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Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale

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SUMMARY

Urban stormwater runoff remains an important issue that causes local and regional-scale water quantity and quality issues. Stormwater best management practices (BMPs) have been widely used to mitigate runoff issues, traditionally in a centralized manner; however, problems associated with urban hydrology have remained. An emerging trend is implementation of BMPs in a distributed manner (multi-BMP treatment trains located on the landscape and integrated with urban design), but little catchment-scale performance of these systems have been reported to date. Here, stream hydrologic data (March, 2011–September, 2012) are evaluated in four catchments located in the Chesapeake Bay watershed: one utilizing distributed stormwater BMPs, two utilizing centralized stormwater BMPs, and a forested catchment serving as a reference. Among urban catchments with similar land cover, geology and BMP design standards (i.e. 100-year event), but contrasting placement of stormwater BMPs, distributed BMPs resulted in: significantly greater estimated baseflow, a higher minimum precipitation threshold for stream response and maximum discharge increases, better maximum discharge control for small precipitation events, and reduced runoff volume during an extreme (1000-year) precipitation event compared to centralized BMPs. For all catchments, greater forest land cover and less impervious cover appeared to be more important drivers than stormwater BMP spatial pattern, and caused lower total, stormflow, and baseflow runoff volume; lower maximum discharge during typical precipitation events; and lower runoff volume during an extreme precipitation event. Analysis of hydrologic field data in this study suggests that both the spatial distribution of stormwater BMPs and land cover are important for management of urban stormwater runoff. In particular, catchment-wide application of distributed BMPs improved stream hydrology compared to centralized BMPs, but not enough to fully replicate forested catchment stream hydrology. Integrated planning of stormwater management, protected riparian buffers and forest land cover with suburban development in the distributed-BMP catchment enabled multi-purpose use of land that provided esthetic value and green-space, community gathering points, and wildlife habitat in addition to hydrologic stormwater treatment.

1. Introduction

Urbanization is well known to have substantial impacts on watershed hydrology and affects both local and regional-scale water resources. Lower infiltration, greater surficial runoff, greater and more rapidly occurring peak streamflow (reviewed in Paul and Meyer, 2008), and altered riparian zone ecology (Groffman et al., 2003) are generally observed in urban watersheds. Impervious cover has been linked to stream channel erosion and decreased invertebrate and fish indices of biological integrity, collectively termed the 'urban stream syndrome' (Walsh et al., 2005). Stormwater runoff also transports pollutants from urban landscapes; in the Chesapeake Bay watershed, it is responsible for a considerable portion of the total phosphorus (15%), sediment (16%), and nitrogen (8%) load to the Bay (estimates based on data from US EPA, 2010). As urban populations and urban land cover continue to expand, these issues will likely be exacerbated.

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Urban stormwater runoff problems have typically been mitigated through the implementation of stormwater best management practices (BMPs), which are techniques, measures, or structural controls used to manage the quantity and quality of stormwater runoff to the maximum extent practicable (Muthukrishnan et al., 2006a). Structural BMPs used to manage water quantity include dry detention ponds, wet retention ponds, swales, and infiltration systems (Muthukrishnan et al. 2006b). Traditionally, BMPs (primarily wet and dry ponds) have been employed in a centralized manner (a few large BMPs typically in or adjacent to stream channels placed away from development) with a focus of mitigating peak discharge and to minimize hydrologic alterations as compared to pre-urbanized conditions; however, hydrologic issues have still persisted. Recently, BMPs have begun to be implemented in a distributed manner (many decentralized BMPs) to manage stormwater runoff on the landscape and closer to its source with an emphasis on infiltration, retention on the landscape and integration with urban design (Davis, 2005; Roy et al., 2008). For example, BMPs such as bioretention cells and dry swales can be incorporated into the planning process and provide green space and esthetic value in the urban environment. Other BMPs like volume storage facilities and infiltration trenches can be placed underground to enable multipurpose use of the landscape. The goal of distributed use of BMPs is to achieve a site design strategy that replicates a functionally equivalent hydrologic landscape of pre-urbanized conditions, termed Low Impact Development (LID) (US EPA, 2000). Despite the promise and beginning implementation of distributed BMPs, widespread use of distributed BMPs has not occurred in part due to a lack of catchment-scale performance data (Davis, 2005; Roy et al., 2008; Hamel et al., 2013).

