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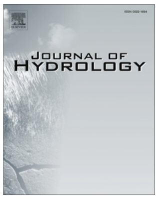

Bioretention function under climate change scenarios in North Carolina, USA

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SUMMARY

The effect of climate change on stormwater controls is largely unknown. Evaluating such effects is important for understanding how well resiliency can be built into urban watersheds by implementing these systems. Bioretention areas with varied media depths, in situ soil types, drainage configurations, and surface infiltration capabilities have previously been monitored, modelled, and calibrated using the continuous simulation model, DRAINMOD. In this study, data from downscaled climate projections for 2055 through 2058 were utilized in these models to evaluate changes in system hydrologic function under two climate change scenarios (RCP 4.5 and 8.5). The results were compared to those generated using a "Base" scenario of observed data from 2001 to 2004. The results showed a modest change in the overall water balance of the system. In particular, the frequency and magnitude of overflow from the systems substantially increased under the climate change scenarios. As this represents an increase in the amount of uncontrolled, untreated runoff from the contributing watersheds, it is of particular concern. Further modelling showed that between 9.0 and 31.0 cm of additional storage would be required under the climate change scenarios to restrict annual overflow to that of the base scenario. Bioretention surface storage volume and infiltration rate appeared important in determining a system's ability to cope with increased yearly rainfall and higher rainfall magnitudes. As climate change effects vary based on location, similar studies should be performed in other locations to determine localized effects on stormwater controls.

1. Introduction

Understanding the effects of climate change remains an ongoing and critical need in the water resources community. At the global scale, variations in climate include temperature fluctuations and changes in precipitation duration, intensity, and frequency (IPCC, 2012). The magnitude of these changes varies based on location, with tropical and high latitudes projected to see the greatest changes (IPCC, 2012). Variations in rainfall patterns and temperature have the potential to influence the hydrologic cycle and strain urban water systems (Willems and Vrac, 2011; Berggren et al., 2012; Rosenberg et al., 2010; Nilsen et al., 2011). This has already led to design standard revisions for urban infrastructure in locations such as the Flanders region of Belgium (Willems, 2013).

The influence of urbanization on the hydrologic cycle and local surface waters has long been recognized (Leopold, 1968). Under projected climate change scenarios, the magnitude and intensity of rainfall may exacerbate the effects of urbanization by overwhelming infrastructure and directing additional runoff to streams and rivers (Semadeni-Davies et al., 2008). Urban Stormwater Control Measures (SCMs, also known as Water Sensitive Urban Designs (WSUDs), and Sustainable Urban Drainage Systems (SUDS)) are commonly implemented to ameliorate the effects of urbanization. At the watershed scale, studies such as Semadeni-Davies et al. (2008) and Waters et al. (2003) have shown the potential for SCMs to provide some amount of resiliency to urban stormwater infrastructure, mitigating at least a portion of the impact of climate change on surface waters. These studies suggest the benefit of SCMs, but evaluations have not been performed at the site scale, that is, for individual SCMs. Determining the functionality of individual SCMs under various climate change scenarios is important to further understand climate change impacts on urban hydrology and how well these practices can build resiliency into urban watersheds when implemented en masse.

One increasingly popular SCM is bioretention (or biofilter) which promotes infiltration, evapotranspiration, and treatment of stormwater runoff through filtration. Bioretention has experienced

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wide implementation across the United States and globally due to its ability to restore and/or maintain predevelopment hydrology in urban watersheds (Davis et al., 2009). Multiple studies have shown the ability of bioretention to reduce and delay peak flows from urban catchments (Hunt et al., 2008; Hatt et al., 2009; Davis, 2008). Field studies have also demonstrated the ability of bioretention to reduce annual runoff volumes by 27–86%, suggesting a wide variation of performance depending on system size, underdrain configuration, and in situ soil type (Hatt et al., 2009; Davis et al., 2012; Li et al., 2009). Complicating the goal of promoting sustainable urban hydrology is climate change, which may cause variations in SCM performance with changes in precipitation duration, frequency, and intensity. Given the finite surface storage volume and surface infiltration capacity in bioretention, more intense climate patterns may result in reduced runoff capture. No studies have been performed to date which model the performance of bioretention under climate change scenarios. However, advances in continuous simulation modelling of bioretention (Brown et al., 2013; Lucas, 2010) now provide the opportunity to analyze the performance of these systems in fine temporal resolution, allowing an analysis of climate change impacts on performance.

Evaluations of individual SCM performance under climate change projections have not been thoroughly performed, resulting in a lack of understanding as to the resiliency these SCMs provide and how climate change might affect their function. Advances in both continuous simulation modelling of bioretention and downscaling of climate change models now allow such analyses. The purpose of this study is to use calibrated and validated continuous simulation models of bioretention in North Carolina, USA, to characterize the hydrologic performance of these systems under existing and projected climate scenarios.

