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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.

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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]

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

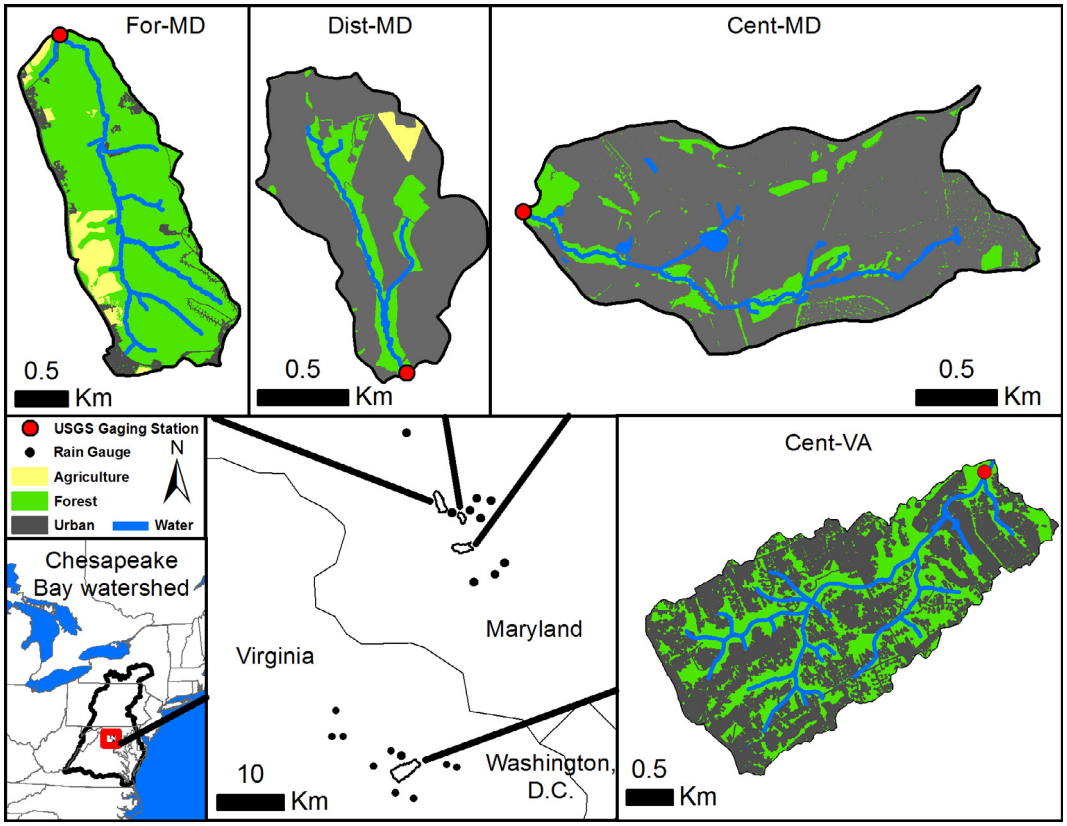

Fig. 1. Study catchments in the Washington, D.C. metropolitan area located in the Chesapeake Bay watershed.

The minimum mapping unit for land cover analyses was 5 m^2, which was the typical area for a tree and its canopy. Stormwater BMP maps were generated by digitizing BMPs and storm sewer system information from field inspections and construction as-built drawings into a geographic information systems (GIS)-environment. Stormwater BMP data for the Maryland catchments were obtained from Montgomery County, MD Department of Environmental Protection and the Planning Department; data for the Cent-VA catchment were courtesy of the Fairfax County, VA Department of Public Works and Environmental Services (data in Fig. A1).

The analysis period of hydrologic data in this study extended from 3/1/2011, following the conversion of all erosion and sediment control BMPs to stormwater management BMPs in the recently developed Dist-MD catchment, through 9/30/2012. Approved daily mean discharge data were downloaded from the U.S. Geological Survey (USGS) National Water Information System (http://waterdata.usgs.gov/nwis) and approved instantaneous (5-min) discharge data were downloaded from the USGS Instantaneous Data Archive (http://ida.water.usgs.gov/ida/index_usgs.cfm). Daily data were used to augment periods with missing data in the instantaneous discharge dataset in Section 3.2. No pre-development discharge data were available in the urban study catchments. Precipitation quantity data were collected on 5-min intervals using RG-400-8 Rain Gauges[2] (J&S Instruments, Inc., Springfield, OH) deployed on roof-tops away from tall objects as per manufacturer recommendations. Hourly precipitation data were obtained from the National Weather Service National Climatic Data Center (http://www.ncdc.noaa.gov) to supplement occasional gaps in the 5-min data. All rain gauge locations are shown in Fig. 1. Hourly precipitation records for each catchment were calculated using the inverse distance method (Eq. (1); Brutsaert, 2005):

$$\langle P \rangle = \left(\sum_{i=1}^{n} d_i^{-1} \right)^{-1} \sum_{i=1}^{n} d_i^{-1} P_i \tag{1}$$

where $\langle P \rangle$ is the mean precipitation in the study catchment (mm); n the total number of precipitation stations; d_i the distance from the catchment centroid to the ith precipitation station (km); and P_i is the measured precipitation at the ith precipitation station (mm).

Monthly stormflow and baseflow fractions of runoff volume were estimated by averaging output from three baseflow separation models. One model relies on a digital filter originally used in signal processing (Lyne and Hollick, 1979) that separates quickflow from lower-frequency baseflow signals with the model parameter $\alpha = 0.925$ (Nathan and McMahon, 1990). Next, the Local Minimum Method connects local minimum values via a straight line to designate baseflow with minimum values identified by the lowest value in a designated interval (Sloto and Crouse, 1996). The digital filter and local minimum methods were performed using the Web-based Hydrograph Analysis Tool (WHAT; Lim et al., 2005). Finally, the USGS PART model relies on streamflow partitioning and designates baseflow based on antecedent streamflow recession (Rutledge, 1998); this model was downloaded from the USGS Water Resources Application Software website (http://water.usgs.gov/software/). These models were selected to obtain objective and reproducible estimates of baseflow as compared to those generated though manual hydrograph separation (Nathan and McMahon, 1990; Sloto and Crouse, 1996; Rutledge, 1998), with the three distinct methods chosen to appreciate differences in calculated baseflow and stormflow. All three methods have been demonstrated to generate reasonable estimates of baseflow (e.g., Rutledge, 1998; Arnold and Allen, 1999; Mosner, 2002) and are

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

Table 1
Land cover characteristics for the study catchments.

