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Calibration and validation of DRAINMOD to model bioretention hydrology

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SUMMARY

Previous field studies have shown that the hydrologic performance of bioretention cells varies greatly because of factors such as underlying soil type, physiographic region, drainage configuration, surface storage volume, drainage area to bioretention surface area ratio, and media depth. To more accurately describe bioretention hydrologic response, a long-term hydrologic model that generates a water balance is needed. Some current bioretention models lack the ability to perform long-term simulations and others have never been calibrated from field monitored bioretention cells with underdrains. All peer-reviewed models lack the ability to simultaneously perform both of the following functions: (1) model an internal water storage (IWS) zone drainage configuration and (2) account for soil–water content using the soil–water characteristic curve. DRAINMOD, a widely-accepted agricultural drainage model, was used to simulate the hydrologic response of runoff entering a bioretention cell. The concepts of water movement in bioretention cells are very similar to those of agricultural fields with drainage pipes, so many bioretention design specifications corresponded directly to DRAINMOD inputs. Detailed hydrologic measurements were collected from two bioretention field sites in Nashville and Rocky Mount, North Carolina, to calibrate and test the model. Each field site had two sets of bioretention cells with varying media depths, media types, drainage configurations, underlying soil types, and surface storage volumes. After 12 months, one of these characteristics was altered – surface storage volume at Nashville and IWS zone depth at Rocky Mount. At Nashville, during the second year (post-repair period), the Nash–Sutcliffe coefficients for drainage and exfiltration/evapotranspiration (ET) both exceeded 0.8 during the calibration and validation periods. During the first year (pre-repair period), the Nash–Sutcliffe coefficients for drainage, overflow, and exfiltration/ET ranged from 0.6 to 0.9 during both the calibration and validation periods. The bioretention cells at Rocky Mount included an IWS zone. For both the calibration and validation periods, the modeled volume of exfiltration/ET was within 1% and 5% of the estimated volume for the cells with sand (Sand cell) and sandy clay loam (SCL cell) underlying soils, respectively. Nash–Sutcliffe coefficients for the SCL cell during both the calibration and validation periods were 0.92.

1. Introduction

Increased land development and the stormwater runoff it contributes have been identified as reasons for impairment of surface waters in the US (USEPA, 2007). As the focus of new stormwater rules shifts to prioritize water quality and annual hydrologic balance, in addition to peak flow reduction and flood control, incorporating infiltration-based stormwater control measures (SCMs) is becoming necessary. These low impact development (LID) practices help to restore a site's natural hydrology and reduce the negative effects associated with increased impervious areas in urbanized watersheds. Bioretention cells are one of the most commonly used LID practices.

Intensive research and installation experience have assisted in the evolution of bioretention design recommendations (Hunt et al., 2012). For unlined bioretention cells, one common theme has been a large variation in hydrologic performance based on a number of design characteristics and the site's location. Deeper media depth increased exfiltration and reduced outflow volume and frequency (Li et al., 2009; Brown and Hunt, 2011a). Also, as the ratio of bioretention surface area to drainage area increased, outflow volume was reduced (Hatt et al., 2009; Jones and Hunt, 2009). These studies imply that as volume of bioretention media is increased, outflow is reduced. Site location impacts rainfall patterns and underlying soils. Bioretention cells constructed at sites with sandier underlying soils have greater exfiltration than those with tighter underlying soils (Brown and Hunt, 2011b; Passeport et al., 2009). Brown and Hunt (2011b) and Li et al. (2009) also determined that an internal water storage (IWS) zone design feature can further reduce outflow volume; results were magnified in locations with sandy underlying soils. Additionally, Hunt et al. (2008) identified a steep hydraulic gradient from the bottom of the bioretention cell as being responsible for enhancing hydrologic performance. Despite these generalized conclusions about

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hydrologic performance, it is difficult to apply specific values to a bioretention water balance because of the variety of site and design variables. Benefits of a water balance include: (1) quantifying groundwater recharge (exfiltration), (2) comparing a design to the pre-developed hydrologic condition of the landscape, and (3) estimating pollutant load reduction.

To evaluate the life cycle response of bioretention cells, a long-term, field tested model is needed. DRAINMOD, a long-term, continuous simulation drainage model that was first developed in the 1970s at North Carolina State University is a model that can be used for this purpose. DRAINMOD has been used to model agricultural drainage systems, controlled drainage, subirrigation, wetland hydrology, nitrogen dynamics and losses from drained soils, impacts of drainage system and irrigation management on soil salinity in irrigated arid soils, on-site wastewater treatment, forest hydrology, and other applications (Skaggs, 1978, 1982, 1999; Youssef et al., 2005). DRAINMOD continues to be improved and extended, and bioretention hydrology is one of the new applications.

Increased confidence of predicting hydrologic performance of bioretention cells could lead to the development of a ‘‘flexible’’ design methodology. Two drivers for developing a ‘‘flexible’’ bioretention design methodology are: (1) a site’s physical constraints could force under-sized designs, such as in retrofits, and (2) monitored bioretention cells have been shown to have large variations in hydrologic performance. The current North Carolina state standard, like most regulatory authorities, uses a ‘‘one size fits all’’ approach for designing and awarding credit for bioretention cells (NCDENR, 2009).

Currently, no widely accepted long-term model exists for bioretention. Some current bioretention models lack the ability to perform long-term simulations and others have never been calibrated from field monitored bioretention cells with underdrains. Features that all current models lack are the ability to simultaneously perform both of the following functions: (1) model an internal water storage (IWS) zone drainage configuration and (2) account for soil–water content using the soil–water characteristic curve. The importance of incorporating the soil–water characteristic curve is discussed in further detail later.

Initial modeling studies did not include underdrains (Brander et al., 2004; Dussaillant et al., 2004, 2005; Heasom et al., 2006). Brander et al. (2004) and Heasom et al. (2006) used single-event models to predict overflow from bioinfiltration cells (no underdrain). Single-event models are useful to assist in bioretention design by routing a design event; however, they do not account for antecedent soil moisture conditions which can have a large effect on performance. For this reason, continuous simulation models are preferred.

Dussaillant et al. (2004) developed a long-term, continuous simulation, numerical model that was based on the mixed formulation of the one-dimensional Richards equation (RECHARGE). Later, Dussaillant et al. (2005) developed a simplified numerical model, RECARGA, based on the Green–Ampt infiltration model for surface infiltration and van Genuchten relationships for drainage between soil layers. When compared to the more complex RECHARGE, RECARGA had good results (Dussaillant et al., 2005). However, at the time, an option to include underdrains was not available for either model. RECARGA has since been modified, and the updated version available online, Version 2.3, has an option to include an underdrain. However, RECARGA’s method of including an underdrain is not commensurate with typical field installations, and underdrain flow is calculated using the orifice equation after the user enters the diameter for only one drain.

He and Davis (2011) recently developed a two-dimensional variable saturated flow model, based on the Richards equation to explore general impacts of using different media types, surrounding soils, initial water content in the media, drainage to bioretention area ratios, and cell length to width ratios. However, the model simulations were based on a variety of single events, so it did not compute a water balance for a continuous period of record. Therefore, it was not capable of evaluating the effect of wet periods or sequence of weather events on performance. In some of the simulations presented, the He and Davis (2011) model included parallel underdrain pipes for the modeling scenario with the largest bioretention cell width. It should be noted that the underdrains were only surrounded by 0.05–0.08 m of gravel instead of being installed in a uniform depth of gravel across the entire bottom area. The He and Davis (2011) model predicted lateral flows as well, and the results showed that 88–95% of the exfiltration volume was through the bottom.

Palhegyi (2010) developed a computation bioretention hydrology model to assist with sizing bioretention cells to meet flow duration criteria. The model used a soil moisture computational procedure based on the algorithms used in Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) (USACE, 2000). This algorithm follows the principle that water will leave the profile via ET, percolation (exfiltration), and drainage (if underdrains are installed) until the water content equals the field capacity. Then water will only leave via ET until the water content equals the wilting point. Underdrain flow is modeled using an algorithm solving Bernoulli’s equation for a user-specified pipe length and diameter. The model showed good results when field tested to a bioinfiltration cell in Villanova, PA; however, this cell did not include an underdrain, so its applicability to bioretention cells with underdrains was not evaluated. A concern with using field capacity when the local water table is close to the bottom of a bioretention cell (within 1 m) is that the soil–water content in the media will likely not reach field capacity estimates because field capacity for coarse textured soils is generally estimated as the water content at a suction of 10 kPa (Cassel and Nielsen, 1986).