2. Materials and methods

2.1. Site descriptions

Four bioretention systems were utilized in this study, each of which was monitored and modelled under two separate design configurations, for a total of eight design scenarios evaluated. The bioretention systems were spatially paired, with two located in Nashville, NC, USA, and two in Rocky Mount, NC, USA. For the Nashville sites, insufficient oversight during installation and improper construction practices led to sites which were undersized and partially clogged with sediment from construction runoff (“Pre” scenarios). After a year of monitoring, the surface storage volume was increased and the layer of clogged soil was removed, effectively enhancing system performance through greater surface storage volume and infiltration capacity (“Post” scenarios). Monitoring was performed on the rehabilitated sites for an additional year. Further description of the Nashville sites and associated Pre and Post hydrologic analysis are available in Brown and Hunt (2011a, 2012). At the Rocky Mount sites both underlying soils and drainage configurations varied. Monitoring was conducted at two cells underlain by either sand or sandy clay loam (SCL) soils. For the first 16 months, the underdrain outlet was set 0.88 and 0.72 m from the bottom of the media for the SCL and Sand cells, respectively (“Deep” internal water storage zone (IWS)). For the next 12 months at both cells, the IWS zone was decreased by 0.3 m (“Shallow”). The IWS effectively creates a water storage zone within the bioretention media, enhancing infiltration. The Rocky Mount sites are described and characterized by Brown and Hunt (2011b).

A robust set of design configurations are present in the data set, with various media depths, media types, underlying soil types, surface infiltration rates, and drainage configurations being represented (Table 1, and Fig. 1). Runoff, drainage, and overflow volumes were either measured or estimated at each location. Runoff for all sites entered via sheet flow, and thus was estimated using the initial abstraction method based on the assumption that in highly impervious watersheds, shallow depressions are filled first before the remainder of precipitation becomes runoff. Pandit and Heck (2009) found nearly all rainfall became runoff for asphalt on a slight slope. This was further supported by studies such as Line et al. (2012). At the Nashville sites, overflow and drainage were measured concurrently via a sharp crested 90° v-notch weir and separated based on the resultant hydrograph shape and characteristics (see Brown and Hunt, 2011a). At Rocky Mount, drainage was monitored via a sharp crested 30° v-notch weir. Overflow was estimated based on bioretention physical characteristics, rainfall intensity, and measured surface infiltration rates. Based on the overall water balances for each site, rainfall not leaving via overflow or drainage was considered to be lost through evapotranspiration and/or exfiltration (seepage). As evapotranspiration was found to account for only 3–5% of the water balance (Brown and Hunt, 2011a,b), the primary loss mechanism of this residual water was exfiltration from the cells. These data allowed calibration and validation of the models utilized herein. Detailed descriptions of all sites, monitoring protocols, and performance for the Nashville and Rocky Mount sites are available in Brown and Hunt (2011a,b, 2012).

2.2. Model development

Model calibration and validation were conducted using the continuous simulation model, DRAINMOD, as described in Brown et al. (2013). DRAINMOD simulates drainage rates as a function of soil properties and drainage characteristics, and offers more comprehensive modelling of water movement through soil profiles and predictions of soil–water content changes with water level depth than other continuous simulation stormwater models such as the Storm Water Management Model (SWMM), windows based Source Loading And Management Model (WinSLAMM), and Model of Urban Stormwater Improvement Conceptualization (MUSIC). DRAINMOD’s governing equations are two water balances performed at the soil surface (1) and in the soil profile (2). At the surface, the water balance is computed by:

$$P = F + \Delta S + RO \tag{1}$$

where P = precipitation, F = infiltration, ΔS = change in storage volume at the surface, and RO = runoff during time period ΔT. Within the soil profile, the water balance is performed on a section of soil of unit surface area extending from the soil surface to the impermeable layer and located at the midpoint between adjacent drains:

$$\Delta V_a = D + ET + DS - F \tag{2}$$

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 during time period ΔT. Infiltration rate is calculated via the Green and Ampt equation (Green and Ampt, 1911). To limit computational time, the time increment (ΔT) adjusts automatically based on the rate of processes occurring in the system. It is reduced to as small as 0.05 h when rainfall rate exceeds infiltration capacity (such as when surface ponding occurs). If ΔT is less than the rainfall input interval (1 h), the rainfall depth is evenly distributed across the interval. Descriptions of the governing equations, modelling components, and subroutines utilized in DRAINMOD can be found in Skaggs (1978, 1980, 1982, 1999). Other than the deep seepage parameters for the Nashville sites, all input parameters for DRAINMOD were determined onsite or at the North Carolina State University Soil and Water Laboratory. Deep seepage parameters at the Nashville site were estimated using the Nash County soil survey (USDA, 1989) after it was confirmed that the in situ soil surrounding the bioretention cell matched the texture

Table 1
Characteristics of bioretention and design configurations.