Catchment[a]	USGS gaging station no.	Drainage area[b] (km^2)	Land cover			Impervious cover[c] (%)
			%Urban	%Forest	%Agriculture	
Little Seneca Creek Tributary near Clarksburg, MD (Dist-MD)	01644371	1.11	77	21	2	30
Little Seneca Creek Tributary near Germantown, MD (Cent-MD)	01644375	3.50	85	15	0	39
South Fork Little Difficult Run above mouth near Vienna, VA (Cent-VA)	01645762	7.02	43	57	0	14
Soper Branch at Hyattstown, MD (For-MD)	01643395	3.03	6	85	9	3

[a] Parentheses indicate name used herein.
[b] Obtained from USGS National Water Information System.
[c] Percentage of total catchment area.

commonly cited in the literature (e.g., Neff et al., 2005; Eckhardt, 2008). Runoff ratios were calculated by normalizing runoff to total precipitation that occurred during the runoff period. Hydrologic stream response during individual precipitation events was calculated as the ratio of maximum discharge observed during a precipitation event to baseflow discharge prior to precipitation. Statistical analyses performed in R (R Core Team, 2012) included non-parametric Wilcoxon paired-sample tests of monthly runoff volume, Pearson's product moment correlation of individual precipitation event data, and linear and piecewise regression modeling of discharge and precipitation data calculated using the segmented package (Muggeo, 2008). Dates to investigate seasonal differences in stream hydrology due to tree canopy presence (i.e. November–April vs. May–October) were selected based on field site photography and data from the USA National Phenology Network (https://www.usanpn.org/). All discharge and runoff volume data reported here were normalized to catchment drainage area to enable direct comparison between catchments.

3. Results

3.1. Quantification of stormwater management infrastructure

The distribution, connectivity, and density of stormwater BMPs varied considerably between the study catchments with distributed and centralized stormwater BMPs (Table 2; Appendix A). First, there were nearly three times more stormwater BMPs present in Dist-MD as compared to the centralized BMPs catchments, a difference that is exacerbated when normalizing for drainage area. Second, almost all of the distributed stormwater BMPs were constructed as part of seven stormwater treatment trains (e.g., Fig. A2), which provided water quantity and quality treatment in series with an average of 16 stormwater BMPs in each treatment train. Finally, these distributed stormwater BMPs were located entirely on the upland landscape (as opposed to instream BMPs) and integrated with the suburban development to provide infiltration, hydraulic detention, and water quality treatment of stormwater runoff before it was discharged to riparian zones and reached local stream channels. Riparian zone forests in Dist-MD were specifically preserved throughout development to provide stream protection (MNCPPC, 1994).

In Cent-MD, stormwater BMPs were located in both the channel and on the upland landscape. In-stream stormwater BMPs provided hydraulic detention or retention and most upland landscape BMPs were designed for water quality treatment with limited hydraulic detention capacity. Effluent from stormwater BMPs located on the upland landscape in Cent-MD was discharged either directly into local stream channels via storm sewer pipes or to riparian zones. Stormwater runoff in Cent-MD and Dist-MD was primarily routed to stormwater BMPs via traditional curb and gutter system linked with storm sewer pipes. In Cent-VA, all stormwater BMPs were located in stream channels (both perennial and ephemeral) and were primarily designed for hydraulic detention. Here, stormwater runoff was typically transmitted to ephemeral and perennial stream channels via storm sewer pipes and ditches. All stormwater BMPs in the study catchments relied on gravity-flow with no active management operations (e.g., pumping) apart from routine maintenance and cleaning.

Different design standards were used for the more recently developed Maryland-catchments as compared to Cent-VA. In Dist-MD, terminal stormwater BMPs of each treatment train, typically dry ponds, were designed with storage capacity to attenuate the 100-year, 24-h peak discharge to pre-development rates (MDE, 2000). Upstream of the terminal dry pond BMPs in Dist-MD, nearly all of the bioretention facilities, dry swales, and sand filters were designed to treat the 10-year event (i.e. prevent the post development 10-year, 24 h storm peak discharge rate from exceeding the pre-development peak discharge rate; MDE, 2000) while water quality-focused BMPs like oil/grit separators and underground storm filters were designed to capture and treat the first flush (i.e. runoff from 90% of the average annual rainfall; MDE, 2000). In Cent-MD, nearly all of the dry and wet pond BMPs were designed for the 100-year event and water quality-focused stormwater BMPs captured and treat the first flush, like in Dist-MD. In Cent-VA, half of the BMPs were constructed after 2004 and were likely subject to 1999 Virginia state stormwater regulations (Virginia Department of Conservation and Recreation, 1999) to provide 10-year flood control (i.e. attenuation of the 10-year event peak discharge to not exceed the pre-development 10-year event peak discharge rate). The remaining BMPs were likely designed to achieve 2-year or 10-year event control based on stormwater planning documentation prior to increased urbanization in the

Table 2
Stormwater BMP implementation in the study catchments.

Catchment	Total number of BMPs[a]	Number of BMPs designed for infiltration	Number of BMPs designed for hydraulic detention	Number of stormwater treatment trains
Dist-MD	121[b]	73[c]	17[c]	7
Cent-MD	43[b]	0	12	0
Cent-VA	25	0	25	0

[a] Includes both water quantity and water quality BMPs.
[b] In addition, 40 and 11 flow splitters (to separate first flush from peak stormflow) were also present in the Dist-MD and Cent-MD catchments, respectively.
[c] 5 Bioretention cells were doubled counted that provide both infiltration and hydraulic detention.

catchment (County of Fairfax, 1989). Attenuation of peak discharge rates from nearly all dry and wet pond BMPs was achieved by restricting effluent flow from the BMP outlet pipes. A detailed listing of the stormwater BMPs can be found in Appendix A.

3.2. Daily stream discharge and precipitation patterns

Time-series records of daily discharge and precipitation (Fig. 2A–C) revealed hydrologic differences between the study catchments during relatively wet and dry periods. Daily mean discharge during baseflow from all catchments was comparable during the wet spring months. A seasonal decrease in baseflow discharge was observed in all catchments during the late summer months with much lower baseflow observed in Cent-VA and For-MD. Maximum daily discharge during precipitation events was generally highest in Dist-MD and Cent-MD (Fig. 2C). The pattern of precipitation that fell on the study catchments was largely similar between the Maryland and Virginia catchments with 20% more total precipitation occurring in the Maryland sites (mean = 2071 mm) as compared to Virginia (1724 mm) throughout the entire study period (Fig. 2D). Maximum daily discharge, measured at all catchments on 9/8/2011, was the highest noted in historical discharge records for the Maryland (dating back to early 2004) and Virginia (dating back to 2007) catchments and were a result of intense precipitation occurring from the remnants of Tropical Storm Lee (herein referred to as Tropical Storm Lee) during 9/5/2011 to 9/8/2011. This 1000-year precipitation event (NWS, 2011) resulted in 248 mm and 254 mm, or 12% and 15% of the total precipitation that fell in the Maryland and Virginia catchments, respectively, during the study period. On 9/8/2011 alone, 128 mm (6% of study period total) and 153 mm (9% of study period total) of precipitation fell on the Maryland and Virginia catchments, respectively.