While the hydrologic effects of individual landscape BMPs have been studied (e.g., Rushton, 2001; Davis, 2008; Emerson and Traver, 2008), relatively less hydrologic monitoring has been reported in fully-developed catchments larger than the lot and individual-BMP scale. Paired-catchment ($\leqslant$0.15 km^2) monitoring studies have revealed that relative to traditional development, LID BMPs (e.g., bioretention cells, grassed swales, infiltration basin, and permeable pavement integrated into original development plans) resulted in: lower peak discharge and runoff volume, increased lag times, greater runoff thresholds, and retention of smaller, more frequent precipitation events (Hood et al., 2007; Selbig and Bannerman, 2008). Compared to pre-existing conditions, catchments developed ($\leqslant$0.15 km^2) using LID techniques resulted in minimal hydrologic disturbance (Selbig and Bannerman, 2008) and significantly reduced weekly stormflow volume (Bedan and Clausen, 2009). The addition of LID BMPs (rain barrels and rain gardens) to fully-developed and uncontrolled catchments ($\leqslant$0.69 km^2) resulted in slightly, but significantly reduced stormflow volume (Shuster and Rhea, 2013).

Mathematical modeling of spatially distributed BMPs used to achieve LID has been performed on the individual lot-scale (0.001 km^2) up to the catchment-scale (21 km^2). At the lot-scale, modeling of distributed BMPs (e.g., rain gutters, driveway interceptor, lawn retention basin, cisterns and bioretention pits) have predicted effective reduction of stormwater runoff (Xiao et al., 2007; Gilroy and McCuen, 2009) with the spatial location of the BMPs being an important consideration (e.g., BMPs directly downstream of impervious surfaces to reduce runoff volumes; Gilroy and McCuen, 2009). In larger drainage areas, up to 21 km^2, models have predicted that distributed BMPs as part of LID are effective in controlling stormwater runoff from small storm events, but not for larger flood events (Holman-Dodds et al., 2003; Brander et al., 2004; Williams and Wise, 2006; Damodaram et al., 2010). Models have also predicted that LID, as compared to traditional BMPs, are less effective at mitigating peak stormflow, but were predicted to better preserve runoff timing observed during predevelopment conditions (Williams and Wise, 2006; Damodaram et al., 2010). The spatial pattern of urban development and land use, in addition to stormwater BMPs, has also been predicted to be an important factor in achieving hydrologic improvements. For example, clustered housing and maximization of undeveloped open space resulted in reduced stormwater runoff in hydrologic models (Brander et al., 2004; Williams and Wise, 2006). In addition to affecting stormflow, infiltration-focused BMPs have been predicted to increase groundwater and baseflow levels (Hamel et al., 2013) with the spatial distribution of the BMPs an important factor dictating groundwater levels (Endreny and Collins, 2009).

While these modeling studies provide predictions into the catchment-scale effects of distributed stormwater BMPs and LID, and only limited field-data exist for small catchments, monitoring observations at a larger catchment-scale remain largely unreported. To address this gap, hydrologic monitoring data were linked with stormwater infrastructure and geospatial databases in this paired-catchment study. The goal was to understand how distributed or centralized stormwater management strategies in urban catchments affect stream hydrology including (1) stormflow and baseflow contributions to monthly runoff volume, (2) maximum discharge and stream response during individual precipitation events, and (3) runoff volume during an extreme precipitation event.

2. Material and methods

2.1. Study sites

Catchments analyzed in this study were located in the Chesapeake Bay watershed in the Washington, D.C., metropolitan area and include: two catchments utilizing largely centralized stormwater BMPs (Cent-MD and Cent-VA), one catchment developed entirely with distributed stormwater BMPs (Dist-MD), and a non-urbanized forested catchment (For-MD) (Fig. 1, Table 1, and Appendix A). Urban land cover in the study catchments was composed of impervious surface (i.e. roadways, driveways, sidewalks, rooftops), urban grass, barren, and water land cover. While non-forested land cover existed in For-MD, urban land was low-density/single-family homes and agricultural land cover was unmanaged meadow. Impervious surface cover was much more prevalent in Dist-MD and Cent-MD as compared to Cent-VA. Land cover in For-MD, Cent-MD, and Cent-VA has been relatively constant since 1998; Dist-MD recently underwent land cover change from agriculture to urban from 2004 to 2010 (Hogan et al., 2013). All catchments were located in the Piedmont physiographic province, with 100% of the underlying crystalline bedrock consisting of a phyllite/slate unit in the Maryland catchments and 81% schist/gneiss and 18% meta-argillite in Cent-VA (Dicken et al., 2008).

2.2. Data sources and analytical methods

Land use/land cover for the study catchments (Fig. 1 and Table 1) was determined by digitization of 2010 aerial imagery for the Maryland catchments and 2007 aerial imagery for the Virginia catchment using the Habitat Digitizer Extension Tool (http://ccma.Nos.noaa.gov/products/biogeography/digitizer/) in ArcMap 9.2[1] (Esri, Redlands, CA). Imagery of Montgomery County, MD, was natural color digital orthophotography with a spatial resolution of 0.3 m, obtained with a Leica ADS-40 digital pushbroom sensor.[1]

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[1] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.