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Reducing combined sewer overflows by using outlet controls for Green Stormwater Infrastructure: Case study in Richmond, Virginia

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SUMMARY

Combined sewer overflows (CSOs) are a major problem in many cities. This paper assesses two Low Impact Development (LID) Green Stormwater Infrastructure (GSI) alternatives applied within a 7.05 ha catchment of the Shockoe Creek tributary of the James River in Richmond, Virginia. The LID alternatives were the "Green-Free" (typical free discharge underdrains) and the "Green-Control" (underdrains with flow controlled outlets). These alternatives were compared to two non-LID alternatives: "Existing" (existing conditions) and "Gray" (tunnel storage). A normal year scenario with average rainfall depths and intensities was compared to a scenario with anticipated higher intensity rainfall due to climate change (CC).

In the normal year, the Green-Control alternative performed substantially better than both the Green-Free and the Gray alternatives in terms of volume control. However it experienced slightly more CSO events than Grey. The relative performance of both green alternatives improved with the CC climate year, indicating that GSI is more resilient than gray infrastructure. In particular, Green-Control exhibited much better performance. While the gray infrastructure solution reduced CSOs to the fewest number of occurrences, the smallest overflow volumes, lowest peak flows and the most resilient system was obtained by the Green-Control alternative. Since CSO volume is strongly related to the negative ecological impacts from overflows, and CSO occurrences are not, GSI provides a more sustainable solution than gray. These results find that hydraulic control of discharges should be the preferred option when considering GSI in CSO mitigation.

1. Introduction

Low Impact Development (LID) Green Stormwater Infrastructure (GSI) facilities such as bioretention have been widely applied for control of combined sewer overflows (CSOs) throughout the US, e.g., Philadelphia Water Department (PWD) (2009). The dominant approach to implementing LID stormwater control measures (SCMs) is by using the infiltration rate of LID media to control hydrologic responses e.g., Hinman (2009). A review of extant manuals for LID practices throughout the US reveals that only the states of Minnesota (Davidson et al., 2008), Wisconsin (Wisconsin Department of Natural Resources, 2010), Maine (Maine Department of Environmental Protection, 2012) and Nebraska (Hartsig and Szatko., 2012) promote the use of valves to control underdrain discharges to extend drawdown times to at least 12–24 h. Fairfax County (2012) (VA) mandates the use of outlet valves to control porous pavement discharges. Although several other counties in CA and PA also support this concept, no other states have published any requirements for valves to control underdrain discharges. As these jurisdictions represent approximately 5% of the US population, outlet controls are rarely applied for LID SCMs in the US.

As the current trend is toward sand media with high permeability to prevent clogging and intercept more runoff (Davis et al., 2009; Guo, 2012), the resultant flow rate through the media is rapid. Compared to CSO flow thresholds which are typically well under 10 L-s^{-1}-ha^{-1} of contributing area, flow rates at 50 cm-h^{-1} through a 500 m^2 bioretention system sized at a 5% capture ratio would be an order of magnitude higher. As such, flow controls would be very beneficial in meeting specific discharge criteria to reduce CSOs and provide proper flow duration curves (FDCs) to reduce channel erosion.

This apparent need for outlet controls in bioretention has received some attention, mainly in the grey literature. A primitive

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dynamic modeling approach using an orifice intended to reduce flows to meet (2-year) surface discharge criteria in a bioretention system was reported by Lucas (2004). Guo (2012) modeled the flow reduction at maximum ponding depth from installing a cap-orifice control on a bioretention underdrain. PowerPoint presentations by Beyerlein (2011) and Goodman et al. (2013) recently outlined the potential hydrologic benefits and methods for underdrain outlet control to achieve desired FDCs. Thus, outlet control represents an emerging path of bioretention design, and is the main focus of this paper.

One of the first modeling applications that used a highly restrictive low flow orifice to reduce outflow rates was the Lucas-PWD planter trench (Lucas, 2010). The PWD planter trench is a combination of bioretention planters and stone infiltration trenches, within which most storage is retained by stone trenches with very high media flow rates. Using a 3-compartment design, representing surface ponding, media, and the stone/underdrain layers of a typical LID facility, simulations were developed using the U.S. EPA's Storm Water Management Model, or SWMM (Huber et al., 1988; Rossman, 2004). Based on these detailed simulations using outlet controls applied to the underdrain, the citywide simplified SWMM LID model for Philadelphia was verified as being conservative, and thus became the basis of Philadelphia's Long Term Control Plan Update (Philadelphia Water Department, 2009). Continuous simulation (CS) modeling using SWMM 5.0.13 indicated that the outlet controlled system sized at 3% of the impervious source area could infiltrate nearly half the annual runoff, and reduce CSO volumes by 87% (Lucas, 2008, 2010). The SCMs discussed in that paper have now become the first deployment of such a system at the city block scale. An upgraded version of the Lucas-PWD planter trench was deployed at the study site.