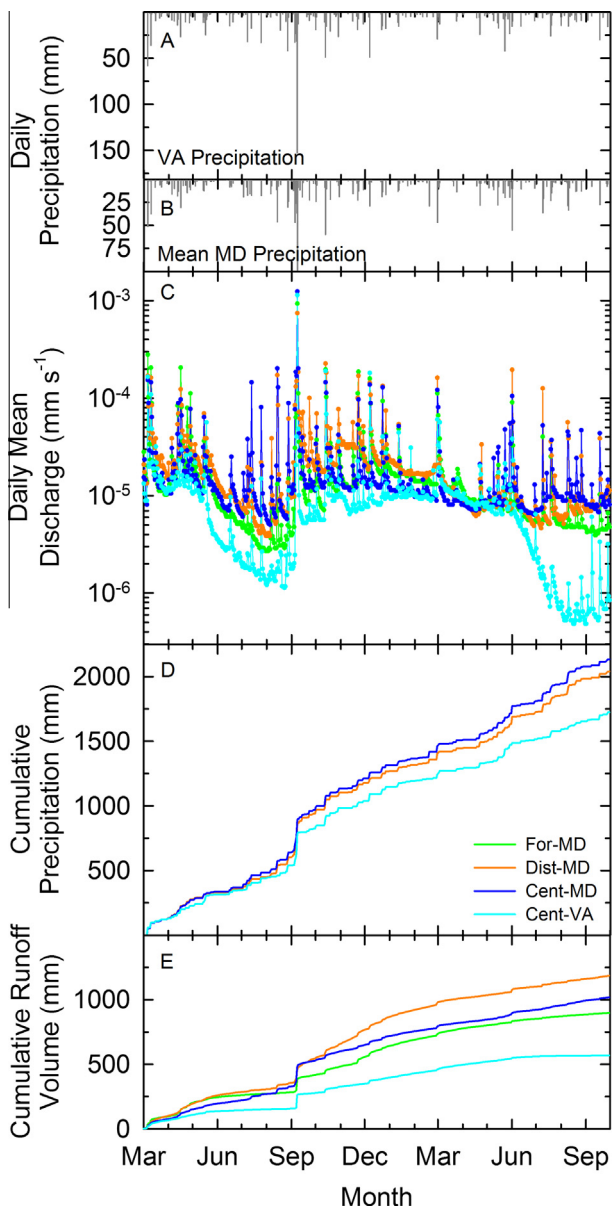

Fig. 2. Daily precipitation in Virginia (A) and Maryland (mean of three MD catchments; (B), daily mean discharge (C), cumulative precipitation (D) and cumulative runoff volume (E) from the study catchments during 3/1/2011 through 9/30/2012. *Note:* For-MD curve in panel D is covered by Dist-MD curve.

Total runoff volume and the total runoff ratio during the entire study period were lowest in Cent-VA and increasingly greater in For-MD, Cent-MD, and Dist-MD (Fig. 2E, Table 3). Percent differences in total runoff volume (45–70%) between Cent-VA and the Maryland catchments decreased when normalizing runoff volume to total precipitation (i.e. runoff ratio; 29–55%). Tropical Storm Lee, which occurred during only 1.0% of the study period, accounted for a large percentage of total runoff volume for the study period in For-MD (12%), Dist-MD (11%), Cent-MD (17%) and Cent-VA (19%).

3.3. Baseflow and stormflow runoff volume

Mean stormflow and mean baseflow (herein referred to as simply stormflow and baseflow, respectively) fractions of total runoff volume revealed differences in water export between the catchments during the study period (Table 3). While the highest total stormflow occurred in Cent-MD, the lowest occurred in Cent-VA. The highest total runoff volume, baseflow, and baseflow index (BFI; the volumetric ratio of baseflow to total runoff volume) occurred in Dist-MD. Total runoff volume, stormflow, and baseflow were greater in the urban-Maryland catchments with greater impervious cover (Dist-MD and Cent-MD) as compared to the relatively more forested catchments (For-MD and Cent-VA).

Statistically significant differences in monthly stormflow were detected among the study catchments (Fig. 3A). Monthly stormflow was significantly (Wilcoxon paired sample test, $p < 0.02$) lower in Cent-VA than in Cent-MD and Dist-MD for the entire study period. Monthly stormflow was significantly lower ($p \leqslant 0.01$) in the For-MD and Cent-VA catchments as compared to the Dist-MD and Cent-MD catchments during May through October but not during November through April. These statistically significant differences were detected for both raw and precipitation-normalized stormflow (i.e. stormflow runoff ratio).

Statistically significant differences in the magnitude of monthly baseflow were detected among the study catchments (Fig. 3B). Monthly baseflow was significantly greater ($p \leqslant 0.02$) in Dist-MD than in all other catchments for the entire study period. Monthly baseflow was significantly lower ($p < 0.01$) in Cent-VA than in all Maryland catchments for the entire study period. Baseflow in For-MD was significantly greater ($p = 0.01$) than in Cent-MD from November through April and significantly lower ($p < 0.01$) from May through September. Significant statistical differences were detected for both raw and precipitation normalized baseflow (i.e. baseflow runoff ratio). Monthly BFI (Fig. 3D) was significantly greater ($p = 0.02$) in Dist-MD and For-MD as compared to Cent-MD.

3.4. Watershed differences in stream discharge during typical precipitation events

Regression modeling of maximum stream discharge and stream response vs. total storm event precipitation (Fig. 4 and Table 4) was

Table 3
Mean stormflow and baseflow fractions of total runoff volume and runoff ratio, and three baseflow indices from the study catchments during 3/1/2011 to 9/30/2012.

Catchment	Runoff volume ($\times 10^2$ mm)			Runoff ratio			Baseflow index			
	Mean stormflow[a]	Mean baseflow[a]	Total	Mean stormflow	Mean baseflow	Total	Digital filter	LMM	PART	Mean[a]
For-MD	3.6 (0.26)	5.4 (0.26)	9.0	0.18	0.26	0.44	0.63	0.58	0.59	0.60 (0.03)
Dist-MD	4.3 (0.36)	7.6 (0.36)	12	0.21	0.37	0.58	0.66	0.60	0.65	0.64 (0.03)
Cent-MD	4.6 (0.33)	5.6 (0.33)	10	0.22	0.26	0.48	0.56	0.56	0.51	0.55 (0.03)
Cent-VA	2.5 (0.15)	3.2 (0.15)	5.7	0.14	0.19	0.33	0.60	0.55	0.57	0.57 (0.03)

LMM = local minimum method.
[a] Standard deviation in parentheses.

