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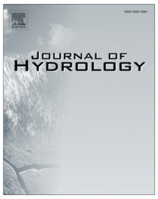

Bioretention function under climate change scenarios in North Carolina, USA

J.M. Hathaway[a,*], R.A. Brown[b], J.S. Fu[a], W.F. Hunt[c]

[a] *Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN, USA*
[b] *ORISE Postdoctoral Fellow, United States Environmental Protection Agency, Edison, NJ, USA*
[c] *Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC, 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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[*] Corresponding author.
E-mail address: hathaway@utk.edu (J.M. Hathaway).

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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