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SI URBAN HYDROLOGY

Evaluation of infiltration-based stormwater management to restore hydrological processes in urban headwater streams

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Abstract
Urbanization threatens headwater stream ecosystems globally. Watershed restoration practices, such as infiltration-based stormwater management, are implemented to mitigate the detrimental effects of urbanization on aquatic ecosystems. However, their effectiveness for restoring hydrologic processes and watershed storage remains poorly understood. Our study used a comparative hydrology approach to quantify the effects of urban watershed restoration on watershed hydrologic function in headwater streams within the Coastal Plain of Maryland, USA. We selected 11 headwater streams that spanned an urbanization–restoration gradient (4 forested, 4 urban-degraded, and 3 urban-degraded) to evaluate changes in watershed hydrologic function from both urbanization and watershed restoration. Discrete discharge and continuous, high-frequency rainfall-stage monitoring were conducted in each watershed. These datasets were used to develop 6 hydrologic metrics describing changes in watershed storage, flowpath connectivity, or the resultant stream flow regime. The hydrological effects of urbanization were clearly observed in all metrics, but only 1 of the 3 restored watersheds exhibited partially restored hydrologic function. At this site, a larger minimum runoff threshold was observed relative to the urban-degraded watersheds, suggesting enhanced infiltration of stormwater runoff within the restoration structure. However, baseflow in the stream draining this watershed remained low compared to the forested reference streams, suggesting that enhanced infiltration of stormwater runoff did not recharge subsurface storage zones contributing to stream baseflow. The highly variable responses among the 3 restored watersheds were likely due to the spatial heterogeneity of urban development, including the level of impervious cover and extent of the storm sewer network. This study yielded important knowledge on how restoration strategies, such as infiltration-based stormwater management, modulated—or failed to modulate—hydrological processes affected by urbanization, which will help improve the design of future urban watershed management strategies. More broadly, we highlighted a multimetric approach that can be used to monitor the restoration of headwater stream ecosystems in disturbed landscapes.

KEYWORDS
hydrologic connectivity, restoration, stormwater, stream ecosystems, urbanization, watershed storage

1 | INTRODUCTION

Watershed storage controls the flow regime in downstream channels, which in turn shapes the structure and function of their aquatic ecosystems (Bunn & Arthington, 2002; Poff et al., 1997). Many factors control watershed storage, such as geology, soils, and topography (Sayama, McDonnell, Dhakal, & Sullivan, 2011), vegetation and climate (Christensen, Tague, & Baron, 2008), and antecedent moisture conditions (Tromp-van Meerveld & McDonnell, 2006). A suite of hydrological processes contribute to watershed storage, including retention in depressional areas (Phillips, Spence, & Pomeroy, 2011); infiltration and redistribution in the unsaturated zone (Rimon, Dahan, Nativ, & Geyer, 2007); and the removal of water from these storage zones by deep percolation to groundwater, evapotranspiration, and routing of water to streams via surface and subsurface flow pathways. The type, size, and spatial distribution of storage zones across a watershed control the magnitude of rainfall partitioning into runoff, as well as spatial and temporal patterns of runoff delivery to streams (Wagener, Sivapalan, Troch, & Woods, 2007).

Landscape disturbances, such as urbanization, can profoundly alter watershed storage. During urbanization, impervious surfaces replace soil and vegetated surfaces, thereby reducing infiltration opportunities into subsurface storage zones (Gregory, Dukes, Jones, & Miller, 2006). Urbanization increases and concentrates runoff, leading to the need for centralized drainage to route runoff directly to streams (Leopold, 1968). As a result, urban streams experience more frequent high flows with greater peak discharge and runoff volumes, altered groundwater recharge rates, and more synchronous flowpaths delivering runoff to the stream channel than reference watersheds (Rose & Peters, 2001; Walsh, Fletcher, & Burns, 2012). Altered flow regimes in urban streams can affect sediment transport processes, thereby degrading aquatic habitat and reducing aquatic biodiversity, a globally documented phenomenon known as the "urban stream syndrome" (Booth & Jackson, 1997; Paul & Meyer, 2001; Walsh et al., 2005b). Whether watershed management practices implemented in urban landscapes can sufficiently increase lost watershed storage remains an open question (Bernhardt & Palmer, 2007; Palmer & Bernhardt, 2006; Shuster & Rhea, 2013; Walsh et al., 2005b).