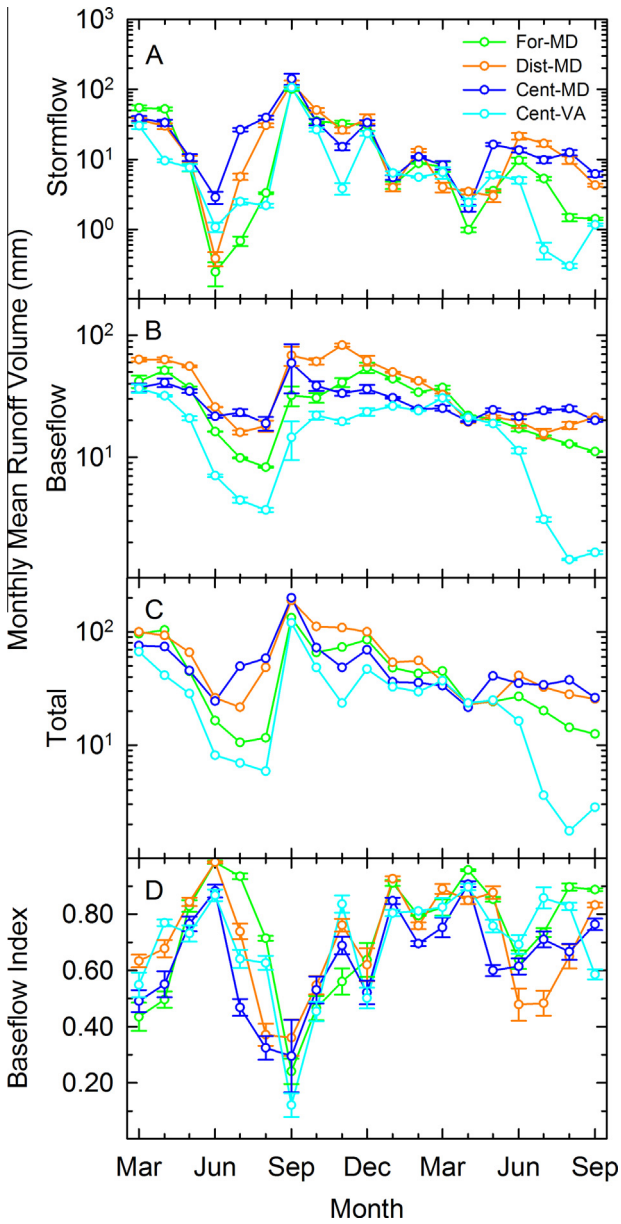

Fig. 3. Stormflow (A) and baseflow (B) fractions of total monthly runoff volume (C) and baseflow index (D) from study catchments during 3/1/2011 to 9/30/2012. Error bars denote the standard deviation of monthly mean estimates from the digital filter, local minimum method, and PART models used in this study.

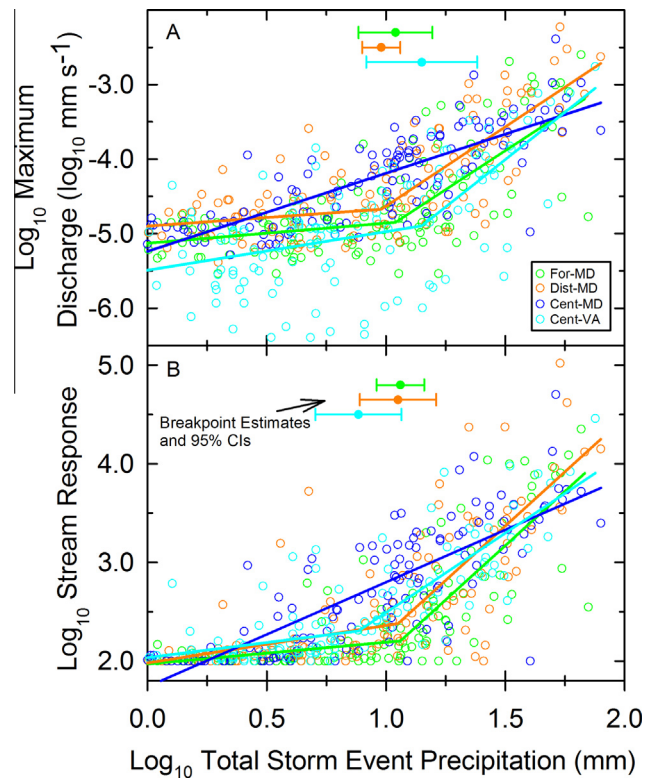

Fig. 4. Log_{10} (maximum discharge) (A) and Log_{10} (stream response) (B) vs. Log_{10} (total precipitation) for typical precipitation events in the study catchments from 3/1/2011 to 9/12/2012. *Note:* stream response = (maximum discharge/prior baseflow discharge during a storm event) * 100%; analysis excludes Tropical Storm Lee.

performed to gain insight on catchment performance and export of runoff during typical precipitation events (i.e. excluding Tropical Storm Lee). While significant piecewise regression models were calculated for Dist-MD, For-MD and Cent-VA, a significant piecewise regression model could not be obtained for Cent-MD. Thus, simple linear regression models were calculated for Cent-MD. R^2 values for piecewise regression models were greater than R^2 values for simple linear models in Dist-MD, For-MD and Cent-VA (average difference = 0.10 ± 0.03).

The left segment of the piecewise regression models (i.e. slope 1 in Table 4) provides insight to how catchments stored and exported stormwater runoff during precipitation events smaller than the average breakpoint of 10 mm. In Cent-MD, the simple linear regression model indicated that runoff volume increased with precipitation amount for even the smallest precipitation events. This finding reflects a lack of complete storage capacity of runoff for the smaller precipitation events in Cent-MD. Slope 1 for models in both For-MD (0.15, 0.15) and Dist-MD (0.23, 0.38) was not significantly different than zero (and was significantly less than the simple linear slope for the Cent-MD models [1.05, 1.06]) indicating the presence of storage capacity sufficient to retain runoff from smaller events. In the Cent-VA catchment, while slope 1 of the stream response model (0.31) was not significantly different than zero and significantly less than the slope for the Cent-MD model

Table 4
Results for Log_{10} (maximum discharge) and Log_{10} (stream response) vs. Log_{10} (total precipitation) piecewise and linear regression models shown in Fig. 4 for typical precipitation events. *Note:* stream response = (maximum discharge/prior baseflow discharge during a precipitation event) * 100%; analysis excludes Tropical Storm Lee.