In Lucas (2010), a bioretention planter system with an elevated lower outlet was modeled for a design storm using HydroCAD and then with SWMM 5.0.014, a continuous simulation model, to determine impacts on combined sewer overflows. Both models gave comparable results when modeling a single synthetic rainfall event; however, neither model was field tested in this application. These models used an orifice to control inflow rates into the media and once the media was saturated it used Darcy’s Law. ‘‘Dummy’’ nodes, areas, and cylinders were added in the models to route water through the system (Lucas, 2010). Lucas and Greenway (2011) verified that the HydroCAD model using this procedure accurately simulated flow under saturated conditions for a synthetic event in a 240-L mesocosm with multiple elevated outlets.

Some other models with continuous simulation capabilities that are currently available to designers to model bioretention hydrology include: Storm Water Management Model (SWMM) 5.0, windows-based Source Loading and Management Model (WinSLAMM) 9.4, and Model for Urban Stormwater Improvement Conceptualism (MUSIC) 5.0. These models also have the capability to model an elevated outlet. However, the processes used by these models and some of the ones presented earlier to predict soil–water content changes with water level depth and to model water movement through the media and into the drains under variably saturated and unsaturated conditions are not as comprehensive as those in DRAINMOD. Predicting soil–water content variations with depth is of particular importance when the water level is within the media profile, such as for an elevated outlet.

DRAINMOD calculates drainage rates as a function of soil properties and drainage configuration, and it incorporates the impact of having the water level close to the surface by using the soil–water characteristic curve to account for soil–water content of the media. The other previously described bioretention models either calculate available water storage by subtracting field capacity from total porosity or by using a constant, user-provided, void ratio of the

Table 1
Comparison of calculating volume of water drained from media based on water level distance from soil surface by using soil–water characteristic curve versus subtracting field capacity from saturated volumetric water content.

Water level distance from soil surface (m)	Volume drained: soil–water characteristic curve (cm^3/cm^2)		Volume drained: saturation minus field capacity (cm^3/cm^2)		Percent difference	
	Rocky Mount media (cm)	Nashville media (cm)	Rocky Mount media (cm)	Nashville media (cm)	Rocky Mount media	Nashville media
0.1	0.008	0.0003	0.031	0.017	−273	−6017
0.3	0.056	0.013	0.092	0.052	−65	−289
0.6	0.147	0.055	0.184	0.103	−25	−88
1.0	0.269	0.120	0.306	0.172	−14	−43

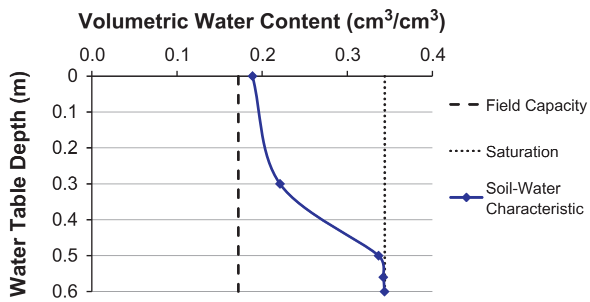

Fig. 1. Volumetric water content present in profile for Nashville media when the water table depth is 0.6 m, using the soil–water characteristic (solid line) and field capacity (long dashes) methods.

media. In actuality, the soil–water content of unsaturated media varies with distance to the water table. Using field capacity to calculate the amount of water stored in the profile is not appropriate when the bioretention water table is close to the surface, such as cases with an elevated outlet or IWS zone, or when the local water table is close to the bottom of the gravel layer. The water table introduces capillary fringe that increases soil moisture above the saturated zone, reducing pore space available for storage according to the soil–water characteristic curve. As an example, in Table 1, the volume of water drained based on the water level being 0.6-m from the soil surface was calculated per the soil–water characteristic curve and by subtracting the field capacity [volumetric water content at a suction of −1.0 m (9.8 kPa)] from the saturated volumetric water content. Results are given for two types of media, both of which were subsequently used in the calibration of DRAINMOD. One was predominantly sand (Rocky Mount site), while the other had a mixture that was typical of current NC design recommendations (Nashville site) (NCDENR, 2009). The Nashville media has a higher fraction of fine particles, so it holds more water in the media at larger suctions. Table 1 describes that the largest errors occur with the Nashville media and when the water level is closest to the surface. The soil–water characteristic curve provides a more accurate representation of the water present in the media. This concept is especially important for modeling bioretention cells with an IWS zone because the water level would likely remain within the media profile for the entire inter-event period. When the water level was 0.6-m below the soil surface, the error associated with neglecting the soil–water characteristic curve is 88% (Nashville). This is an inherent error and important omission in models for shallow water table systems that use the field capacity concept. An illustration of this example is presented in Fig. 1.

As design questions regarding minimum fill media depth, fill media composition, maximum ponding depth, and underdrain configuration still persist (Davis et al., 2009), a continuous, long-term hydrologic model is needed. DRAINMOD appears to be a tool that could help answer some of these design questions as well as improve overall design recommendations. The objective of this project was to test DRAINMOD to determine its reliability for describing the hydrologic response and performance of field-monitored bioretention cells.

2. Model application

2.1. DRAINMOD description

Detailed descriptions on the governing equations, model components, subroutines, and time steps are presented in Skaggs (1978, 1980, 1982, 1999). The governing equations for DRAINMOD are based on two water balances: (1) in the soil profile (Eq. (1)) and (2) at the soil surface (Eq. (2)). In the soil profile, the water balance is computed for a section of soil of unit surface area, located at the midpoint between adjacent drains, and extending from the impermeable layer to the soil surface:

$$\Delta V_a = D + \mathrm{ET} + \mathrm{DS} - F \tag{1}$$

where ΔV_a = change in the air volume, D = lateral drainage from the section, ET = evapotranspiration, DS = deep seepage, and F = infiltration entering the section in Δt (time increment). DRAINMOD uses the Green and Ampt equation to calculate infiltration rate (Green and Ampt, 1911). The water balance at the surface is computed per unit surface area by:

$$P = F + \Delta S + \mathrm{RO} \tag{2}$$

where P = precipitation, F = infiltration, ΔS = change in volume of water stored on the surface, and RO = runoff during time period Δt.

DRAINMOD computes each water balance for a time increment Δt, with all units expressed in terms of depth (cm). The time increment is normally 1 h; however, when the rainfall rate exceeds the infiltration capacity, Δt decreases to 0.05 h or less. When there is no rainfall and the drainage rate is rapid, Δt is increased to 2 h, and when the drainage and ET rates are slow, Δt is further increased to daily.

To solve for the losses via drainage, DRAINMOD uses Hooghoudt's equation (Eq. (3)) to compute drainage flux when the water table is below the surface. The flux is evaluated in terms of the water table at the midway point between the drains and the hydraulic head in the drains.

$$q = \frac{8Kd_e m + 4Km^2}{L^2} \tag{3}$$

where K = effective lateral hydraulic conductivity, L = drain spacing, m = water table height above the drains at the midpoint, and d_e = equivalent drain depth. To correct for convergence near the drain, an equivalent depth is calculated using equations developed in Moody (1967). For typical bioretention installations, the drain depth to drain spacing ratio will likely be less than 0.3, so Eq. (4) is used to calculate the equivalent depth.

$$d_e = \frac{d}{1 + \frac{d}{L}\left[\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \left(3.55 - \frac{1.6d}{L} + 2\left(\frac{2}{L}\right)^2\right)\right]} \tag{4}$$

In this equation, r = drain radius and d = drain depth. If the depth to spacing ratio exceeds 0.3, a different equation is used. When the surface is ponded and the profile is saturated, drainage rate is calculated with the Kirkham equation (Kirkham, 1957).

$$q = \frac{4\pi K(t + d - r)}{GL} \tag{5}$$

In this equation, t = ponding depth and G is a term dependent on drain depth and spacing and depth of the profile. It is called Kirkham's coefficient G in DRAINMOD and is defined in

$$G = 2\ln\left[\frac{\tan(\pi(2d-r)/4h)}{\tan(\pi r/4h)}\right] + 2\sum_{m=1}^{\infty}\ln\left[\frac{\cosh(\pi mL/2h)+\cos(\pi r/2h)}{\cosh(\pi mL/2h)-\cos(\pi r/2h)}\cdot\frac{\cosh(\pi mL/2h)-\cos(\pi(2d-r)/2h)}{\cosh(\pi mL/2h)+\cos(\pi(2d-r)/2h)}\right] \tag{6}$$

In this equation, h = depth of profile.