Urban watershed management practices vary greatly in design, but most share the goal of mitigating the effects of stormwater runoff on streams (MDE, 2009). First-generation stormwater best management practices (or BMPs), such as wet or dry ponds, were designed to reduce peak flows by temporarily retaining runoff generated in the watershed and releasing it slowly over time (Burns, Fletcher, Walsh, Ladson, & Hatt, 2012). These practices, however, often fail to fully mitigate the effects of stormwater runoff (Hancock, Holley, & Chambers, 2010), and stormwater runoff remains a major stressor to urban stream ecosystems (NRC, 2001). In response to continued urban stream ecosystem degradation, stream ecologists have called for watershed management to focus on restoring the entire flow regime in order to recover stream ecosystem function (Walsh et al., 2005a, 2016). To achieve this, stormwater management projects should enhance watershed storage and minimize hydrologic connectivity between impervious surfaces and stream ecosystems (Walsh, Fletcher, & Ladson, 2009). Newer stormwater management approaches that emphasize infiltration, evapotranspiration, and distributed storage may have the greatest potential for restoring streamflow patterns (Holman-Dodds, Bradley, & Potter, 2003; Hood, Clausen, & Warner, 2007). For example, site-scale studies on individual bioretention basins demonstrated their effectiveness for both runoff reduction and pollutant retention (Davis, Hunt, Traver, & Clar, 2009; Hunt, Jarrett, Smith, & Sharkey, 2006). Other infiltration-based stormwater BMPs, such as permeable pavement (Brattebo & Booth, 2003), green roofs (VanWoert et al., 2005), and, most recently, regenerative stormwater conveyances or RSCs (Cizek, 2014; Palmer, Filoso, & Fanelli, 2014) have shown the potential for reducing runoff and improving water quality.

Many of these studies on stormwater management practices are conducted as case studies and often lack reference sites, making it difficult to identify factors beyond the site that may affect performance. For example, a recent synthesis highlighted the important role local hydrological conditions play in the effectiveness of watershed management practices to reduce nitrogen loading (Koch, Febria, Gevrey, Wainger, & Palmer, 2014). In contrast, comparative hydrological studies across known environmental gradients are powerful for identifying factors that might be affecting watershed management performance. Urban watershed hydrology remains rich with opportunities which can both support basic discovery about watershed hydrological processes in disturbed landscapes (Burt & McDonnell, 2015), and address urgent watershed management issues if these are explicitly included in the study design.

The objective for this study was to understand how stormwater management practices mitigate hydrological processes impacted by urbanization. Specifically, we sought to (a) quantify the changes in watershed hydrologic function due to both urbanization and stormwater management implementation; (b) identify watershed characteristics that influence the hydrological processes supported within the stormwater management practices; and (c) identify key hydrologic metrics that can be applied in future urban hydrology field studies to assess watershed hydrologic function. We developed hydrologic metrics to describe watershed storage, flowpath connectivity, and the resulting stream flow regime in 11 headwater watersheds spanning an urbanization–restoration gradient. We used regenerative stormwater conveyance systems (RSCs) systems as an example stormwater BMP for this study, which are an emerging approach being widely adopted in the mid-Atlantic region to restore urban streams.