Description	Nash-0.6 m-Pre (1)	Nash-0.6 m-Post (2)	Nash-0.9 m-Pre (3)	Nash-0.9 m-Post (4)	RM-SCL-Shallow-IWS (5)	RM-SCL-Deep-IWS (6)	RM-Sand-Shallow-IWS (7)	RM-Sand-Deep-IWS (8)
Location	Nashville	Nashville	Nashville	Nashville	Rocky Mount	Rocky Mount	Rocky Mount	Rocky Mount
Media depth (m)	0.6	0.6	0.9	0.9	1.1	1.1	0.96	0.96
Surface ponding depth (m)	0.13	0.2	0.15	0.27	0.16	0.16	0.13	0.13
Watershed 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]
Bioretention to watershed area ratio (%)	4.2	4.7	4.7	5.2	6.8	6.8	6.0	6.0
Drainage configuration	Conventional	Conventional	Conventional	Conventional	Internal water storage (IWS)	Internal water storage (IWS)	Internal water storage (IWS)	Internal water storage (IWS)
IWS thickness[a] (m)	None	None	None	None	0.58	0.88	0.42	0.72
Soil media composition	86–89% sand, 8–10% silt, 3–4% clay				96% sand, 2.9% silt, 1.1% clay			
Underlying soil type	Sandy loam/loamy sand				Sandy clay loam	Sandy clay loam	Sand	Sand
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	
Length of field monitoring (months)	12	12	12	12	12	16	12	16
Length of calibration (months)	6	6	6	6	12[b]	0	12[b]	0
Length of validation (months)	6	6	6	6	0	16[b]	0	16[b]

[a] IWS thickness is the distance from the bottom of the media to the invert of the underdrain discharge point.

[b] For the Rocky Mount SCL and Sand sites, calibration was performed with a shallow IWS and validated under a deep IWS (see Brown et al., 2013).

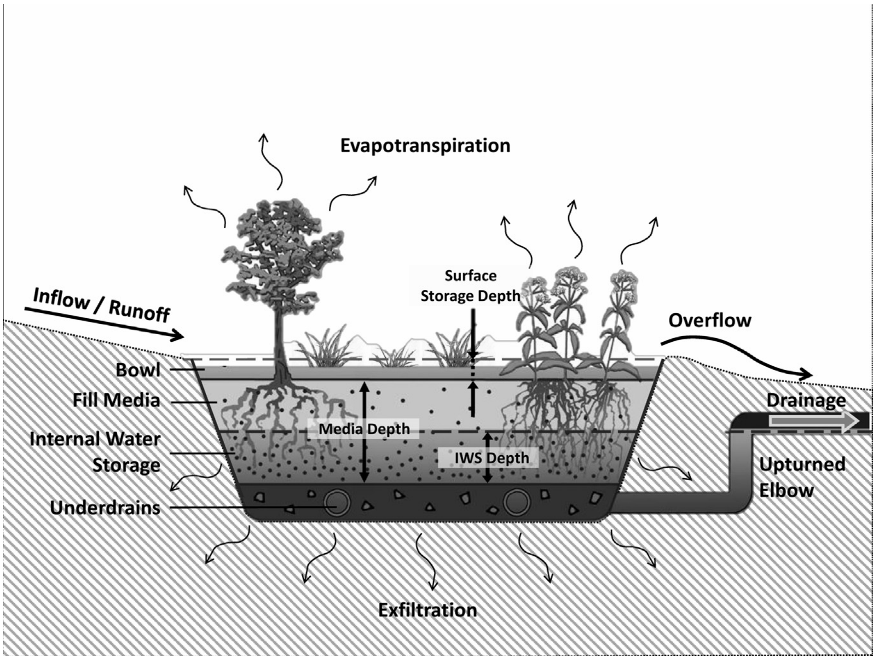

Fig. 1. Bioretention with IWS identifying system components and hydrologic pathways.

of the mapped soil series (sandy loam and loamy sand); more details are available in Brown et al. (2013).

Each design configuration was calibrated and validated for a period of at least six months. As noted above, runoff, drainage, and overflow volumes were either measured or estimated at each location for each event. The Rocky Mount site also used measured water table depth in the IWS zone for calibration. DRAINMOD successfully predicted the hydrologic performance of the bioretention systems described in Table 2 (Brown et al., 2013). Using DRAINMOD, a comprehensive estimation of each bioretention's water balance over multiple months was generated, including inflow (runoff), drainage, overflow, exfiltration, and evapotranspiration (ET). These DRAINMOD outputs were compared to field observations using Nash–Sutcliffe model efficiency coefficients. It should be noted that ET and exfiltration were pooled for these analyses as ET was only estimated monthly based on the hydrologic monitoring at the sites. The modelling results for the eight configurations are presented in Table 2, where Nash–Sutcliffe model efficiency coefficients were calculated using:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}(Q_{i,measured} - Q_{i,predicted})^2}{\sum_{i=1}^{N}(Q_{i,measured} - Q_{average})^2} \tag{3}$$

where $Q_{i,measured}$ = measured volume for event i, $Q_{i,predicted}$ = predicted volume for event i, $Q_{i,average}$ = average measured volume for N events, N = total number of events for the monitoring period,

Table 2
Nash–Sutcliffe coefficients for calibration and validation periods for all bioretention configurations (Brown et al., 2013).