If the drainage flux is limited by the hydraulic capacity of the drainage network (i.e., size and slope of the receiving pipes/channels or features of the outlet structure), a user-defined constant that accounts for these limitations can be applied. This constant that sets the maximum allowable drainage rate is termed in DRAINMOD as the drainage coefficient. For example, if the drainage rate as calculated by Eqs. (3) or (5) exceeds the user-defined drainage coefficient, the drainage rate is set equal to the drainage coefficient.

As the profile of a bioretention cell consists of multiple layers (i.e., bioretention media, sand, and gravel), the effective lateral hydraulic conductivity is calculated using

$$K_e = \frac{K_1 d_1 + K_2 D_2 + K_3 D_3 + K_4 D_4}{d_1 + D_2 + D_3 + D_4} \tag{7}$$

where D_i is the depth of a given soil layer, K_i is the saturated hydraulic conductivity associated with layer D_i, and d_1 is the distance from the top of the second layer to the top of the water table at the midpoint between the drains. If the water table is below the top layer (layer 1), then d_1 is set equal to zero and d_2 is substituted for D_2.

Potential evapotranspiration (PET) can be incorporated into DRAINMOD by entering a file of daily PET depths based on any type of PET method. There are multiple ways to calculate PET, with some methods requiring more meteorological data than others. Under the default method, DRAINMOD uses daily maximum and minimum air temperatures provided by the user with the Thornthwaite method to calculate daily PET (Thornthwaite, 1948). The Thornthwaite method is the simplest (and least accurate) method to calculate PET because it requires mean monthly air temperature as its sole input. To improve the accuracy of PET for this method, there is an option in DRAINMOD to include correction factors to correct the daily PET estimate. PET is distributed daily for the 12 h between 6:00 a.m. and 6:00 p.m., and PET is set equal to zero when rainfall occurs. ET is calculated based on the soil–water con-

Table 2
Comparison of DRAINMOD inputs to typical bioretention design parameters.

Bioretention design parameters	DRAINMOD inputs
Drain depth	Depth from soil surface to drain
Drain size	Effective radius of drains
Drain spacing	Spacing between drains
Average surface storage depth	Maximum surface storage
Depth from surface to bottom of gravel	Distance from surface to impermeable layer
Drainage coefficient	Drainage rate as limited by hydraulic capacity of the drainage system in bioretention cell
Media/gravel characteristics and depths	Inputs for soil–water characteristic curve andsaturated hydraulic conductivity for each layer
Internal water storage zone design	Weir setting for controlled drainage
Drainage area: bioretention area ratio	Field ratio of contributing land area
Vegetation root depth	Vegetation root depth
Exfiltration rate of subsoil	Vertical or deep seepage parameters
Weather conditions	Rainfall and temperature files
Evapotranspiration	Either enter a file of calculated PET or use Thornthwaite method (with or without adjusted parameters)

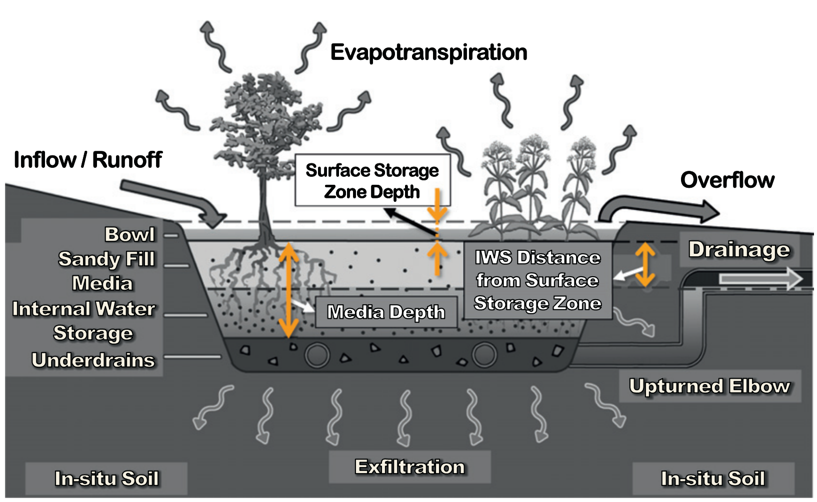

Fig. 2. Example of a bioretention cell with an internal water storage (IWS) zone and description of bioretention cell characteristics and various forms of flow.

Table 3
DRAINMOD outputs applicable to bioretention cells.

DRAINMOD outputs	Potential meaning for bioretention
ET	Evapotranspiration (volume eliminated from stormsewer network)
Drainage	Underdrain flow volume (treated portion)
Runoff	Overflow volume (untreated portion)
Seepage	Exfiltration (volume eliminated from stormsewer network)
Wet stress	Vegetation stress indicator
Dry stress	Vegetation stress indicator
Rank files for each of the above outputs	Quantify impact of severe events or large consecutive events (i.e. 1 in 10 years)

ditions. If the conditions are not limiting, ET is set equal to PET. However, as the soil–water conditions become limiting (dry zone depth exceeds root depth), ET is set equal to the upward flux from the bioretention water table.

2.2. Application of bioretention design in DRAINMOD

Brown (2011) provides a summary description of DRAINMOD and a detailed step-by-step description for using DRAINMOD to model bioretention hydrology. In general, the first step of the modeling procedure is to simulate runoff from the contributing area. Since the most of the contributing area is typically impervious, the majority of rainfall will run off the surface. Therefore, to mimic a small initial loss of rainfall from the contributing area, the model input parameters to simulate runoff were adjusted to have a wide drain spacing, shallow surface storage, and low infiltration rate. The contributing area runoff file created from this initial simulation is included in the next simulation for the bioretention design. The model input parameters for the bioretention design are entered based on the various design configurations and site conditions. One drawback of the model is that inputs are held constant for the entire period of the simulation. Emerson and Traver (2008) and Braga et al. (2007) have shown seasonal variation of infiltration SCMs because the influence of temperature on infiltration rates.

The concepts of water movement in bioretention cells when installed with underdrains are very similar to agricultural fields drained by tiles. Because of the similarities, many DRAINMOD inputs corresponded directly to bioretention cell design specifications. A comparison of these inputs is presented in Table 2. In DRAINMOD, an option exists to model an IWS zone created by an upturned elbow, similar to the setup in the diagram presented in Fig. 2, through the model input for controlled drainage. This model feature forces water to pass through the entire media profile and exit at a rate regulated by the reduced hydraulic head of the elevated outlet. It can also simulate multiple drains. In Table 3, examples of DRAINMOD outputs are related to bioretention cell measures.

3. Determination of input parameters

3.1. Site description

DRAINMOD was calibrated and validated for field-monitored bioretention cells located in Nashville and Rocky Mount, NC. Detailed descriptions of the site characteristics are described in Brown and Hunt (2011a, 2012) for Nashville and Brown and Hunt (2011b) for Rocky Mount. At each site, there were two different bioretention cells that were monitored for approximately 24 months. One of the main differences between the two sites was drainage configuration. The Nashville site was conventionally drained and the Rocky Mount site had an elevated underdrain outlet, which created an IWS zone. An example of a bioretention cell with an IWS zone and some of the bioretention cell characteristics are presented in Fig. 2. Bioretention cell characteristics varied between the two cells at each site. At Nashville, the cells had varying media depths (0.6 m versus 0.9 m), while at Rocky Mount, the underlying soil varied (sandy clay loam versus sand). Among them, the bioretention cells had a variety of different underlying soil types, media depths, drainage configurations, surface storage volumes, design events, and ratios of drainage area to bioretention surface area.