Catchment	n	R^2	Breakpoint		Slope 1		Slope 2		Slope 1 ≠ slope 2 p-value
			Est.	95% CI	Est.[a]	95% CI	Est.	95% CI	
Log_{10} maximum discharge									
For-MD	131	0.57	1.04	0.89–1.20	0.27[a]	−0.09–0.63	2.09	1.62–2.55	<0.01
Dist-MD	121	0.62	0.98	0.82–1.14	0.23[a]	−0.19–0.66	2.13	1.65–2.60	<0.01
Cent-MD	121	0.64	–	–	1.05[b]	0.90–1.19	–	–	0.09
Cent-VA	118	0.41	1.15	0.92–1.39	0.52[ab]	0.04–0.99	2.54	1.38–3.70	<0.01
Log_{10} stream response									
For-MD	131	0.73	1.06	0.96–1.15	0.22[a]	−0.02–0.47	2.20	1.87–2.54	<0.01
Dist-MD	121	0.62	1.05	0.89–1.21	0.38[a]	−0.03–0.73	2.20	1.60–2.64	<0.01
Cent-MD	121	0.65	–	–	1.06[b]	0.91–1.29	–	–	0.10
Cent-VA	118	0.70	0.88	0.72–1.05	0.31[a]	−0.03–0.64	1.61	1.27–1.95	<0.01

Est. = estimate.
CI = confidence interval.
[a] Letters indicate statistically significant differences ($p \leqslant 0.05$).

(1.06), slope 1 for the maximum discharge model was significantly greater than zero and indistinguishable from the slope for the Cent-MD model (0.52 vs. 1.05).

The right segment of the piecewise regression models provides insight to how catchments stored and exported stormwater runoff during precipitation events greater than the breakpoint average of 10 mm (i.e. slope 2 in Table 4). The simple linear slope of both Cent-MD models (1.05,1.06) was significantly less than slope 2 for both models from For-MD (2.09,2.20) and Dist-MD (2.13,2.20) indicating a greater water storage rate for precipitation events greater than ≈10 mm in Cent-MD. Slope 2 for the Cent-VA maximum discharge model was significantly greater than the Cent-MD slope (2.54 vs. 1.05) but, slope 2 for the Cent-VA stream response model was indistinguishable from the Cent-MD stream response model slope (1.61 vs. 1.06). Maximum discharge and stream response regression models for Dist-MD were lower than for Cent-MD for smaller precipitation events (≈2–27 mm) suggesting the presence of more runoff storage in Dist-MD during smaller events. However, the opposite was true for larger events (>27 mm). A similar situation existed when comparing Cent-MD to Cent-VA and For-MD with regression models intersecting near 50 mm of total precipitation.

Correlation of maximum discharge with cosine-transformed Julian date (cosine[π^*(Julian date)/182.5]) can reveal how individual event stream hydrology changes with season. Lower maximum discharge was significantly correlated with cosine-transformed Julian date in For-MD (Pearson's correlation coefficient, $r = 0.34$, $p < 0.01$), Cent-VA ($r = 0.41$, $p < 0.01$), and Dist-MD ($r = 0.19$, $p = 0.04$), meaning decreased maximum discharge in these catchments occurred during summertime. Stream response was not significantly correlated with Julian date in any catchment. Maximum discharge was significantly correlated with total precipitation occurring during the prior 10 ($r = 0.19$, $p = 0.04$) and 21 ($r = 0.18$, $p = 0.05$) days in Dist-MD, but not in the other three study catchments.

3.5. Stream discharge response to Tropical Storm Lee

Tropical Storm Lee was a 1000-year event (NWS, 2011) that resulted in an average of 249 mm of precipitation in the study catchments over a 6-day period and was a ten-fold larger storm than BMPs in the study catchments were designed to treat. Thus, this event serves as an interesting test case to understand catchment hydrologic responses under extreme conditions. Overall, cumulative precipitation, runoff volume and runoff ratio were relatively similar in For-MD, Dist-MD, and Cent-VA; however, in Cent-MD, cumulative runoff volume and runoff ratio were 48% and 51% greater, respectively, as compared to the average of the other three catchments (Fig. 5).

Relatively greater runoff volume during Tropical Storm Lee in Cent-MD was due to higher maximum peak discharge and the presence to high-flow periods that were longer in duration relative to the other catchments. The magnitude of maximum

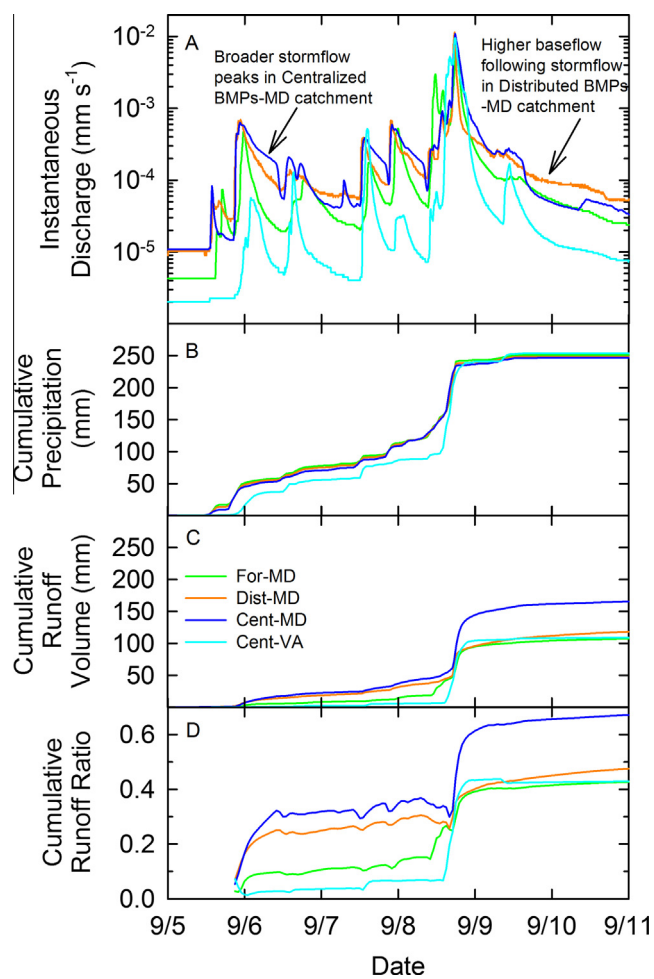

Fig. 5. Instantaneous discharge (A), cumulative precipitation (B), cumulative runoff volume (C), and cumulative runoff ratio (D) in the study catchments from 9/5/2011 to 9/11/2011 during Tropical Storm Lee revealed differences in water export during this extreme (1000-year) precipitation event.