Site	Period	Runoff	Drainage	Overflow	Exfiltration/ET
Nash-0.6 m-Pre	Calibration (7 April 2008–29 September 2008)	1.00	0.70	0.87	0.62
	Validation (30 September 2008–10 March 2009)	1.00	0.73	0.86	0.69
Nash-0.6 m-Post	Calibration (11 March 2009–16 September 2009)	1.00	0.90	0.82	0.87
	Validation (17 September 2009–24 March 2010)	1.00	0.96	0.58	0.81
Nash-0.9 m-Pre	Calibration (7 April 2008–29 September 2008)	1.00	0.72	0.88	0.73
	Validation (30 September 2008–10 March 2009)	1.00	0.71	0.81	0.72
Nash-0.9 m-Post	Calibration (11 March 2009–16 September 2009)	1.00	0.94	0.71	0.88
	Validation (17 September 2009–24 March 2010)	1.00	0.93	0.4	0.81
Rocky Mount – SCL – Shallow-IWS	Calibration (13 January 2009–11 January 2010)	0.99	0.92	0.88	0.92
Rocky Mount – SCL – Deep-IWS	Validation (14 September 2007–12 January 2009)	0.99	<0[a]	0.69[a]	0.92
Rocky Mount – Sand-Shallow-IWS	Calibration (13 January 2009–11 January 2010)	0.99	<0[b]	<0[b]	0.98
Rocky Mount – Sand-Deep-IWS	Validation (14 September 2007–12 January 2009)	0.99	<0[b]	<0[b]	0.99

[a] Poor performance attributed to difficulty modelling bypass due to parking lot slope directing runoff around cell before the bioretention surface storage was filled during some events.

[b] Only 0–5 events had drainage and/or overflow during this period, so Nash–Sutcliffe coefficients are not considered to be an accurate depiction of performance.

and NSE = Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970).

2.3. Climate data

Three climate scenarios were utilized in this project, each with hourly observations over a four-year period. This four-year period is considered sufficiently long to establish bioretention hydrologic performance, but short enough to offer a snapshot of performance under each scenario without the complicating factors of continually increasing effects of climate change over time. For the "Base" scenario, data from the State Climate Office of North Carolina (SCONC, 2014) were obtained from 2001 to 2004 for the North Carolina Upper Coastal Plain Research Station (UCPRC). This location is approximately 12 km from the Rocky Mount sites and 25 km from the Nashville sites. Although highly localized data is most desirable, this was the closest, most reliable, long term precipitation monitoring station to both sites. Although utilizing data from the UCPRC was necessary, the distance of this station from the project sites does add some amount of error to this analysis. Thus, these analysis more accurately reflect the Rocky Mount metropolitan area (which includes Nashville) than the project locations themselves. The Base scenario is intended to present climate conditions as they currently exist for comparison to future climate change scenarios. This approach is similar to that used by Gao et al. (2012). For the Base scenario data, the annual rainfall between 2001 and 2004 averaged 1060 mm with a range of 812–1341 mm. The average annual rainfall for the North Carolina Upper Coastal Plain Research Station between 2001 and 2013 was 934 mm with a range of 632–1341 mm (SCONC, 2014).

For climate change predictions, site specific data were gleaned from Gao et al. (2012). Gao et al. (2012) generated climate projection data for the eastern United States at high resolution by performing dynamic downscaling using the Weather Research and Forecasting (WRF) model. Modelling was performed on a 4 km × 4 km high resolution scale with the Community Earth System Model version 1.0 (CESM v1.0) serving to establish boundary conditions for the WRF model. Dynamic downscaling requires a number of surface and three-dimensional variables, which were extracted from Community Atmosphere Component Version 4 (CAM4) and Community Land Model (CLM4) output taken from CESM v1.0. The WRF pre-processing system was used to horizontally interpolate surface variables from CESM v1.0 output to the WRF domains. A full description of the downscaling methodology is available in Gao et al. (2012).

The high spatial resolution provided by dynamic downscaling allows an analysis of climate change impacts on a highly resolved regional basis. Additionally, this methodology has advantages over statistical downscaling techniques as stationary relationships between present weather observations and those in the future based on emission projections need not be assumed. To ensure the WRF model performed adequately for this specific location, modelling was performed for the 2001–2004 period for both Nashville, NC, and Rocky Mount, NC, and compared to the Base data observed at the North Carolina Upper Coastal Plain Research Station. The model overestimated average yearly rainfall for the two sites by less than 110 mm compared to the observed data, and had comparable median and 90th percentile rainfall. The difference in yearly rainfall between the observed and modelled data is within the standard deviation of annual rainfall between 2001 and 2013 (SCONC, 2014). Similarly, the median and 90th percentile consecutive dry days were similar between the modelled and observed data.

Data from two IPCC's Representative Concentration Pathways (RCP 4.5 and RCP 8.5) were utilized in this study, allowing an analysis of bioretention performance under two scenarios of fossil fuel usage in the future, one moderate (RCP 4.5) and one intensive (RCP 8.5). Predictions from 2055 to 2058 were used for both climate change scenarios. For further information on the dynamic downscaling procedures see Gao et al. (2012). It should be noted that determining differences in bioretention function between the two RCPs was not the intent of this study. Observations were generally constrained to differences in performance noted between the Base and both climate change scenarios. Due to the uncertainty surrounding climate projections and future fossil fuel usage, utilizing two RCPs allowed a more robust analysis of climate change impacts.