After 1 year of monitoring, a design specification was altered at each site to measure the impact of the change. From year 1 to year 2, the surface storage zone was increased and a clogging layer was removed at the Nashville site (year 1 – pre-repair period, year 2 – post-repair period) (Brown and Hunt, 2012). At the Rocky Mount site, the IWS zone was decreased by 0.3 m (year 1 – deep IWS period, year 2 – shallow IWS period). A summary of bioretention cell and drainage area characteristics for each bioretention cell and for each monitoring period are described in Table 4.

3.2. Monitoring methods

With the exception of the deep seepage parameters for the Nashville site, the DRAINMOD input parameters were either measured on site or in the Soil and Water Laboratory at Weaver Laboratory on NC State University campus. The hydrologic monitoring methods at Nashville and Rocky Mount, NC, are described in detail in Brown and Hunt (2011a, 2011b), respectively. In general, runoff, drainage, and overflow volumes were measured or estimated for each site. These different forms of flow are described in Fig. 2. Because the contributing area at each site was mostly impervious, runoff was estimated using an initial abstraction method that assumed shallow depressions were filled first and then the rest of the rainfall was transmitted as runoff. For asphalt on a shallow slope, Pandit and Heck (2009) found that nearly all of the rainfall would be transmitted as runoff. The abstraction depths measured by Pandit and Heck (2009) were in the range of those used for the initial abstraction method. On an annual basis, the ratio of runoff to rainfall using the initial abstraction method was 0.92 for a smoothly graded, 100% impervious asphalt surface. These results were similar to a site where runoff was measured from a 3.0 ha, 97% impervious commercial shopping center; the ratio of runoff to rainfall was 0.89 (Line et al., 2012).

At the Nashville site, overflow and drainage were measured together using a sharp-crested 90° v-notch weir. Based on the outflow hydrograph, overflow could be separated from drainage to allow for each to be summed separately (Brown and Hunt, 2011a). At Rocky Mount, drainage was measured with a sharp-crested 30° v-notch weir, and overflow was estimated based on rainfall intensity, bioretention cell surface storage characteristics, drainage area characteristics, and measured surface infiltration rates that varied by month. Based on a water balance, all of the runoff that did not exit via overflow or drainage was assumed to be lost via exfiltration or ET. Exfiltration and ET were grouped for calibration because ET was estimated on a monthly basis from the flow monitoring program. Additionally, the output in DRAINMOD is on a daily basis, so it was more difficult to separate exfiltration and ET on an event basis. At each site, estimations of ET suggested that water was primarily released through exfiltration, attributable to the relatively sandy underlying soils. At all four bioretention cells, the estimated ET ranged from 3% to 5% of cumulative runoff volume (Brown and Hunt, 2011a, 2011b).

Water level loggers, manufactured by Infinities USA, were installed during the second year of the monitoring period to measure the water levels in the surface storage zone of all cells and in the

Table 4
Bioretention cell and drainage area characteristics for each bioretention cell and monitoring period.

Site description	Nashville 0.6-m media depth	Nashville 0.6-m media depth	Nashville 0.9-m media depth	Nashville 0.9-m media depth	Rocky Mount SCL cell	Rocky Mount SCL cell	Rocky Mount Sand cell	Rocky Mount Sand cell
Monitoring period	Pre-repair	Post-repair	Pre-repair	Post-repair	Deep IWS	Shallow IWS	Deep IWS	Shallow IWS
Media depth (m)	0.6	0.6	0.9	0.9	1.1	1.1	0.96	0.96
Drainage area (ha) [% impervious]	0.68 [83]	0.68 [83]	0.43 [97]	0.43 [97]	0.22 [76]	0.22 [76]	0.245 [72]	0.245 [72]
Surface storage [ponding] zone volume (m^3)	35	66	32	60	23.6	23.6	18.5	18.5
Surface infiltration rate (mm/h)	2.5–12.7	10–115	2.5–6.4	11–51	25–125	25–125	Rapid (ponding never recorded during shallow IWS period)	
Drainage configuration	Conventional	Conventional	Conventional	Conventional	Internal water storage (IWS)	Internal water storage (IWS)	Internal water storage (IWS)	Internal water storage (IWS)
IWS zone distance from surface storage zone (m)	N/A	N/A	N/A	N/A	0.3	0.6	0.3	0.6
Media characteristics	86–89% sand, 8–10% silt, 3–4% clay				96% sand, 2.9% silt, 1.1% clay			
In situ soil type	Sandy loam; loamy sand				Sandy clay loam	Sandy clay loam	Sand	Sand

IWS zone at the cells in Rocky Mount. The water level drawdown rates in the IWS zone were 7–11 mm/h (0.28–0.43 in./h) and 200–300 mm/h (8–12 in./h) for the Sandy Clay Loam (SCL) and Sand cells, respectively. To calculate the exfiltration rate, the IWS drawdown rate was multiplied by the effective drainable porosity of the bioretention media, which was estimated to be 30% based on the soil–water characteristic curve. This equated to an exfiltration rate of 2.1–3.3 mm/h (0.08–0.13 in./h) in the SCL cell and 60–90 mm/h (2.4–3.6 in./h) in the Sand cell. Initial soil–water content prior to rainfall has a major influence on infiltration rate (Green and Ampt, 1911). In order to assume that the measured infiltration rate (drawdown rate of surface storage zone) would represent the final constant infiltration rate that occurs under saturated conditions, only the tail ends of rainfall events greater than 25 mm (1 in.) were used to verify the saturated hydraulic conductivity parameter used in the Green and Ampt infiltration model in DRAINMOD. At the Nashville site, the media had a measured saturated hydraulic conductivity of 55 mm/h for the 0.6-m media depth cells and 35 mm/h for the 0.9-m media depth cells. This was in the range of the average final constant infiltration rates measured for seven events greater than 25 mm for the post-repair period – 49 mm/h and 29 mm/h for the 0.6-m and 0.9-m media depth cells, respectively. These rates are also in the range recommended in the NC state design guidance manual of 25–51 mm/h (NCDENR, 2009).

At the Nashville site, there was no IWS zone and drainage rarely occurred for more than 12 h after runoff ceased in year 2. This made it difficult to collect water level readings within the media to compare to the daily output of bioretention water table depth in DRAINMOD, so HOBO soil moisture sensors were installed to measure soil–water content in the media. Four Soil Moisture smart sensors (model: S-SMC-M005) with a HOBO Micro-Station (manufacturer: Onset Computer Corporation) were used to measure volumetric soil–water content in one 0.6-m and one 0.9-m media depth cell. In the 0.9-m media depth cell, sensors were installed at the following depths: 0.05, 0.3, 0.6, and 0.9 m, and in the 0.6-m media depth cell, sensors were installed at the following depths: 0.05, 0.2, 0.4, and 0.56 m. These soil moisture sensors used time-domain reflectometry (TDR) to measure volumetric soil–water content by measuring the velocity of a voltage pulse passing between the two parallel rods. Volumetric water content was measured at each depth for two separate occasions to confirm the readings of the soil moisture sensors. The average absolute error was 0.017 cm^3/cm^3, and the range of error was -0.020 cm^3/cm^3 to 0.046 cm^3/cm^3. The volumetric water content measurements were used to assist in selecting the vertical seepage parameters.

At each site, the drainage area, bioretention cell area, average surface storage zone depth, media depth, drain depth, and depth to drain outlet (for IWS designs) were surveyed. The bioretention design specifications were entered into DRAINMOD per surveyed measurements (described later) of the media's soil–water characteristic curves, saturated hydraulic conductivities, and infiltration and exfiltration rates.

3.3. Drainage coefficient

It was suspected that the water movement through the profile and to the drain pipe would be the limiting factor, and it would be accounted for with Eqs. (3), (5), or the Green and Ampt equation. However, since the sites were monitored for over 2 years and had a variety of extreme events, calibration of the model input, drainage coefficient, was set by examining the maximum drainage rate from each bioretention cell. The maximum measured drainage rate was applied in case the hydraulic capacity was limited by other means. For application of DRAINMOD to unmonitored sites, it is expected that the water movement through the profile and to the drain pipe should be the limiting factor, so an unrealistically large drainage coefficient can be entered to prevent the drainage coefficient input from restricting drainage rate that would be computed with Eqs. (3) or (5).