instantaneous discharge recorded for the four largest coincidental peaks during Tropical Storm Lee were similar in Dist-MD and Cent-MD (between 2% and 12% different) while maxima recorded in the For-MD catchment were much lower (between 18% and 76% different) than averaged Cent-MD and Dist-MD discharge maxima. Hydrologic responses varied qualitatively as well. Discharge peaks tended to occur over a shorter period in For-MD as compared to the urban Maryland catchments while the longest stormflow peak duration occurred in Cent-MD. Storm hydrographs in Cent-VA qualitatively resembled those observed in For-MD with shorter-duration peaks and lower discharge on the falling limb of the hydrograph. Stormflow peaks in Cent-MD also exhibited a 'shoulder' following maximum discharge, which is possibly due to discharge levels that exceeded freeboard or emergency overflow bypasses in wet and dry pond BMPs. Peak stormflow events in Dist-MD were shorter in duration as compared to Cent-MD. Elevated baseflow following stormflow peaks in the Dist-MD catchment is readily apparent on 9/7/11 and 9/10/11; throughout the 6-day period, a greater BFI was calculated in Dist-MD (0.33) as compared to Cent-MD (0.29). Tropical Storm Lee appeared to have a long-term (≈2 months) effect on baseflow in Dist-MD as the slope of the cumulative runoff volume curve (Fig. 2E) and monthly baseflow (Fig. 3B) were both greater following Tropical Storm Lee than in periods prior to the event.

4. Discussion

4.1. Stormwater management strategy effects on urban stream hydrology

Contrasting stormwater management strategies in the study catchments are likely responsible for some differences in the magnitude of total runoff and the percentage of runoff exported as baseflow. To discern changes in water export caused by stormwater management strategy, Dist-MD and Cent-MD provide for a suitable direct comparison due to relatively similar drainage area, land cover, precipitation patterns, geology, close spatial proximity, and similar maximum flood control design standards (100-year event) for the BMPs. Distributed stormwater BMPs led to slightly less stormflow export and significantly greater baseflow and total export of water as compared to centralized BMPs (Table 3). Greater baseflow was likely due to the presence of infiltration BMPs including storm-drain recharge facilities, drywell recharge facilities, recharge chambers, and bioretention cells (Tables 2 and A1). A lower total runoff ratio in Cent-MD could be a result of water loss through evaporation from wet pond BMPs. During typical precipitation events, distributed stormwater BMPs appeared to enable better hydrologic control of small events (<27 mm) while centralized BMPs enabled better hydrologic control of larger events (>27 mm) (Fig. 4). Small storm control observed in Dist-MD was likely enabled by disconnection of impervious cover with local streams by the distributed stormwater BMPs network via first flush volume storage capacity of BMPs designed for stormwater infiltration and detention. In Cent-MD, directly connected impervious area and baseflow water surface elevations at wet pond weir heights meant that even the smallest storms would generate a hydrologic response in the catchment. During Tropical Storm Lee, reduced total runoff volume (29% smaller) and elevated BFI (14% greater) suggested that distributed stormwater BMPs can provide better urban stormwater runoff control during extreme precipitation events, although the magnitude of maximum discharge was similar in Dist-MD and Cent-MD (2–12% difference during four major peaks).

Findings in this study largely support previous research of distributed and centralized stormwater BMPs. In this study, a greater precipitation threshold for hydrologic stream response provided by distributed, as opposed to centralized, stormwater BMPs is consistent with findings from field-data results in Hood et al. (2007). In addition, the observed reduced maximum discharge associated with distributed BMPs during smaller typical precipitation events (<27 mm) agrees with previous findings (Hood et al., 2007; Selbig and Bannerman, 2008). However, the relatively better treatment of large precipitation events by centralized stormwater BMPs observed here differs with field-data results from previous work and could be due to larger storms analyzed in this study (maximum = 80 mm) vs. Hood et al. (2007; maximum = 44 mm) and greater impervious cover in the urban Maryland catchments (30% and 39%) compared to catchments monitored in Selbig and Bannerman (2008; 6% and 9%). Stream hydrology in Dist-MD mirrors model predictions of improved stormwater control during small events by infiltration-focused BMPs (Holman-Dodds et al., 2003; Brander et al., 2004; Williams and Wise, 2006; Damodaram et al., 2010), and model predictions of better maximum discharge and large-storm control by centralized stormwater BMPs (Williams and Wise, 2006; Damodaram et al., 2010). Elevated baseflow and BFI in the Dist-MD catchment is consistent with higher predicted groundwater and baseflow level in prior modeling studies (Endreny and Collins, 2009; Hamel et al., 2013).

4.2. Land cover effects on urban stream hydrology

In addition to stormwater management strategy, land cover differences in the study catchments were also a likely contributor to the magnitude and pattern of water exported from the study catchments. Forest land cover dominated the For-MD (85%) and Cent-VA (57%) catchments but was less prevalent in the higher-density urban Dist-MD (21%) and Cent-MD (15%) catchments. Coinciding with greater forest land cover, total, stormflow, and baseflow runoff volume were on average 33%, 31%, and 35% lower, respectively, in For-MD and Cent-VA than in Dist-MD and Cent-MD. These findings agree with previous modeling efforts, which linked greater undeveloped area in a catchment with reduced stormwater runoff (Brander et al., 2004; Williams and Wise, 2006).

Less total, stormflow, and baseflow runoff volume in For-MD and Cent-VA (Table 3) were likely partially due to greater evapotranspiration and canopy interception of water during precipitation events. Greater transpiration in these catchments is reflected in significantly lower monthly baseflow from May through October (Fig. 3) as forest canopies became fully developed. Tree canopy interception and evaporation of precipitation in urban forests reduces runoff (Xiao et al., 1998) and likely partially explains the significantly lower monthly stormflow from May through October (Fig. 3) and maximum discharge-total precipitation regression models that were shifted lower on the *y*-axis (Fig. 4) in the more forested catchments. Further, in For-MD and Cent-VA, significantly lower maximum discharge during individual precipitation events occurred during the summertime. Weaker, but significant, correlation between maximum discharge and summertime (i.e. Julian date) was detected in Dist-MD and was likely related to tree canopy development in the forested riparian zones. No such significant relationship between maximum discharge and Julian date was detected in Cent-MD.