2.4. Modelling climate scenarios

The calibrated and validated DRAINMOD models described by Brown et al. (2013) were utilized in this study without adjustment. The three climate scenarios (Base, RCP 4.5, and RCP 8.5) were input into each model to allow comparisons. Rainfall input was hourly for all three scenarios, but output was compiled daily for the analyses herein. The smallest temporal resolution available for the projected climate scenarios was 1 h, which likely limited the accuracy of the model for predicting overflow rates. However, an hourly time-scale is expected to be less sensitive to predicting event-based overflow volume than peak overflow rates as the surface storage zone in a bioretention cell provides a buffering capacity against overflow volume. That is, unless the surface storage zone is full, overflow is eliminated regardless of rainfall intensity and distribution across an hour as any runoff entering at a rate in excess of infiltration is stored at the surface. Once the surface storage zone is full, inflow from a large contributing drainage area is expected to exceed the surface infiltration capacity at most sites, thus causing overflow. As an exception, sites with rapid surface infiltration rates (e.g., Rocky Mount Sand site) will be more sensitive to temporal resolution and are more likely to have prediction errors for overflow volume using the hourly time-scale in comparison to finer resolution precipitation data. Despite the uncertainty in global and regional climate modelling at this temporal resolution, analyses such as this are critical to better determine how resiliency can be built into urban watersheds. Analyses will be refined as modelling techniques improve; however, is not prudent to wait for minimal uncertainty before evaluations of the possible effects of climate change on water resources are performed. Further, two RCPs are utilized to allow analysis over a broader range of climate projections. As suggested by Willems et al. (2012), although uncertainty is present in climate modelling and downscaling, planners and engineers can begin to use rainfall data generated by climate models to consider the impacts of climate change on stormwater infrastructure.

3. Results and discussion

3.1. Climate data summary

To better understand the differences in bioretention hydrologic function under two climate change scenarios (RCP 4.5 and 8.5), summary statistics of the climate data were generated (Table 3). For precipitation, the Base scenario had lower total precipitation and a lower mean daily precipitation. As noted by the number of “dry days”, the Base scenario was relatively drier, although the differences among scenarios did not appear substantial. A “dry day” is defined herein as any day with less than 1 mm of rainfall.

3.2. Water balance

DRAINMOD output allowed a complete water balance of each system, including stormwater runoff entering the SCM (runoff), stormwater exiting via the bioretention underdrains (drainage), stormwater bypassing the bioretention treatment due to storage being at capacity and infiltration rate being exceeded by rate of input water (overflow), stormwater infiltrating into the in situ soils beneath the bioretention (exfiltration), and runoff stored and released via evapotranspiration (ET). As exfiltration and ET were not calibrated and validated independently by Brown et al. (2013), they are combined in the water balances presented in Table 4.

3.2.1. Nashville

For all scenarios at the Nashville location, the changes between the Base and climate change water balances were relatively moderate in terms of the fate of the inflow (runoff). No water fate (e.g., overflow or drainage) varied in its contribution to the water balance by more than 10 percentage points when comparing the Base and climate change models. As climate change caused an increase in total runoff, most scenarios showed an increase in total depth of drainage, overflow, and exfiltration/ET. The trend in the climate change scenario water balances compared to the Base was for the percentage of runoff leaving as drainage, exfiltration, and ET to slightly decrease, while the percentage leaving as overflow increased. Given the increase in overall precipitation and 90th percentile daily precipitation observed in Table 3, it is logical that a larger number of storms would overwhelm the storage and/or infiltration capacities of the Nashville systems.

The increase in overflow from the bioretention cells due to climate change is of particular interest. Overflow represents uncontrolled, untreated runoff which effectively bypasses the bioretention treatment mechanisms. The percent difference between overflow amounts under the Base scenario and the RCP scenarios ranged from 60% to 114%. This corresponded to an increase in average annual overflow of between 239 and 427 cm/bioretention area for RCP 4.5 and between 180 and 387 cm/bioretention area for RCP 8.5. The percent differences were larger for the Post sites, under which storage volume and surface infiltration were restored. This is likely due to the relatively poor performance of the Pre sites even under Base conditions, where 29% and 28% of the runoff overflowed from the two sites due to a lack of storage capacity and restrictive infiltration rate.

3.2.2. Rocky mount

For the Rocky Mount sites, the change in the water balance was slightly higher than that observed for Nashville. However, shifts in the water balance for any given water fate were still less than 7% when climate change scenarios were compared to the Base. The trend in the data was for the percentage of runoff leaving as exfiltration and ET to decrease under the climate change scenarios, while the percentage leaving as overflow and drainage slightly

Table 3
Precipitation and temperature summary statistics for Nashville and Rocky Mount under all climate scenarios.

Parameter	Statistic	Base (observed)	Nashville		Rocky Mount	
			RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	No. days < 1 mm rainfall	1081	1065	1084	1052	1065
Consecutive dry days	Maximum	41	24	23	24	25
	90th Percentile	9.0	9.0	9.0	8.3	9.0
	Mean	3.8	3.7	3.8	3.6	3.6
	Median	2.0	2.0	2.0	2.0	2.0
	St. Dev.	4.2	4.1	3.9	4.0	3.8
Daily precipitation	Total (mm)	4240	5035.7	5106.4	5099.3	5048.0
	No. day ⩾ 1 mm rainfall	380.0	396.0	377.0	409.0	396.0
	Max (mm)	150	94.1	114.7	109.2	121.0
	90th Percentile	27.2	31.0	30.8	28.6	30.2
	Mean (mm)	11.0	12.5	13.3	12.3	12.6
	Median (mm)	6.5	6.4	7.7	6.8	8.2
	St. Dev. (mm)	13.1	15.9	15.5	14.9	14.6
Temperature	Mean (°C)	15.9	17.9	18.4	19.3	19.8
	Median (°C)	17.2	19.3	20.1	20.5	21.4
	St. Dev. (°C)	9.3	9.3	9.7	9.4	9.8
	Maximum hourly (°C)	38.3	38.2	39.3	40.1	41.4
	Minimum hourly (°C)	−10.6	−18.8	−8.6	−17.3	−8.4

Table 4
Average annual water balances for each site scenario and climate profile – depths in terms of cm/bioretention area.