The maximum drainage rate at the Nashville site occurred during the post-repair period because the clogging layer limited infiltration capacity during the pre-repair period. The maximum drainage rate at the Rocky Mount site occurred during the shallow IWS period because the hydraulic gradient between the media surface and IWS outlet when the profile was saturated was larger than compared to the deep IWS period. Based on the maximum observed drainage rates from each set of cells at the Nashville site, the drainage coefficients applied to the 0.6-m and 0.9-m media depth cells were 85 and 60 cm/day, respectively. Based on the maximum observed drainage rate at Rocky Mount, the drainage coefficient applied in the model was 75 cm/day. Water level monitoring described that for the events selected with the maximum drainage rates, the entire profile was saturated and the surface storage zone was full.

3.4. Soil

The soil file preparation program in DRAINMOD requires two soil properties for each layer in the profile – soil–water characteristic curve and saturated hydraulic conductivity. Up to five soil layers can be entered in DRAINMOD. These properties were measured for the bioretention media using six, 77-mm diameter soil cores collected from each type of media. The soil–water characteristic curves were measured using a pressure plate apparatus, which measures the water released from a saturated soil core under various pressures. The average volumetric water contents at the various pressures for the two types of media are presented in Table 5. Based on the user-specified soil–water characteristic curve and associated depth for each layer in the profile, the soil preparation program computes a relationship of water table depth to volume drained to account for the soil–water content in the profile as the water level within the bioretention profile fluctuates. Saturated hydraulic conductivity of the bioretention media was measured with a constant head permeability test, as described in Klute (1986). The saturated hydraulic conductivity of the underlying sand layer was estimated at 15 cm/h (Rawls et al., 1998), and the gravel layer was estimated at 200 cm/h (Domenico and Schwartz, 1990).

In the soil preparation program in DRAINMOD, the two required inputs above allow for the initial soil–water deficit parameter for the Green and Ampt model to be generated as a function of water level depth. The final parameter of suction head at the wetting front was based on the soil textural class. At the Nashville site during the pre-repair period, there was a restricting layer present at a depth of approximately 0.25 m from the surface, so an additional layer was added from the surface to the bottom of the restricting layer. The effective saturated hydraulic conductivity for this layer was set at 1 mm/h based on observed infiltration rates during this period. The saturated hydraulic conductivity of the remaining depth of the media was set equal to the rate measured with the constant head permeability test.

In Nashville, 12 samples of the surrounding in situ soil were collected with a hand auger at depths from 0.3 to 0.9 m below the surface of the media to determine the soil texture. Soil texture was measured with a hydrometer and followed the procedure in Gee and Bauder (1986). These measurements confirmed the underlying soil texture with that listed for the soil series described in the Nash County soil survey – predominantly sandy loam and loamy sand (USDA, 1989). Vertical (deep) seepage parameters for the Nashville site were estimated from the Nash County soil survey. At the Rocky Mount site, the measured exfiltration rates were used to calibrate the vertical seepage parameters in DRAINMOD. All exfiltration was modeled using the vertical seepage function only, which was a similar approach used by most other available bioretention models. DRAINMOD can model lateral seepage, but it was not used in these examples because of the complexity in gathering the necessary model input data from this site after it had been constructed.

Table 5
Soil–water characteristics for Rocky Mount and Nashville media.

Pressure head		Volumetric water content (cm^3/cm^3)	
m	kPa	Rocky Mount media	Nashville media
0	0	0.350	0.344
−0.04	−0.39	0.291	0.342
−0.1	−0.98	0.175	0.337
−0.3	−2.94	0.05	0.221
−0.6	−5.88	0.045	0.189
−1.0	−9.81	0.044	0.172
−2.0	−19.6	0.044	0.151
−3.0	−29.4	0.044	0.139
−4.0	−39.2	0.044	0.131
−6.0	−58.8	N/A	0.117
Notes		Too sandy (96% sand)[a]	Typical NC composition[a]

[a] NCDENR (2009) standards.

3.5. Climate

3.5.1. Temperature

Maximum and minimum daily air temperatures are climate inputs for DRAINMOD to estimate daily potential evapotranspiration (PET). These measurements were obtained for the entire monitoring period at both the Rocky Mount and Nashville sites from the State Climate Office of NC monitoring station, "NRKM – Rocky Mount," in Rocky Mount, NC (NCSCO, 2010). This monitoring station was the closest available weather station to either site. It was 12 km (7.5 mi) and 2.5 km (1.5 mi) from the Nashville and Rocky Mount sites, respectively.

3.5.2. Precipitation

Precipitation depths were measured in 2 min intervals, at each site, using an ISCO 674 tipping bucket rain gauge. Since the shortest time increment to input precipitation depths in DRAINMOD is hourly, the measured rainfall depths were summed on an hourly basis throughout the entire monitoring period for each site.

3.5.3. Potential evapotranspiration

In this application, the DRAINMOD default method (Thornthwaite) was used to calculate PET. Monthly correction factors were applied to improve the accuracy of the PET input. Amatya et al. (1995) calculated correction factors for three sites in eastern North Carolina (Tarboro, Carteret, and Plymouth). Tarboro is within 35 km of both field sites, so the correction factors from this location were used.

4. Model calibration and validation

Four methods were used to quantify the calibration and validation of the model. At Rocky Mount, measured and predicted bioretention water table depths were compared. At both sites, measured/estimated and predicted depths of runoff and the outflow (cm, or cm^3/cm^2 of bioretention surface area) were compared and percent differences of each variable were calculated. Finally, Nash–Sutcliffe coefficients were calculated by comparing the event-based cumulative volumes measured/estimated with the flow monitoring program to event-based cumulative volumes predicted by DRAINMOD. Nash–Sutcliffe model efficiency coefficients (NSE) were calculated on an event-basis using

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}(Q_{i,measured} - Q_{i,predicted})^2}{\sum_{i=1}^{N}(Q_{i,measured} - Q_{average})^2} \tag{8}$$

where $Q_{i,measured}$ = measured volume for event i, $Q_{i,predicted}$ = predicted volume for event i, $Q_{average}$ = average measured volume for N events, N = total number of events for the monitoring period, and NSE = Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970).

Contributing area runoff was the first process calibrated, by adjusting the drain spacing, drain depth, surface storage depth, and Green and Ampt infiltration parameters for the soil file surrogate for asphalt. These parameters were adjusted to limit infiltration and promote runoff from the contributing drainage area. At each site, results from the second monitoring period and first monitoring period were used to calibrate and validate DRAINMOD, respectively. Once predicted runoff was in agreement with the estimated runoff, the different forms of outflow were calibrated from the various bioretention cells based on their site and design characteristics. Since the change between monitoring periods at Rocky Mount was relatively minor (reducing the IWS outlet elevation), measurements collected for the entire shallow IWS period were used to calibrate DRAINMOD. Measurements collected for the deep IWS period were used to test or validate the model. At Nashville, the presence of a clogging layer in the pre-repair period made the transition between modeling the two periods more complex than solely changing an outlet depth. For this reason, both monitoring periods were split into two equal (6 month) periods to calibrate and validate the model. The post-repair period was calibrated first because the profile was more uniform and not impacted by a restricting layer. The same vertical seepage parameters and drain characteristics from the post-repair period were used for the pre-repair period.

In calibrating the contributing area runoff, there were three combinations of impervious percentage and consistency (depressions versus smoothly graded asphalt) in the impervious area in the four separate bioretention cells. The parking lot at the Rocky Mount site had larger depressions compared to the Nashville site, which was smoothly graded. Therefore, less runoff per unit area was generated at the Rocky Mount site. Also, the impervious portion of the drainage area at Rocky Mount was approximately 75% for the two bioretention cells, where, in Nashville, it was 83% and nearly 100% for the 0.6-m and 0.9-m media depth cells, respectively. In the model setup to predict runoff from the contributing area, the surface storage parameter was increased for the sites with larger impervious depression storage and larger portions of pervious area. The Nashville site with nearly 100% impervious area had a surface storage parameter equal to 0.01 cm. This was increased to 0.07 cm for the Nashville site with 83% impervious area and 0.28 cm for the Rocky Mount sites with approximately 75% impervious area and several shallow depressions in the asphalt surface.