2 | METHODS

2.1 | Study site description

This study was conducted in the greater Annapolis region, Maryland, USA (Figure 1). This region is an urbanized area within the Coastal Plain physiographic province, where subsurface geology is composed of mainly unconsolidated marine sediments, primarily sands, silts, and clay (Angier, McCarty, & Prestegaard, 2005). Precipitation falls mostly as rainfall with an annual average of 1120 mm, evenly distributed throughout the year. Throughout the study area, urban development is drained by pipes to storm sewer outfalls, which discharge into ephemeral first-order streams. RSC systems, which are the focus of this study, have been implemented between many of these storm sewer outfalls and the channel head of first-order streams to manage stormwater runoff (Palmer et al., 2014).

By design, RSCs have the potential to increase both surface detention storage and the infiltration of runoff through the seepage bed (Flores, Markusic, Victoria, Bowen, & Ellis, 2009), which, if effective, could lead to increased watershed storage and restore a more natural flow regime in the perennial channel below. RSCs are composed of a series of connected infiltration pools underlain by a seepage bed

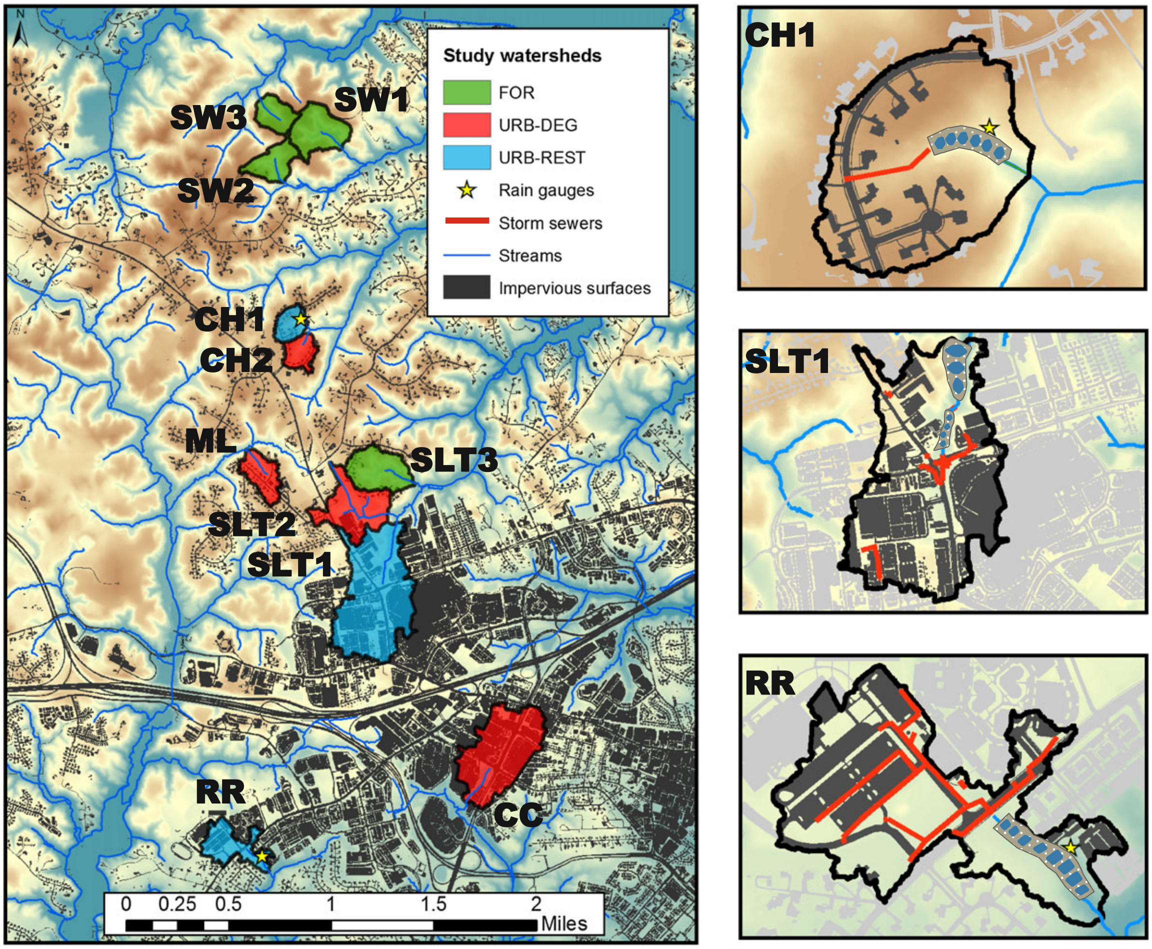

FIGURE 1 Site map of the 11 watersheds and locations of rain gauges within the study area (left), and additional site details of the three restored watersheds (right three panels), including storm sewer networks and location of the watershed restoration practice (depicted by blue pools)

constructed of sand and organic matter, similar to the porous media used in bioretention basins (Davis et al., 2012). Although their design borrows concepts of bioretention, RSCs differ from bioretention in their placement within the landscape. Bioretention basins are typically placed in the upland portions of the watershed near sources of runoff, whereas RSCs are often placed in topographic depressions within the drainage network.

All study watersheds are drained by first-order perennial streams. Four of the 11 study watersheds have less than 10% impervious cover and no stormwater infrastructure, and therefore serve as "forested" or reference sites (Figure 1; Table 1). The remaining seven watersheds have varying levels of urbanization (20–76.7% total impervious cover) and storm sewer networks. Three of the seven urban watersheds have been implemented with an RSC watershed restoration project between the main storm sewer outfall and the downstream channel (Figure 1 insets). For these structures to comply with state water quality regulations (MDE, 2009), they must provide adequate storage for runoff generated from a 1-in., 24-hr rainfall event; the storage is a combination of surface storage in pools and subsurface storage in the seepage bed.