Site	Climate scenario	Runoff	Drainage			Overflow			Exfiltration and ET		
		Depth (cm)	Depth (cm)	% of Runoff	% diff[a]	Depth (cm)	% of Runoff	% diff[a]	Depth (cm)	% of Runoff	% diff[a]
Nashville – 0.6 m – Pre	Base	2180	870	40	–	640	29	–	671	31	–
	RCP 4.5	2671	922	35	6	1067	40	67	683	26	2
	RCP 8.5	2712	991	37	14	1027	38	60	694	26	3
Nashville – 0.6 m – Post	Base	1988	977	49	–	272	14	–	740	37	–
	RCP 4.5	2435	1096	45	12	566	23	108	774	32	5
	RCP 8.5	2472	1175	48	20	502	20	85	795	32	8
Nashville – 0.9 m – Pre	Base	2052	661	32	–	573	28	–	819	40	–
	RCP 4.5	2495	706	28	7	957	38	67	833	33	2
	RCP 8.5	2541	759	30	15	921	36	61	861	34	5
Nashville – 0.9 m – Post	Base	1869	776	42	–	210	11	–	883	47	–
	RCP 4.5	2272	897	39	16	450	20	114	926	41	5
	RCP 8.5	2314	961	42	24	391	17	86	962	42	9
Rocky Mount – SCL – Shallow-IWS	Base	1243	227	18	–	167	13	–	851	68	–
	RCP 4.5	1802	381	21	68	322	18	93	1098	61	29
	RCP 8.5	1886	389	21	71	335	18	101	1163	62	37
Rocky Mount – SCL-Deep-IWS	Base	1243	115	9	–	167	13	–	963	77	–
	RCP 4.5	1802	225	12	96	321	18	93	1255	70	30
	RCP 8.5	1886	197	10	72	345	18	107	1346	71	40
Rocky Mount – Sand-Shallow-IWS	Base	1407	44	3	–	56	4	–	1308	93	–
	RCP 4.5	2043	77	4	74	95	5	70	1872	92	43
	RCP 8.5	2139	74	3	66	131	6	136	1935	90	48
Rocky Mount – Sand – Deep-IWS	Base	1407	3	0	–	56	4	–	1349	96	–
	RCP 4.5	2043	3	0	32	95	5	70	1946	95	44
	RCP 8.5	2139	2	0	−28	131	6	136	2007	94	49

[a] Percent difference of depth as compared to Base scenario calculated as: Percent difference $= \frac{Depth_{Base} - Depth_{RCP}}{Depth_{Base}} \times 100$.

increased. Regardless, exfiltration remained the most dominate portion of the water balance for all Rocky Mount sites. This is due, in part, to the IWS components of each design, forcing additional subsurface storage within the system. Further, the in situ soils at this site were quite permeable.

As noted for the Nashville sites, the increase in overflow is of interest when assessing the effect of climate change. The percent difference in overflow from the Base to climate change scenarios ranged from 70% to 136%, representing large increases. This corresponded to an increase in average annual overflow of between 39

Table 5
Daily overflow days summary statistics and DM-DD quantification for all sites and climate scenarios.

Site	Climate profile	Number of inflow days	Overflow days						DM-DDs[a]	Increased storage to match base overflow depth (cm)
			Number	Max (cm)	90th Percentile (cm)	Mean (cm)	Median (cm)	St. Dev. (cm)		
Nashville – 0.6 m – Pre	Base	500	96	295	62	27	15	76	34	–
	RCP 4.5	523	125	214	81	34	19	41	12	21.5
	RCP 8.5	506	138	207	68	30	16	36	35	17.5
Nashville – 0.6 m – Post	Base	500	38	238	52	29	19	40	33	–
	RCP 4.5	523	72	171	96	31	19	37	12	30
	RCP 8.5	506	66	158	68	30	22	33	35	22.5
Nashville – 0.9 m – Pre	Base	500	95	268	58	24	14	33	4	–
	RCP 4.5	527	120	194	79	32	18	38	0	21
	RCP 8.5	513	125	189	68	30	17	34	3	16.5
Nashville – 0.9 m – Post	Base	500	31	213	51	27	19	38	4	–
	RCP 4.5	527	60	154	90	30	17	36	0	31
	RCP 8.5	513	52	140	77	30	23	31	4	21
Rocky Mount – SCL – Shallow-IWS	Base	500	33	160	35	20	13	28	60	–
	RCP 4.5	530	68	100	43	19	10	20	33	15.5
	RCP 8.5	511	70	124	46	19	10	23	23	16.0
Rocky Mount – SCL – Deep-IWS	Base	500	33	160	35	20	13	28	60	–
	RCP 4.5	530	68	100	43	19	10	20	33	15.5
	RCP 8.5	511	70	124	44	20	11	23	23	16
Rocky Mount – Sand – Shallow-IWS	Base	500	13	107	21	17	10	28	28	–
	RCP 4.5	530	25	77	28	15	9	17	7	9
	RCP 8.5	511	24	87	53	22	14	23	4	21.5
Rocky Mount – Sand – Deep – IWS	Base	500	13	107	21	17	10	28	28	–
	RCP 4.5	530	25	77	28	15	9	17	7	9
	RCP 8.5	511	24	87	53	22	14	23	4	21.5