5. Model results

5.1. Contributing area runoff

Nash–Sutcliffe coefficients during the calibration period were 0.99 at Rocky Mount and 1.00 at Nashville. In the validation period, Nash–Sutcliffe coefficients were again 0.99 and 1.00 for the Rocky Mount and Nashville sites, respectively. The predicted runoff volumes for each event were in excellent agreement with the method that was used to estimate runoff volume – initial abstraction method.

5.2. Nashville site – conventional drainage configuration

5.2.1. Post-repair monitoring period (year 2)

As described in Table 6, predicted outflows at the Nashville site were in good agreement with the measured and estimated outflows for both the calibration and validation periods, during the post-repair monitoring period. Of the forms of outflow, drainage had the strongest agreement between measured and predicted values; Nash–Sutcliffe coefficients exceeded 0.9. Nash–Sutcliffe coefficients for exfiltration/ET were approximately 0.9 and 0.8 during the calibration and validation periods, respectively. Nash–Sutcliffe coefficients for overflow during the calibration period were 0.82 and 0.71 for the 0.6-m and 0.9-m media depth cells, respectively. The weakest model agreement occurred during the validation period for overflow, where Nash–Sutcliffe coefficients were 0.58 and 0.40 for the 0.6-m and 0.9-m media depth cells, respectively. However, this may be misleading, as the difference between predicted and measured volumes from each set of cells during the validation period was less than 10%. The cumulative water balance is displayed in Figs. 3 and 4 for the 0.6-m and 0.9-m media depth cells, respectively.

5.2.2. Pre-repair monitoring period [clogged and under-sized] (year 1)

Modeling the performance of the Nashville bioretention cells for the pre-repair period was difficult because of the thin restrictive layer that formed at the 25-cm depth, as discussed in Brown and Hunt (2011a). The clogging layer formed during construction and was present during the entire pre-repair monitoring period. Results predicted by DRAINMOD were in good agreement with the measured/estimated values for the pre-repair monitoring period,

Table 6
Comparison of measured/estimated and predicted (modeled) results for the Nashville bioretention cells, during the post-repair period.

Monitoring period	Method of comparison	0.6-m Media depth cells Fate of runoff: (cm per bioretention surface area per monitoring period [percent of annual runoff])				0.9-m Media depth cells			
		Runoff	Drainage	Overflow	Exfiltration/ET	Runoff	Drainage	Overflow	Exfiltration/ET
Calibration period (11 March 2009–16 September 2009)	Measured/estimated volume [percent of annual runoff]	1005	470 [46.8]	120 [11.9]	415 [41.3]	974	418 [42.9]	108 [11.0]	448 [46.0]
	Predicted volume [percent of annual runoff]	1010	538 [53.3]	100 [9.9]	372 [36.8]	981	454 [46.3]	63 [6.4]	464 [47.3]
	Difference between measured and predicted volumes	5	68	−20	−43	7	36	−45	16
	Percent difference between measured and predicted volumes	0.6	14.5	−16.5	−10.4	0.6	8.5	−41.7	3.5
	Nash–Sutcliffe coeff.	1.00	0.90	0.82	0.87	1.00	0.94	0.71	0.88
Validation period (17 September 2009–24 March 2010)	Measured/estimated volume [percent of annual runoff]	1300	744 [57.3]	150 [11.5]	406 [31.2]	1257	564 [44.8]	147 [11.7]	547 [43.5]
	Predicted volume [percent of annual runoff]	1292	652 [50.4]	165 [12.8]	475 [36.8]	1254	540 [43.0]	141 [11.3]	574 [45.7]
	Difference between measured and predicted volumes	−8	−92	15	69	−3	−24	−6	27
	Percent difference between measured and predicted volumes	−0.6	−12.4	10.5	17.1	−0.2	−4.3	−3.6	4.9
	Nash–Sutcliffe coeff.	1.00	0.96	0.58	0.81	1.00	0.93	0.40	0.81

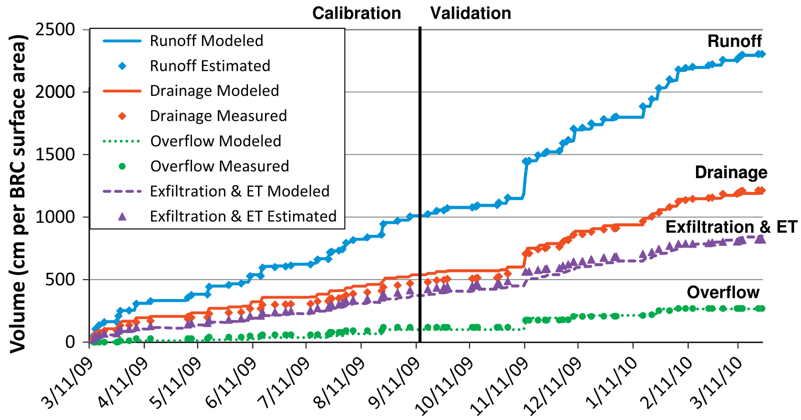

Fig. 3. Cumulative fate of runoff for 0.6-m media depth cells at Nashville, during the post-repair monitoring period.

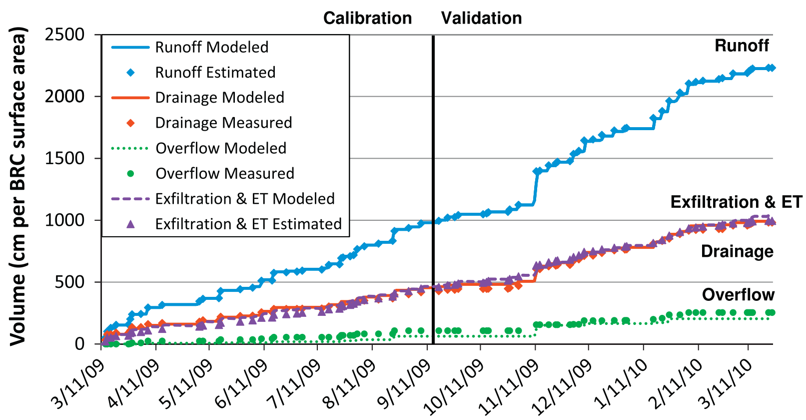

Fig. 4. Cumulative fate of runoff for 0.9-m media depth cells at Nashville, during the post-repair monitoring period.

Table 7
Comparison of measured/estimated and predicted (modeled) results for the Nashville bioretention cells, during the pre-repair period.

Monitoring period	Method of comparison	0.6-m Media depth cells				0.9-m Media depth cells			
		Fate of runoff: (cm per bioretention surface area per monitoring period [percent of annual runoff])							
		Runoff	Drainage	Overflow	Exfiltration/ET	Runoff	Drainage	Overflow	Exfiltration/ET
Calibration period (7 April 2008–29 September 2008)	Measured/estimated volume [percent of annual runoff]	1357	426 [31.4]	576 [42.4]	355 [26.2]	1295	299 [23.1]	501 [38.7]	495 [38.2]
	Predicted volume [percent of annual runoff]	1355	375 [27.7]	634 [46.8]	346 [25.5]	1292	290 [22.4]	546 [42.3]	457 [35.3]
	Difference between measured and predicted volumes	−2	51	58	−9	−3	−9	45	−38
	Percent difference between measured and predicted volumes	−0.1	−11.8	10.1	−2.8	−0.2	−3.0	9.0	−7.7
	Nash–Sutcliffe coeff.	1.00	0.70	0.87	0.62	1.00	0.72	0.88	0.73
Validation period (30 September 2008–10 March 2009)	Measured/estimated volume [percent of annual runoff]	742	250 [33.6]	205 [27.6]	288 [38.8]	725	157 [21.6]	209 [28.8]	359 [49.6]
	Predicted volume [percent of annual runoff]	744	292 [39.3]	191 [25.7]	261 [35.0]	729	227 [31.1]	156 [21.5]	345 [47.4]
	Difference between measured and predicted volumes	2	42	−14	−27	4	70	−53	−14
	Percent difference between measured and predicted volumes	0.2	17.2	−6.8	−9.5	0.5	44.5	−25.1	−3.8
	Nash–Sutcliffe coeff.	1.00	0.73	0.86	0.69	1.00	0.71	0.81	0.72