Increased presence and connectivity of impervious land cover was likely an important factor dictating increased total runoff volume and the proportion of runoff as baseflow from the study catchments (Table 3). Lower total runoff was detected in For-MD and Cent-VA catchments with much less impervious cover (3%, and 14%, respectively) than in higher density urban Maryland catchments (30–39%). In this study, the lowest BFI, and greater stormflow, maximum discharge and stream response (Fig. 4, Table 4) were detected in Cent-MD where runoff from impervious areas was either directly discharged to streams or channelized

sections of the riparian zone. Impervious cover was far less abundant in Cent-VA resulting in low total runoff, but impervious cover that did exist was directly connected and was associated with a relatively low BFI in the catchment. A sizeable portion of the stormwater runoff from impervious cover in Dist-MD was directed through infiltration-focused stormwater BMPs resulting in groundwater conveyance of infiltrated stormwater runoff during smaller precipitation events and a high BFI. However, once small-event treatment and infiltration capacity had been exceeded, water more quickly flowed from impervious surfaces through the distributed stormwater BMP network and riparian zone, into local streams. This partially-connected impervious cover likely contributed to the greater stormflow runoff volume and a higher maximum discharge-total precipitation regression model (Fig. 4) during large events in the Dist-MD as compared to For-MD and Cent-VA. Runoff volume during Tropical Storm Lee was lower in For-MD and Cent-VA as compared to Dist-MD and Cent-MD. Previous findings have also noted greater runoff volume and higher maximum discharge in areas with greater directly connected impervious area (Lee and Heaney, 2003; Williams and Wise, 2006).

4.3. Additional factors influencing study results

Total runoff volume and runoff ratio from the Cent-VA catchment was lower than in the Maryland catchments during the study period (Table 3); while greater forest land cover and less impervious cover and precipitation were likely the dominant contributing drivers, local geology could also be an important factor. In the Piedmont physiographic province, recharged groundwater flows to streams via fractures and joints in impermeable bedrock or through the permeable regolith (Denver et al., 2010). As a result, the direction of groundwater flow in the bedrock is controlled by the orientation of fractures. Multiple geologic units exist in and along the borders of the Cent-VA catchment, whereas one unit encompasses all of the Maryland catchments (Dicken et al., 2008). Thus, it is conceivable that a larger (but overall small) portion of infiltrated groundwater may have been transferred out of the Cent-VA catchment across surficial drainage area boundaries or downstream of the streamflow gauge via bedrock fractures than in the Maryland catchments.

Heterogeneities in precipitation patterns likely do not greatly influence the main findings of this study; however, some uncertainty from precipitation heterogeneities is inherent in the results. While precipitation measured at rain gauges near the Maryland catchments was similar, actual precipitation totals occurring in the study catchments likely varied and led to deviation of data from the regression models in Fig. 4. Antecedent conditions could also account for unexplained variance in regression results. Maximum discharge was significantly correlated with total precipitation occurring during the prior 10 and 21 days in Dist-MD, but not in the other three study catchments. Modeling of infiltration-focused stormwater BMPs has predicted relatively poorer performance as compared to detention ponds during periods with wet antecedent conditions (Williams and Wise, 2006) possibly due to water retention in the BMPs or saturated soil conditions.

Application of baseflow separation models in catchments with small drainage areas (e.g., <2.6 km^2 as suggested by Rutledge, 1998) could lead to a bias of high baseflow estimation; although Dist-MD is smaller than 2.6 km^2, evidence suggests relatively high BFI to be a realistic representation of stream hydrology in the catchment. From 2004 to 2010 as infiltration-focused BMPs were implemented in the Dist-MD catchment, annual estimated baseflow steadily increased through time at a significantly greater rate (0.03 per year) as compared to annual baseflow calculated for three nearby catchments: For-MD, Cent-MD, and a smaller (0.96 km^2) agricultural/urban catchment (Hogan et al., 2013).

4.4. Integration of distributed stormwater BMPs with suburban design

Explicit integration of distributed stormwater BMPs with suburban landscape-development in Dist-MD occurred as part of the planning process and enabled several unique outcomes in addition to hydrologic benefits. Underground placement of some stormwater BMPs (e.g., volume storage facilities, storm filters, oil and grit separators) enabled playgrounds to be constructed above on the landscape, which served as community gathering points. Underground installation of storm drain recharge facilities under low-traffic alleyways effectively transformed traditional asphalt roadway into pervious pavement. Esthetically pleasing stormwater BMPs like bioretention cells and swales integrated seamlessly into landscaping plans; these BMPs were constructed with nearby walking paths, provided additional lawn-space, and provided a green substitution for gray concrete stormwater conduits in the dense suburban development. Forested stream riparian areas that existed in pre-development Dist-MD were specifically preserved during and after construction to maintain wildlife habitat and stream water quality while simultaneously providing hydrologic treatment of stormwater runoff (MNCPPC, 1994). These forested areas also provided esthetic value to the community, particularly to houses adjacent to the forest. Overall, the planned integration of the stormwater management infrastructure into the landscape allowed land to serve multiple purposes, namely stormwater treatment and esthetic enhancement.

5. Conclusions

Results from this study highlight the importance of both stormwater management strategy and land cover as factors dictating the magnitude and pattern of water export. In Dist-MD, water export consisted of greater baseflow and lower maximum discharge and stream response during smaller precipitation events relative to Cent-MD with similar land cover but with centralized stormwater BMPs. The water export pattern in Dist-MD, as compared to Cent-MD, more closely resembles the hydrologic response observed in the For-MD catchment, albeit with greater total runoff volume.

Implications of a different hydrologic pattern of this nature in an urban catchment could be considerable. For example, shorter periods of less intense discharge could result in reduced erosion and particulate transport, improved stream ecology, and increased nutrient retention and removal. Better treatment of small precipitation events could limit the export of urban pollutants associated with the first flush. Greater infiltration in Dist-MD would likely result in higher surficial groundwater tables. In areas predicted to receive more frequent and more intense precipitation events under climate change, distributed BMPs may be an effective means to achieve some reduction in runoff volume during extreme precipitation events as was observed during Tropical Storm Lee.

Although hydrologic improvements provided by distributed BMPs were substantial, land cover appeared to play a dominant role in reducing total runoff volume and decreasing stream response during precipitation events. Thus, it is important to consider land cover factors (e.g., decreased impervious cover and greater forested area) as effective stormwater BMPs with respect to urban stream hydrology in addition to the implementation of distributed BMPs. Increasing demand for efficient use of limited land in urban catchments stresses the importance for integration of stormwater management and forest land cover with urban development throughout the entire planning process. This urban planning strategy helped enable multi-purpose use of land to provide hydrologic improvements, habitat for wildlife, and enhanced esthetics in Dist-MD. Water quality improvements offered by forested as opposed to urban land cover also is an important

Table A1
Stormwater BMPs present in the study catchments.