[a] DRAINMOD Dry Days – days during which soil moisture in the root zone is insufficient for potential evaporation to be met.

and 155 cm/bioretention area for RCP 4.5 and between 76 and 178 cm/bioretention area for RCP 8.5. The likelihood of overflow between the two IWS depths appeared inconsequential. Thus, surface infiltration rates and bowl storage volume appear to be critical components of system resiliency.

3.3. Overflow events

As climate change models predict more rainfall quantity and higher intensity for this region, more overflow would be expected as intense storms overwhelm the bioretention cells. Thus, the overflow data were further analyzed for trends. Daily overflow data were extracted, allowing summary statistical analysis for the days during which overflow occurred (Table 5). For all sites, a greater number of overflow days occurred during the climate change scenarios, with additional overflow days ranging up to 42 days. While the mean depth of overflow events was only consistently higher relative to the Base for the Nashville sites, the 90% daily overflow was larger under climate change scenarios for all sites.

The maximum daily overflow depth was calculated over the four-year period modelled for each climate scenario. For all sites, the maximum overflow depth under the Base scenario was actually higher than that under climate change. However, climate change effects are projected to manifest as an overall increase in rainfall amount and intensity over time. It is possible to have large storms represented in the Base scenario, while still having a greater number of large events under the climate change scenarios. Thus, the 90th percentile daily overflow for each climate scenario better characterizes the higher magnitude overflow events. The climate scenarios (RCP 4.5 and 8.5) showed higher 90th percentile daily overflow, and probability plots confirmed the presence of larger overflow events under these scenarios (see examples in Fig. 2). In short, the bioretention cells experienced overflow more frequently and with higher magnitudes. Again, similar overflow trends were observed for the Rocky Mount sites with varying IWS depth, suggesting surface storage and infiltration characteristics are the most important factor for climate change resiliency in these systems.

3.4. Overflow analysis

Modelling was performed for each site to determine the additional storage required under the climate change scenarios to limit overflow to that of the Base climate profile (Table 5). For this analysis, the bioretention surface area was held constant while storage depth was increased in intervals of 0.5 cm. Overflow depth under the Base scenario was matched to within 1% during this exercise. For the Nashville sites, an additional 15.5–31.0 cm and 16.0–22.5 cm were required under RCP 4.5 and 8.5, respectively. For Rocky Mount, an additional 9.0–15.5 cm and 16.0–21.5 cm were required under RCP 4.5 and 8.5, respectively. These represent substantial increases in storage required to maintain the Base scenario of overflow depth under climate change projections. These increases are substantially higher than the construction tolerances for bioretention observed by Wardynski and Hunt (2012), and thus are higher than the error associated with bioretention construction and are realistic to consider. It should be noted that some of these increases in storage depth may be infeasible or undesirable due to public safety. Thus, another option would be to increase storage volume by expanding the footprint of a given system.

3.5. Dry periods

Climate change predictions generally consist not only of changes in rainfall amount and intensity, but also rainfall frequency. Thus, periods of drought are likely to increase in some regions (IPCC, 2012). Within the bioretention environment, prolonged dry conditions may cause stress to biotic components such as plants and microbes. DRAINMOD simulates soil water dynamics and thus can provide an estimate of how prolonged periods of drought influence soil moisture. An estimate of water limiting days is provided in the DRAINMOD output. DRAINMOD Dry Days (DM-DD) are defined in DRAINMOD as days during which soil moisture in the root zone is insufficient for potential evaporation to be met. As defined, modelled, and calibrated by Brown et al. (2013) based on site specific attributes, a 30 cm root zone was specified for the Nashville 0.6 m and Rocky Mount SCL Sites, while a 45 cm root zone was specified for the Nashville 0.9 m and Rocky Mount Sand sites.