Five of the 11 urbanized watersheds do contain additional smaller stormwater BMPs. These BMPs were implemented in the upland portions of each watershed and, collectively, drain very small portions of these watersheds (between 0% and 8% of the contributing areas; Table SI-II). The exception is the SALT1 (an urban-restored watershed), whose watershed includes upland BMPs draining 12.9% of the watershed area. Because we are most interested in the effects of the RSC watershed restoration projects, we discounted the impervious cover values for watersheds containing these upland BMPs to remove the redundant effect of imperious cover treated by both upland BMPs and the RSC (see Section A of the Supporting Information for details on how this adjustment was made). The adjusted impervious cover values reflect impervious cover not treated by anything other than the RSC restorations. Although impervious cover was adjusted down in some watersheds (Table 1), the adjustment did not alter the relative magnitude of imperious cover among the watersheds (so the order remained the same). Untreated impervious cover was used for all subsequent statistical analyses in this study.

2.2 | Field data collection

We monitored precipitation, stream stage, channel morphology, and baseflow discharge to develop a set of hydrologic metrics to directly compare across the study watersheds. Hydrologic metrics derived from streamflow records have long been used to quantify changes in the flow regime from landscape disturbances (Richter, Baumgartner, Powell, & Braun, 1996). Stage-based monitoring has been used as an alternative to discharge time series to assess hydrological effects of

TABLE 1 Watershed characteristics for the 11 streams in the study area

Site ID	Watershed type	Watershed area (ha)	Impervious area (%)	Adjusted (untreated) impervious area (%)[c]
SW3	Forest	6.9	1.0	1.0
SW1	Forest	13.1	1.9	1.9
SW2	Forest	8.5	4.9	4.9
SALT3	Forest	13.9	8.6	8.5
SALT2	Urban-degraded	18.6	22.0	21.5
CH1[a]	Urban-restored	5.4	22.2	22.2
ML	Urban-degraded	8.0	22.5	22.5
CH2	Urban-degraded	5.6	23.2	23.2
RR[a]	Urban-restored	11.4	43.0	40.0
SALT1[b]	Urban-restored	48.8	59.0	50.7
CC	Urban-degraded	33.5	76.7	65.9

Note. BMP = best management practices; RSC = regenerative stormwater conveyances.

