. Future work should consider improvements to the performance of the hydrologic model as well as the development of water quality models that assess pollutant load reductions based on individual ecological processes (e.g. soil filtration, sorption, plant uptake, microbial degradation) occurring in each model layer.

BHM was applied to field monitoring data collected by the TRCA at the Seneca College bioretention facility. Model simulations were found to be particularly sensitive to bioretention soil drainage properties and antecedent soil water content. Once calibrated, the model produced useful total underdrain discharge volume estimates, but simulations of instantaneous underdrain discharge rates remained poor for most storm events. Significant temporal disparity was observed between measured and simulated flows for a number of storms, possibly attributable to the development of preferential flow paths within the bioretention soil media in the field, which would allow a fraction of influent

to reach the underdrain structure without resistance. Modelling results suggest that soil water storage is the most important process for stormwater retention in bioretention systems, with exfiltration potentially significant when native soils are permeable.

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REFERENCES

- Agassi, M., Shainberg, I. & Morin, J. 1981 *Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation*. *Soil Science Society of America Journal* **45** (5), 848–851.
- Allen, R., Pereira, L., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Irrigation and drainage paper 56, Food and Agriculture Organisation of the United Nations, Rome, Italy.
- Aravena, J. & Dussailant, A. 2009 *Stormwater infiltration and focused recharge modeling with finite-volume 2D Richard's equation: Application to an experimental rain garden*. *Journal of Hydraulic Engineering* **135** (12), 1073–1080.
- Barco, J., Wong, K. & Stenstrom, M. 2008 *Automatic calibration of the U.S. EPA SWMM model for a large urban catchment*. *Journal of Hydraulic Engineering* **134** (4), 466–474.
- Brown, R., Skaggs, R. & Hunt, W. 2013 *Calibration and validation of DRAINMOD to model bioretention hydrology*. *Journal of Hydrology* **486**, 430–442.
- Carpenter, D. & Hallam, L. 2010 *Influence of planting soil mix characteristics on bioretention cell design and performance*. *Journal of Hydrologic Engineering* **15**, 404–416.
- Chen, L. & Young, M. 2006 *Green-Ampt infiltration model for sloping surfaces*. *Water Resources Research* **42** (7), 1–9.
- Constantz, J. & Murphy, F. 1991 *The temperature dependence of ponded infiltration under isothermal conditions*. *Journal of Hydrology* **122** (1–4), 119–128.
- Crowe, C., Elger, D. & Roberson, J. 2005 *Engineering Fluid Mechanics*. Wiley, Hoboken, NJ.
- Davis, A. 2008 *Field performance of bioretention: hydrology impacts*. *Journal of Hydrologic Engineering* **13** (2), 90–95.
- Davis, A., Shokouhian, M., Sharma, H., Minami, C. & Winogradoff, D. 2003 *Water quality improvement through bioretention: lead, copper, and zinc removal*. *Water Environment Research* **75** (1), 73–82.
- DeBusk, K., Hunt, W. & Line, D. 2011 *Bioretention outflow: does it mimic nonurban watershed shallow interflow?* *Journal of Hydrologic Engineering* **16** (3), 274–279.

- Dussaillant, A., Cuevas, A. & Potter, K. 2005 Raingardens for stormwater infiltration and focused groundwater recharge: Simulations for different world climates. *Water Supply* **5** (3–4), 173–179.
- Environment Canada 2008 National Climate Data and Information Archive, Toronto Buttonville Airport Weather Station. Meteorological Service of Canada, Ottawa, ON.
- He, Z. & Davis, A. 2011 Process modeling of storm-water flow in a bioretention cell. *Journal of Irrigation and Drainage Engineering* **137**, 121–131.
- Hong, E., Seagren, E. & Davis, A. 2006 Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. *Water Environment Research* **78** (2), 141–155.
- Huang, X., Massoudieh, A. & Young, T. 2006 Measured and predicted herbicide removal by mulch. *Journal of Environmental Engineering* **132** (8), 918–925.
- Li, H. & Davis, A. 2008 Urban particle capture in bioretention media. I: Laboratory and field studies. *Journal of Environmental Engineering* **134** (6), 409–418.
- Lucas, W. 2010 Design of integrated bioinfiltration-detention urban retrofits with design storm and continuous simulation methods. *Journal of Hydrologic Engineering* **15**, 486–498.
- Mein, R. & Larson, C. 1973 Modeling infiltration during a steady rain. *Water Resources Research* **9** (2), 384–394.
- Montalto, F. & Lucas, B. 2011 How are low impact stormwater control measures simulated by different computational models? In: *World Environmental and Water Resources Congress 2011* (R. Beighley II & M. Killgore, eds). ASCE, Reston VA, pp. 538–546.
- Palhegyi, G. 2010 Modeling and sizing bioretention using flow duration control. *Journal of Hydrologic Engineering* **15**, 417–425.
- PGC 2007 Bioretention manual. Prince George's County, Department of Environmental Resources, Environmental Services Division, Largo, MD.
- Rawls, W., Brakensiek, D. & Saxton, K. 1982 Estimating soil water properties. *Transactions of the ASAE* **25** (5), 1316, 1320; 1328.
- Rawls, W., Brakensiek, D., Simanton, J. & Kohl, K. 1990 Development of a crust factor for the Green Ampt model. *Transactions of the ASAE* **33** (4), 1224–1228.
- Rawls, W., Ahuja, L., Brakensiek, D. & Shirmohammadi, A. 1997 Infiltration and soil water movement. In: *Handbook of Hydrology* (D. Maidment, ed.). McGraw-Hill, New York, NY, pp. 5.1–5.51.
- Roy-Poirier, A., Champagne, P. & Filion, Y. 2010 Review of bioretention system research and design: past, present, and future. *Journal of Environmental Engineering* **136** (9), 878–889.
- Schaap, M., Leij, F. & van Genuchten, M. 2001 ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology* **251** (3–4), 163–176.
- TRCA 2008 Performance Evaluation of Permeable Pavement and a Bioretention Swale: Seneca College, King City, ON. Final Report. Toronto and Region Conservation Authority, Toronto, ON.
- USDA 2009a The Plants Database. United States Department of Agriculture, Natural Resources Conservation Service, National Plant Data Center, Baton Rouge, LA.
- USDA 2009b Soil Texture Calculator. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.
- van Genuchten, M. 1980 A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44** (5), 892–898.
- WDNR 2004 Technical Note for Sizing Infiltration Basins and Bioretention Devices to Meet State of Wisconsin Stormwater Infiltration Performance Standards. Wisconsin Department of Natural Resources, Madison, WI.

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