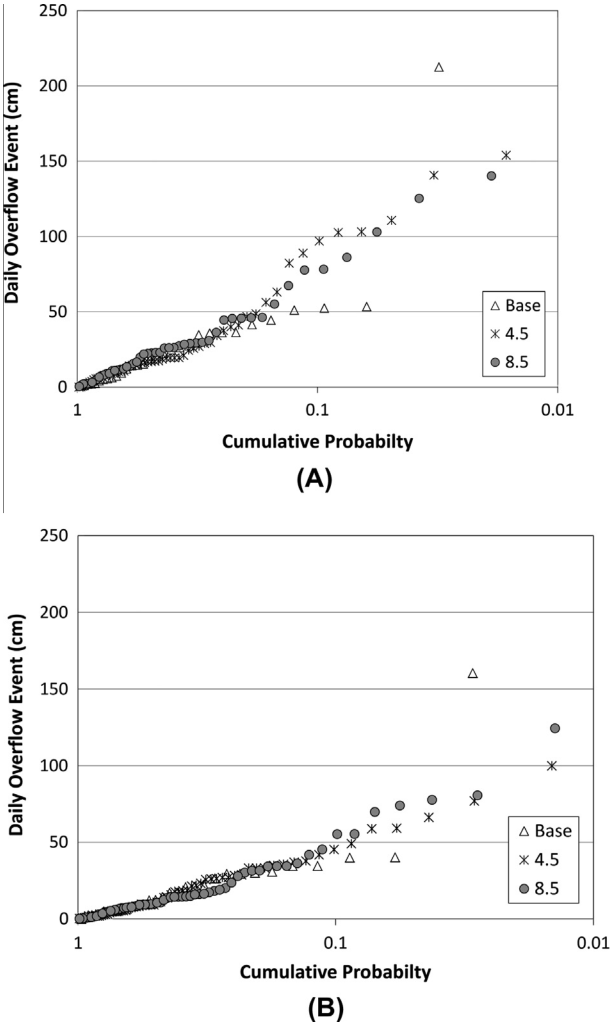

Fig. 2. Example cumulative probability plots of daily overflow events for (A) Nash – 0.9 – Post and (B) RM – SCL – Shallow – IWS.

For the Nashville sites, the system with 0.6 m of bioretention media experienced substantially more DM-DDs than the 0.9 m system under both Pre and Post conditions. Similarly, the Rocky Mount SCL site experienced substantially more DM-DDs than the Rocky Mount Sand site for both IWS depths. As soil depths, configuration, hydrologic performance, and in situ soils varied between all of the sites, the influence of root zone seemed stronger than any other variable. Vegetation schemes which have deeper rooting vegetation, and thus deeper root zones, appear to have more resiliency to dry conditions. The impact of climate change on DM-DDs in the systems was minimal for some sites, and for some sites the number of DM-DDs actually decreased under the climate change scenarios. Further study is needed in this area, as the issue of system tolerance to drying is critical. If droughts become more frequent, plants and microbes in these systems may be severely affected.

4. Conclusions

Calibrated DRAINMOD models were utilized to establish bioretention hydrologic regimes under present day and projected future climate scenarios. The results of this study imply the contribution of each component to the overall water balance within bioretention systems does not substantially change when comparing existing performance to that under climate change scenarios. The total runoff entering the system generally had the same fate (drainage, overflow, or infiltration/evaporation), with no more than a 10 percentage point change being observed among any one category in the water balance.

However, across all site scenarios, the largest and most critical change between the Base and climate change scenarios was the substantial increase in overflow. As this overflow represents largely untreated and uncontrolled bypass of the system, it is the most critical portion of the water balance. In nearly all cases simulated, the climate change scenarios had a higher total volume of overflow, a larger number of overflow events, and higher magnitude events. Increases in overflow from bioretention cells indicates that although these systems can provide some abatement of the influence of climate change on urban hydrology, increased impacts to urban surface waters are likely. At the Nashville site, considering both climate change profiles, 15.5–31.0 cm of additional storage would be required to restrict annual overflow to that of the Base scenario. At Rocky Mount, these values decrease slightly to between 9.0 and 21.5 cm. The lack of influence of IWS depth on performance was observed for the Rocky Mount sites, showing the higher importance of surface storage volume and infiltration rate on system resiliency to climate change.

Two RCPs were utilized in this study to provide some buffer against the uncertainty of climate projections and future fossil fuel usage; however, there are substantial questions as to how global and regional climates will change in the future. Further, the distance of the historical rainfall monitoring station from the project location (12 and 25 km for Rocky Mount and Nashville, respectively) introduces some error due to the lack of temporally specific rainfall data under the Base scenario. Thus, these analyses are considered to illustrate the overall differences in bioretention performance in the Rocky Mount metropolitan area (which includes Nashville), than at the specific project locations. The climate projections and modelling efforts herein suggest more intense and frequent rainfall and overflow events in the future. Although the number of events and their magnitude is likely to differ from those shown herein due to the uncertainty inherent in these data, bioretention areas are expected to more frequently overflow in the future.

It should be noted that this study is specific to this location in central North Carolina, USA, where the influence of climate change on rainfall patterns is projected to be relatively moderate. Similar studies performed in other locations worldwide would be necessary to provide a more robust analysis of the resiliency to climate change provided by bioretention. Further investigation should also be performed to determine which design modifications result in a system most resilient to potential increases in rainfall intensity and more frequent occurrence of drought conditions. Despite the uncertainty in global and regional climate change modelling, in particular for fine time scales, studies such as this are necessary to begin to understand climate change impacts on urban water systems. These analyses should (and will) be refined over time as modelling techniques improve.

Disclaimer

The research described herein was collaborated on by the co-author, a grantee working at the U.S. Environmental Protection Agency (EPA), during his personal time. It was conducted independent of EPA employment and has not been subjected to the Agency's peer and administrative review. Therefore, the conclusions and opinions drawn are solely those of the authors and are not necessarily the views of the Agency.

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