Palhegyi (2010) also noted the benefits of using outlet controls to meet flow duration criteria. However, given media flow rates over an order of magnitude less than typical sandy media used in Lucas (2010, 2011), the infiltration rate was so low that the required treatment area was nearly an order of magnitude greater. Furthermore, the simulated outlet control based upon manipulating underdrain diameter and length required very small underdrains to function. Since the model maintained uniform flows over an extended period (which is only possible with buoyant orifices) it apparently did not carry the hydraulic gradient on the underdrain up through the media as in Lucas (2008, 2010).

Elevated outlets have also been used to reduce underdrain discharge volumes, as more runoff is retained for infiltration prior to discharge through an underdrain Using slow rate media ($\sim$5.0 cm-h^{-1}) combined with an elevated outlet, most runoff was retained within the system, reducing outflows and increasing treatment (Brown and Hunt, 2011). However, the problem with using slow infiltration rate media is that it substantially increases untreated bypass flows, (Lucas and Greenway, 2008, 2011a), unless the system is designed to be much larger, as in Palhegyi (2010). Using higher flow rate media, elevated outlets only slightly attenuated flow rates when the systems are completely saturated (Brown et al., 2013).

Experimental observations using outlets to decrease underdrain flow and increase retention time were first reported by Lucas and Greenway (2006). Using a dual outlet configuration to eliminate bypass, detailed analysis of the bioretention hydraulics with the 3-compartment approach was published by Lucas and Greenway (2011a). The resultant implications for significant improvements in nitrogen removal were presented by Lucas and Greenway (2011b). A version of the dual outlet bioretention system has also been deployed at the study site.

A variety of approaches exists to help assess wet weather infrastructure (Rangarajan et al., 2012). Two of these approaches include the selection of a design event, or using continuous simulation. An example adaptive design storm approach, Madsen and Figdor (2007) found that, in the mid-Atlantic region, a storm with a 1-year return period is anticipated to occur more frequently, due to CC (i.e., every 7.7 months). For Richmond, Virginia, area, which is the subject of this study, downscaled Global Climate Change (GCC) models project that annual rainfall depths will likely increase by 2–4% in the Mid-Atlantic region by 2100. However, the intensity of events is projected to become substantially greater (Hayhoe et al., 2007; Najjar et al., 2010). Milly et al. (2008) suggested that a more probabilistic approach should be applied to current practices in drainage assessment and engineering design than is currently used, which Rosenberg et al. (2010) found are not likely to be conservative. Grimaldi et al. (2012) concluded that continuous simulation methods were preferable to the design storm approach due to underestimation of the hydrograph, leading to non-conservative designs.

In terms of application to LID, Barbu et al. (2009) conducted a paired modeling study between a conventional, pre-developed, and LID site designs for 2-, 10-, and 100-year storm events. The authors found that the LID site design generated much lower runoff volumes, provided more recharge and provided more resilience to changes in extreme events; the same is suggested in Pyke et al. (2011). On the other hand, Freni et al. (2010) evaluated distributed or source controls (LID) versus centralized storage for mitigating CSOs using a simulation model. The authors found that centralized controls were more robust. Weinstein (2009) contended the opposite and points out a variety of financial benefits with LID that are often overlooked. Montalto et al. (2007) presented a simplified hydrologic model using the rational method with a lifecycle analysis of costs and benefits using the known ranges to evaluate different LID implementations for control of CSO in New York, NY. A more complex, physically-based model should provide a more robust tool for evaluating LID implementation for control of CSOs.

This paper summarizes an assessment of the effectiveness of a comprehensive LID implementation to reduce the volume of stormwater contributing to CSOs in the upper Shockoe Creek watershed by the Science Museum of Virginia (SMV), in Richmond, Virginia. Current conditions were compared to deploying either grey infrastructure, free-discharge LID SCMs, or adding simple outlet controls to the SCMs. Specific LID SCMs assessed include Bioretention (BR), Tree planter/trenches (PT), Permeable pavement (PP), and Green Roof (GR). These results are based upon the assumption that the frequency and intensity of storm events are projected by Global Climate Models (GCMs) to increase in the mid-Atlantic region within the next century, consistent with the projections of Najjar et al. (2010).

2. Methods

2.1. Regional setting and site description

Located near downtown Richmond, VA, the 7.0 ha study catchment of upper Shockoe Creek drainage is over 81% impervious. Geographic information system (GIS) data provided by the City of Richmond allocated land cover as either open (pervious), along with roof, walks, parking, or road, all of which are impervious. Fig. 1(a) displays the setting, and Fig. 1(b) displays the corresponding land coverage, along with the individual subcatchment divides for the SCMs discussed in more detail below.

2.2. Monitoring

Flow data for model calibration were collected in a 48 cm wide by 75 cm high "sharp" egg-shape brick sewer. An area-velocity flow meter and sensor (Teledyne Isco model 2150) monitored velocity and depth at 5-min intervals. A rating curve according to