[a]Implemented with vertical storage RSC watershed restoration (see text for details).

[b]Implemented with lateral storage RSC watershed restoration.

[c]Impervious cover was adjusted to account for existing urban BMPs in SALT1, SALT2, SALT3, CC, and RR watersheds. See text and Supporting Information for additional information.

land use–land cover changes (McMahon, Bales, Coles, Giddings, & Zappia, 2003; Roy et al., 2005; Shuster, Zhang, Roy, Daniel, & Troyer, 2008). There are trade-offs between using stage data or discharge data for characterizing hydrologic processes. Discharge is required for quantifying runoff volumes, which is often used to assess hydrologic performance of stormwater BMPs. However, developing a stage–discharge rating curve in urban headwater streams is difficult because short-lived runoff peaks (minutes to hours) often hinder the full development of stage–discharges relationship, or yields one with high uncertainty (Harmel, Cooper, Slade, Haney, & Arnold, 2006). Stage-based metrics, on the other hand, coupled with high-frequency rainfall monitoring, can be used to quantify *relative* differences in hydrologic responses among many watersheds with contrasting characteristics. For this study, we were interested in the relative differences in hydrologic responses among adjacent watersheds with contrasting land cover and management practices, so we used stage-based metrics as a research tool.

Gauging stations for continuous, high-frequency stage monitoring (June 2014–June 2015) were established at the stream outlets of the 11 watersheds. Stream stage was recorded by using unvented pressure transducers (Onset Computer Corporation, Bourne, MA, USA) suspended by steel cables inside of perforated polyvinyl chloride pipes driven into the channel thalweg. Absolute pressure in the stream channels (water level + barometric) was measured using Hobo water level models U20-001-4 (accuracy = ±0.6 cm; resolution = 0.14 cm). All stream pressure datasets were compensated for barometric pressure, which was measured at two locations in the study area using the Hobo water level logger U20L-04 model (accuracy = ±0.4 cm; resolution = 0.14 cm). Time series of barometric pressure at the two locations were nearly identical, and so barometric pressure data from one station were used to correct the stream pressure data. Both pressure transducer models self-correct for temperature. Stage data were collected at 3-min intervals from June 20 to August 14, 2014, and at 2-min intervals from August 14, 2014, until June 20, 2015, to further resolve rapid changes in stage. Streambed aggradation and erosion was monitored monthly by measuring the vertical distance between the top of the pipe and the streambed height.

Baseflow discharge was measured monthly during the monitoring period using the velocity-area method (Marsh McBirney electromagnetic current meter model 201D). Baseflow conditions were defined to be at least 24 hr after a rainfall event, and stage hydrographs were analysed for each discrete discharge measurement to ensure measurements were not taken during unsteady hydrological conditions (e.g., receding limb from a previous storm). Two rain gauges (Onset Hobo model RG3-M) were deployed at the northern and southern ends of the study area where there was no overlying canopy (Figure 1). These recorded the timestamps of each 0.2 mm of rainfall. Daily rainfall totals from these gauges were compared to those from nearby citizen science rain gauges (Community Collaborative Rain, Hail, and Snow network, or CoCoRHAS). Precipitation records were interpolated to 5-min rainfall totals to quantify rainfall intensities, but raw timestamps were used for delineating the duration of individual rainfall events.