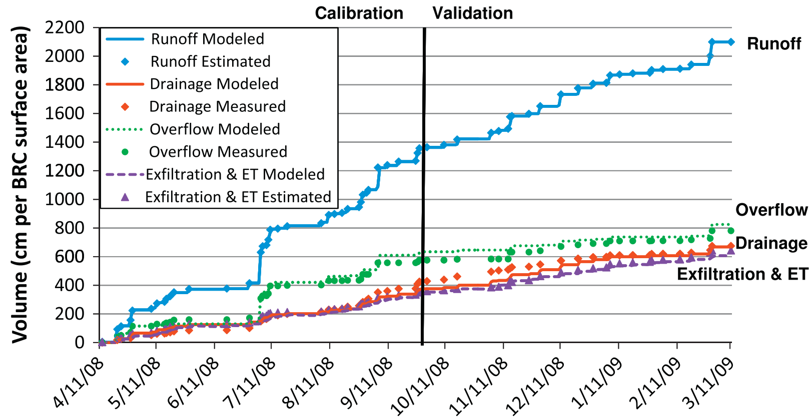

Fig. 5. Cumulative fate of runoff for 0.6-m media depth cells at Nashville, during the pre-repair monitoring period.

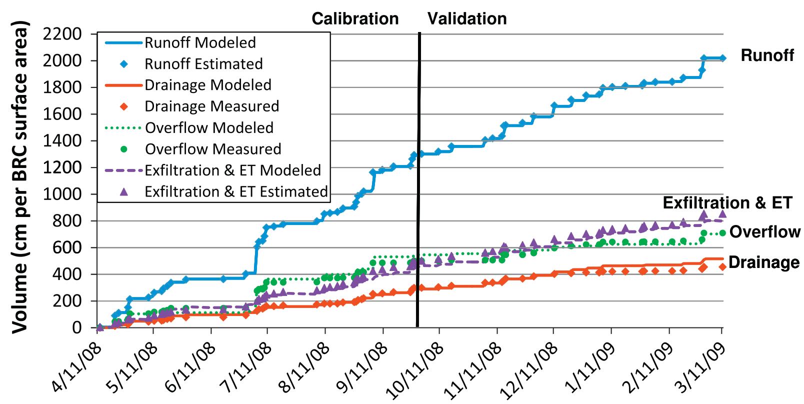

Fig. 6. Cumulative fate of runoff for 0.9-m media depth cells at Nashville, during the pre-repair monitoring period.

as shown in Table 7. Nash–Sutcliffe coefficients during the calibration and validation periods ranged from 0.81 to 0.88, 0.70 to 0.73, and 0.62 to 0.73, for overflow, drainage, and exfiltration/ET, respectively, showing that the model agreement was similar between the calibration and validation periods for the pre-repair monitoring period. The cumulative water balance is displayed in Figs. 5 and 6 for the 0.6-m and 0.9-m media depth cells, respectively.

5.3. Rocky Mount site – IWS drainage configuration

5.3.1. Sandy clay loam (SCL) cell

Results for the SCL cell at Rocky Mount are provided in Table 8. Overall, model predictions for the Rocky Mount site were in good agreement with the measured values. During the calibration period (shallow IWS period), Nash–Sutcliffe coefficients were 0.92 for drainage and exfiltration/ET and 0.88 for overflow. Initial inspection of the results indicates that predicted drainage and overflow were not in good agreement with measured/estimated values during the validation period (deep IWS period). The Nash–Sutcliffe coefficient for overflow reduced to 0.69, and it was negative for drainage. Despite a negative Nash–Sutcliffe coefficient for drainage, the net difference in predicted and measured volumes was only 7.9% of the cumulative runoff volume (124 cm/bioretention surface area out of 1559 cm/bioretention surface area of runoff). The reason for the poor agreement with drainage and overflow was attributable to the shallow slope of the parking lot and the emergency bypass stormwater drop inlet not being installed at the proper elevation. These two factors caused runoff to bypass the bioretention cell and immediately enter the emergency bypass prior to flowing into the surface storage zone for extreme, intense events. These events were more prevalent during the validation period (deep IWS period). It did not matter if there was still storage available, flow bypassed the cell. DRAINMOD will not predict overflow to occur until the surface storage zone has been exceeded. DRAINMOD cannot accurately predict overflow for any site that allows bypass prior to filling the surface storage zone to maximum capacity. Had the storage volume been available, the bypass water would have entered the cell and left via drainage, thus improving agreement between predicted and measured flows. Although the bypass flow problem prevented the model from accurately predicting outflows, overall model prediction of the portion leaving as exfiltration/ET was in good agreement with measured results. In the validation period, the Nash–Sutcliffe coefficient for exfiltration/ET was 0.92. The evolution of the cumulative water balance is displayed in Fig. 7 for the shallow (calibration) IWS monitoring period.

Measured bioretention water table depths were used to calibrate DRAINMOD during the shallow IWS period. While DRAINMOD computes water table depths at a frequency as short as 0.05 h, it currently only provides an output of water table depth at the end of each day. These depths were compared to the measured depths for the SCL cell during the shallow IWS period. Of 320 daily readings, the IWS zone was empty for 178 so a water level reading could not be taken, and drainage was occuring for 7. For the 135 compared bioretention water table depths, the average absolute error was 7.8 cm (3.1 in.), and the interquartile range of the absolute error was −7.9 to 3.5 cm (−3.1 to 1.4 in.). A linear trendline of this relationship had a coefficient of determination of 0.82 and a slope of 1.04. A subset of water level measurements for the period from July 2009 to January 2010 is presented in Fig. 8.

Table 8
Comparison of measured/estimated and predicted (modeled) results for the Rocky Mount bioretention cells.

Monitoring period	Method of comparison	SCL cell Fate of runoff (cm per bioretention surface area per monitoring period [percent of annual runoff])				Sand cell			
		Runoff	Drainage	Overflow	Exfiltration/ ET	Runoff	Drainage	Overflow	Exfiltration/ ET
Calibration period [shallow IWS zone period] (13 January 2009–11 January 2010)	Measured/estimated volume [percent of annual runoff]	1251	231 [20.5]	88 [7.1]	932 [72.5]	1416	4 [0.3]	0 [0.0]	1412 [99.7]
	Predicted volume [percent of annual runoff]	1272	269 [21.2]	88 [7.0]	930 [71.9]	1440	33 [2.5]	0[0.0]	1407 [97.4]
	Difference between measured and predicted volumes	21	38	0	−2	24	29	0	−5
	Percent difference between measured and predicted volumes	2	16	<1	<1	2	651	0	<1
	Nash–Sutcliffe coeff.	0.99	0.92	0.88	0.92				
Validation period [deep IWS zone period] (14 September 2007–12 January 09)	Measured/estimated volume [percent of annual runoff]	1562	31 [2.0]	175 [11.2]	1353 [86.8]	1762	5 [0.3]	30 [1.7]	1727 [98.0]
	Predicted volume [percent of annual runoff]	1559	155 [9.9]	111 [7.1]	1292[83.0]	1765	6 [0.3]	8 [0.5]	1751 [99.2]
	Difference between measured and predicted volumes	−3	124[a]	−64[a]	−61	3	1	−22	24
	Percent difference between measured and predicted volumes	<1	407[a]	−36[a]	−5	0	18	−73	1
	Nash–Sutcliffe coeff.	0.99	<0[a]	0.69[a]	0.92				

[a] Poor results are attributable to difficulty in modeling bypass before the surface storage zone was full (shallow drainage area slope forced runoff to bypass bioretention cell before surface storage zone was full during high intensity rainfall events).