Stormwater BMP types present in study catchments	Number of BMPs in study catchments	Primary design goal
Dist-MD		
Drywell recharge facilities	35	Infiltration
Recharge chambers	2	Infiltration
Storm drain recharge facilities	18	Infiltration
Dry swales	13	Infiltration/stormwater conveyance
Bioretention facilities	5	Infiltration/hydraulic detention/ water quality
Volume storage facilities	6	Hydraulic detention
Dry pond	6	Hydraulic detention
Oil/grit separator	18	Water quality
Underground storm filters	5	Water quality
Sand filter	13	Water quality
Flow splitter	40	First flush separator
Cent-MD		
Volume storage facilities	1	Hydraulic detention
Dry pond – quantity control only	4	Hydraulic detention
Dry pond – quantity and quality control	1	Hydraulic detention/water quality
Wet pond	6	Hydraulic detention/water quality
Water quality infiltration trench	9	Water quality
Water quality bioretention cell	6	Water quality
Oil/grit separator	7	Water quality
Oil/grit separator with sand filter	1	Water quality
Sand filter	8	Water quality
Flow splitter	11	First flush separation
Cent-VA		
Dry pond	20	Hydraulic detention
Wet pond	5	Hydraulic detention/water quality

consideration. Results from this study indicate that a combination of greater forest land cover and use of distributed BMPs can lead to amelioration of the 'urban stream syndrome', improve stream ecosystem health, and create multi-purpose use of urban land.

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Appendix A.

Stormwater best management practices data.
See Table A1 and Figs. A1 and A2.

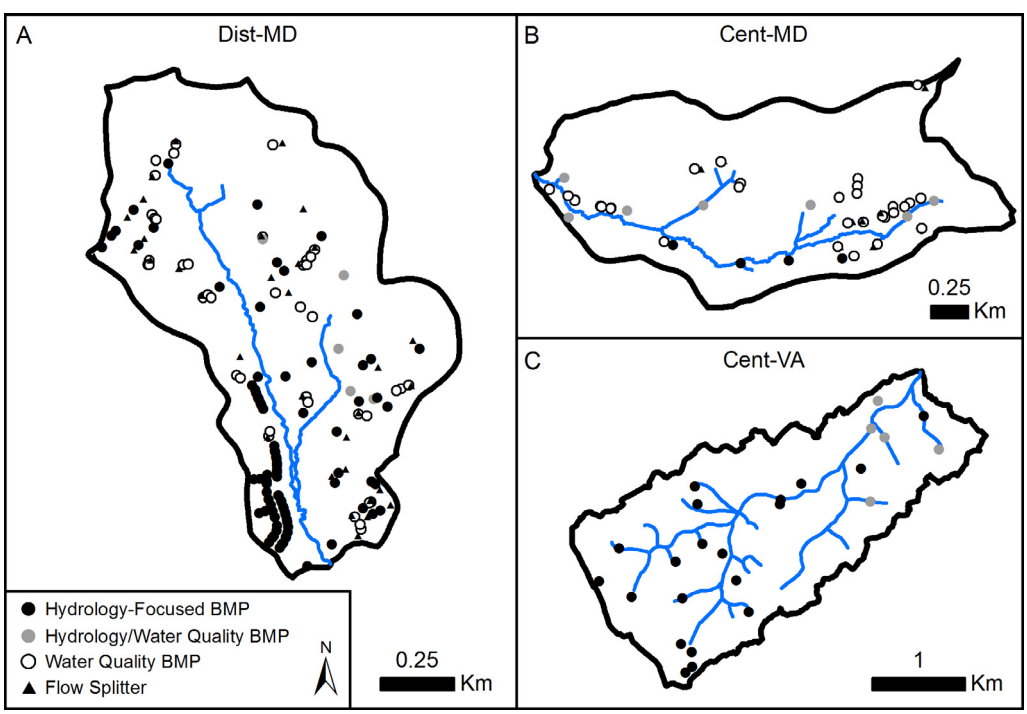

Fig. A1. Map of stormwater BMPs in the Dist-MD (A), Cent-MD (B), and Cent-VA (C) study catchments. *Notes*: stormwater BMP data for the Maryland catchments were obtained from Montgomery County, MD Department of Environmental Protection and the Planning Department; data for the Cent-VA catchment were courtesy of the Fairfax County, VA Department of Public Works and Environmental Services.

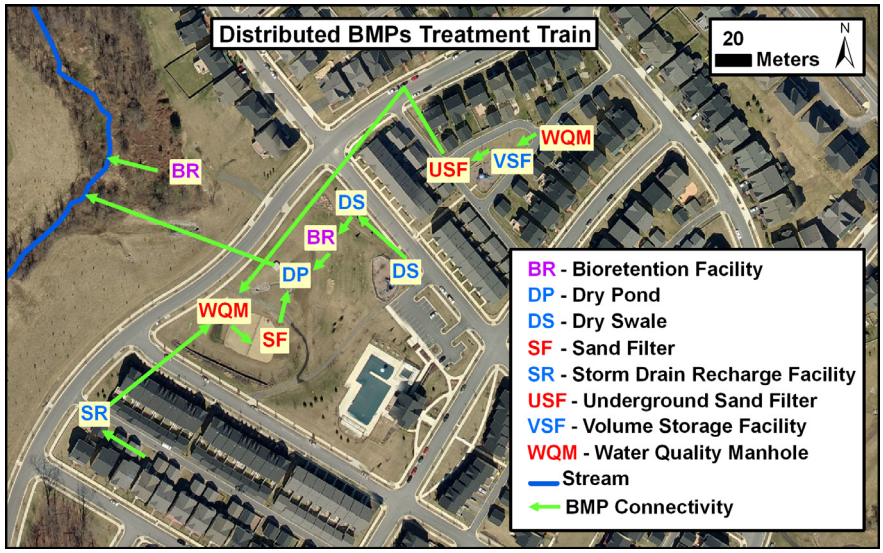

Fig. A2. Example of a distributed stormwater BMP treatment train on the landscape with BMPs located above and below ground. Stormwater runoff is collected through traditional curb and gutter inlets, directed through the treatment train, and is discharged to the stream riparian zones from the terminal dry pond BMP. Blue font indicates hydraulic-control BMPs, red font indicates water quality BMPs, and purple font indicates stormwater BMPs that provide both hydraulic control and water quality treatment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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