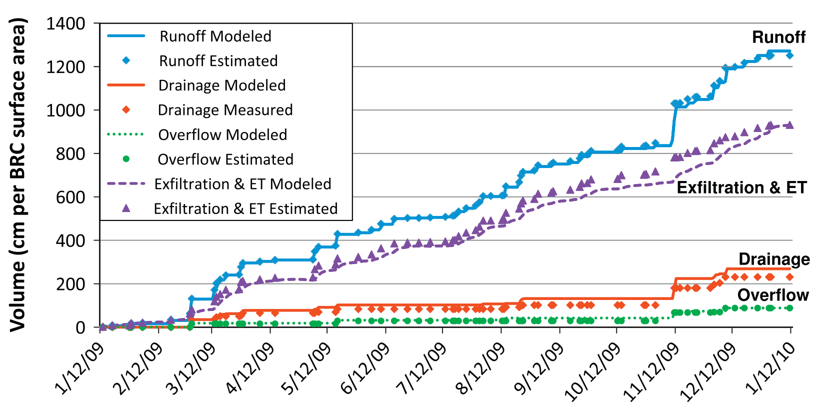

Fig. 7. Cumulative fate of runoff for SCL cell at Rocky Mount, during the calibration period (shallow IWS zone monitoring period).

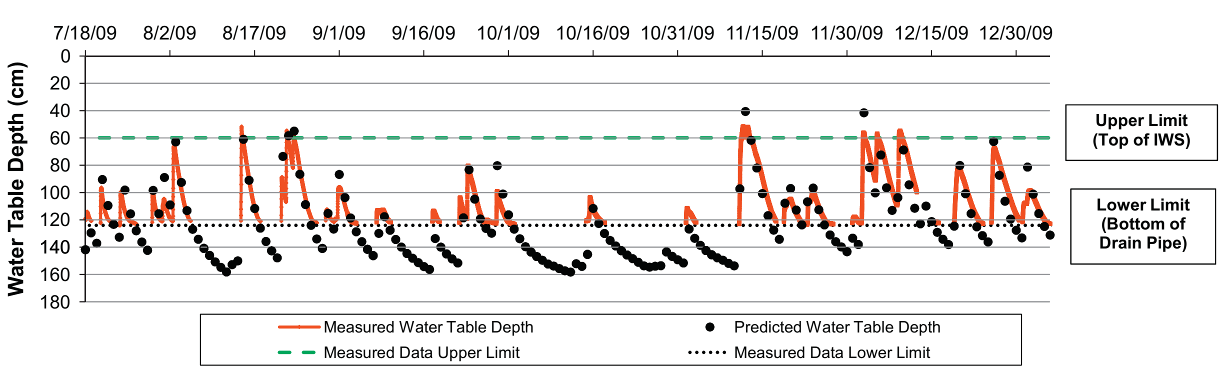

Fig. 8. Comparison of predicted versus measured water table depths for SCL cell [subset of data – July 2009 to January 2010].

The range of valid bioretention water table depths is presented as the values between the two dashed lines (bottom of drain pipe and top of IWS outlet). Overall, model prediction matched well with observations during each event and drawdown was accurately modeled within the IWS zone. It was most accurate in the period between May and October (most of the growing season). From February to April and November to January (most of the dormant season), the measured drawdown was slower than the predicted drawdown rate. This was likely attributable to the local water table underlying the bioretention cell rising closer to the bottom of the cell reducing the downward hydraulic gradient and slowing the exfiltration rate. During these months, local water tables often rise due to reduced ET. In the period between June and July, the measured bioretention water table drawdown was slightly faster than the predicted drawdown. Throughout the year, there was a slight variation in the actual measured exfiltration/seepage rate for the SCL cell 2.1–3.3 mm/h (0.08–0.13 in./h). To balance the faster and slower rates during calibration, 3.0 mm/h (0.12 in./h) was selected to be used in the model.

5.3.2. Sand cell

The Sand cell had extremely high infiltration and exfiltration rates, which made it very different from the other cells that were investigated. The surface infiltration rate was so fast that surface ponding was never recorded during the shallow IWS period. The range of measured exfiltration/seepage rates was 60–90 mm/h (2.4–3.6 in./h), so 75 mm/h (3.0 in./h) was used in DRAINMOD. The media and underlying soil at this site were both classified as a sand texture. For both monitoring periods, there was essentially no outflow and all the runoff left as exfiltration. After setting the deep seepage parameters to the measured exfiltration rate and the internal water storage zone depth to its appropriate levels in the calibration period, DRAINMOD successfully predicted the exfiltration/ET volume to within 1% of the measured volume (Table 8). Likewise, in the validation period, the predicted exfiltration/ET volume was within 1% of the measured volume. The model slightly over-predicted the drainage portion from this cell during the calibration period, but the net difference in predicted and measured volumes was only 2% of the cumulative runoff volume (29 cm/bioretention surface area out of 1440 cm/bioretention surface area of runoff).

6. Conclusions

Bioretention cells are becoming one of the most popular LID stormwater practices; however, their level of performance is very site specific because of the impact of underlying soils, design specifications, and climate. DRAINMOD was used to simulate performance of four bioretention cells that had varying media depths, media types, drainage configurations, surface storage volumes, and underlying soils. Each of the four cells was monitored for two, year-long monitoring periods. One of the design parameters was altered in each cell for the second year of the monitoring period. The modeling results showed that DRAINMOD can be used reliably to predict bioretention hydrologic response to influent runoff on a continuous, long-term basis. The combination of two features set DRAINMOD apart from other bioretention models. They are (1) its ability to model an IWS zone drainage configuration and (2) its methodology of accounting for the soil–water content in the profile. DRAINMOD uses the soil–water characteristic curve to account for the water present in the media, which is a more accurate method than the field capacity concept used in many of the other available models.

DRAINMOD accurately predicted runoff volumes from drainage areas with a varying degree of impervious percentage and consistency. The Nash–Sutcliffe coefficients for runoff from each site's drainage area exceeded 0.99 for both the calibration and validation periods. At Nashville, during the post-repair period, the Nash–Sutcliffe coefficients for drainage and exfiltration/ET both exceeded 0.8 during the calibration and validation periods. In the calibration and validation periods for the pre-repair period, the Nash–Sutcliffe coefficients for drainage, overflow, and exfiltration/ET ranged from 0.6 to 0.9. Good model agreement between predicted and measured bioretention water table depth occurred for the Rocky Mount SCL cell. There was an average absolute error of 7.8 cm, and the linear trend of the predicted and measured values had a coefficient of determination of approximately 0.82 and a slope of approximately 1.04. For both the calibration and validation periods, the predicted (modeled) volume of exfiltration/ET was within 5% of the estimated volume at the SCL cell, and it was within 1% for the Sand cell. Nash–Sutcliffe coefficients for the SCL cell during both the calibration and validation periods were 0.92 for exfiltration/ET.

A continuous, long-term model, like DRAINMOD, could allow designers and regulators to move away from the current "one size fits all" design approach and work towards a "flexible" bioretention design methodology that allows for and credits over-sizing and under-sizing bioretention cells based on site characteristics and design configurations. The subject of a future article will be to model a variety of different combinations of under-sized and over-sized systems and use DRAINMOD to evaluate the effect of cell size and design parameters on amount of runoff treated.

Based on the experiences of using DRAINMOD to model hydrologic response in bioretention cells, it was easier to calibrate the seepage parameters when an IWS zone was present. Once drainage ended, water was primarily released as exfiltration. It was also released through ET, but this percentage was small by comparison. When drainage was not occurring, the change in water level could be used solely to calibrate the seepage parameters instead of trying to calibrate simultaneous processes (drainage and exfiltration) when the water level in the bioretention profile was above the drain outlet. For future bioretention modeling efforts using DRAINMOD, reliability of the model results will increase if site specific physical parameters (i.e., depths, areas, and pipe/outlet elevations) and bioretention media and underlying soil characterstics can be measured. Hydrologic response can be modeled without measurement of soil properties, but either a factor of safety or conservative estimate should be applied. Overall, the reliability of the model results will increase if it can be calibrated against measured water levels and event-based flow (drainage, overflow, and/or runoff) volumes.

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