Individual rainfall events were defined as a period of rainfall separated by at least a 5-hr rain-free period (otherwise known as minimum inter-event time [MIT]); the 5-hr MIT is similar to the widely used 6-hr MIT (Dunkerley, 2008, 2015). We initially explored the effect of variable MIT duration on rainfall event characteristics (see Section B of the Supporting Information for additional results from this analysis). Ultimately, a 5-hr MIT was chosen because it prevented the aggregation of smaller events into single, larger events (Figures SI-4A and SI-4B). This enabled us to examine rainfall–runoff responses under a wide range of rainfall event sizes (Figure SI-6). Only rainfall events with similar rainfall totals and cumulative rainfall patterns at both rain gauges were retained for the analysis to ensure complete and even coverage of the rainfall events across the entire study area (Figure SI-5). In total, 81 rainfall events were defined using these criteria and were evenly distributed across the four seasons. Storm duration, total rainfall, average and maximum rainfall intensity, and a 24-hr antecedent precipitation index (e.g., rainfall total for the previous 24 hr) were quantified for each of the 81 rainfall events.

2.3 | Hydrologic metric descriptions

We developed six metrics to assess changes in watershed hydrological responses across the 11 streams: (a) mean annual baseflow, (b) minimum runoff thresholds, (c) rainfall–runoff lag times, (d) duration of stormflow hydrographs, (e) runoff frequency, and (f) a flashiness index. *Mean annual baseflow* expresses long-term hydrologic storage of a watershed (Bhaskar et al., 2016; Roy et al., 2005) and was calculated as follows:

$$mean\ annual\ baseflow = \frac{1}{n}\sum_{i=1}^{n}\frac{bf_i}{A}$$

where *bf* is the monthly discrete baseflow measurement (litre per second), *A* the watershed area (hectares), and *n* the number of measurements taken during the monitoring period (12). *Minimum runoff thresholds* for each watershed were used to quantify the apparent storage capacity of the watershed during rainfall events (Ali et al., 2015; Hood et al., 2007; Loperfido, Noe, Jarnagin, & Hogan, 2014). Minimum runoff thresholds were identified as breakpoints from a piecewise regression between rainfall depth and the change in stage during the rainfall event for each of the 81 rainfall events (see Figure SI-3 for examples). Breakpoints were quantified using the segmented package in R and identified as the rainfall depth at which a shift in rainfall-stage response occurs (i.e., between the first and second regression lines; Figure SI-3). We hypothesized that, if the restorations were effective at enhancing storage of runoff in the watershed, we would observe greater thresholds relative to the urban-degraded watersheds due to the complete retention of runoff from smaller events. If significant portion of the runoff retained by the restoration infiltrates into groundwater storage zones, then an increase in mean annual baseflow might occur as well, indicating an increase in longer term watershed storage.

Rainfall-runoff lag times have often been used to describe changes in hydrological responses from land use change (Hood et al., 2007; Leopold, Wolmon, & Miller, 1964). Storm sewer networks and gullies increase surface flowpath connectivity and flow velocity, thereby reducing lag times between rainfall inputs and stream responses. We hypothesize that the RSCs in the study area may infiltrate and retain substantial runoff over the course of a rainfall event, thereby increasing lag times (Jarden, Jefferson, & Grieser, 2016). Lag times for this study were calculated as the time between the centre of rainfall mass (50th percent of the cumulative rainfall for the event; the hyetograph centroid) and the stream stage hydrograph peak (Hood et al., 2007). Only rainfall events that generated a runoff response (operationally defined as a 1-cm rise in stage or greater) at all sites were used initially (n = 17 events). These events were further limited to those with simple rainfall patterns (single peak, shorter duration, etc.) that facilitated the lag time analysis.

Similar to lag times, *storm hydrograph durations* are often shorter in urbanized watersheds (Hopkins et al., 2015; Leopold, 1968) due to higher flowpath connectivity from storm sewer networks. The RSC restorations could increase storm hydrograph durations by retaining stormwater runoff and releasing it more slowly during a rainfall event. Average storm hydrograph durations were calculated as follows:

$$Mean\ hydrograph\ duration = \frac{1}{n}\sum_{i=1}^{n}(te_i - ts_i)$$

where *ts* denotes the beginning time of the storm hydrograph (defined as when stage increases more than 1 cm following a rainfall event) and *te* denotes the time when stage returns to pre-event stage conditions, and n is the number of rainfall events to which the stream responded. Pre-event stage conditions was defined as the mean stage for 1-hr prior to the rainfall event.The frequency of high-flow events, or *runoff frequency*, has been associated with increased urbanization (Hopkins et al., 2015; McMahon et al., 2003). Runoff frequency may be mitigated by the RSCs if they are completely infiltrating runoff generated during some rainfall events. Runoff frequency was calculated as follows:

$$Annual\ runoff\ frequency = 100\times\frac{n_{\text{runoff}}}{n_{\text{rainfall}}}$$

where n_{runoff} is the number of rainfall events that generated a 1-cm or greater change in stage, and n_{rainfall} is the total number of rainfall event during the monitoring period. Most changes in stream stage during rainfall events were well above 1 cm (Figure SI-2). A related metric to runoff frequency is *flashiness*, which is a measure of the rate-of-change of streamflow (Baker, Richards, Loftus, & Kramer, 2004). Flow variability, or flashiness, describes how quickly stage or discharge changes during runoff events (Poff et al., 1997). Flashy hydrographs can reduce streambank stability, which can cause bank erosion and channel widening (Konrad, Booth, & Burges, 2005), as well as wash-out of biofilms and drift of macroinvertebrate communities that lack access to flow refugia (Biggs & Close, 1989; Lancaster & Hildrew, 1993). We hypothesized that flashiness would be lower in sites with RSCs due to enhanced retention of runoff through surface or subsurface storage. A flashiness index was quantified as follows:

$$Mean\ Flashiness = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\Delta\text{stage}_i}{\Delta\text{time}_i}\times\frac{1}{WD}\right)$$

Where Δstage = peak stage − stage at the start of the rising limb, Δtime = time at peak − time at the start of the rising limb, WD = the width-depth ratio of the channel, and n = number of rainfall events. Given that this metric explicitly uses changes in stage to compare across sites, we normalized each site's rate-of-change value for their channel's width–depth ratio (WD). Channel WDs were derived from channel cross-sectional surveys competed at each site in July 2014.

2.4 | Statistical analysis

All statistical analyses were conducted using R (version 3.2.0). Inspection of residuals determined that two metrics were not normally distributed (flashiness and minimum runoff thresholds), and these two metrics were natural-log transformed before performing any statistical analyses. Analysis of variance was first conducted on select metrics to test for differences among watershed types (forest, urban-degraded, and urban-restored). Next, we used mixed effects linear regression to test for the effects of percent impervious cover, categorical restoration status (yes or no), and any interaction between impervious cover and restoration status. Watershed area was included in the linear regression models as a continuous covariate. Next, we conducted a principal component analysis on the six metrics using the princomp function in R to reduce the dimensionality of the six response variables (hydrologic metrics). We used the variable loadings to identify the hydrologic metrics that explained the majority of the variability in the dataset and to explore how the 11 watersheds were distributed in the multivariate space bounded by these metrics. Prior to the principal components analysis (PCA), the metrics were centred (means were removed) and standardized (standard deviation was scaled to 1). Finally, we conducted a linear regression analyses between watershed characteristics (impervious cover, restoration status, and watershed area) and the scores of the first two principal components (PC1 and PC2). PC scores are the weighted linear combination of all the metrics included in the PCA and therefore represent the overall hydrological responses at each site. This analysis enables us to test for any watershed characteristics that may explain the overall hydrologic responses across the study sites.

3 | RESULTS

3.1 | Assessing the effects of urbanization

Mean annual baseflow declined with impervious cover (Table 2) and was almost three times higher in the forested watersheds than in the urban-restored or urban-degraded watersheds (Figure 2a; $p < .002$). Mean annual baseflow at each watershed was highly correlated with mean summer baseflow (summer = July, August, and September months; $R^2 = 0.96$; $p < .001$). Mean summer baseflow was also significantly greater in the forested watersheds than that in the two urban watershed groups ($p < .004$). Among the urban watersheds, SALT1 (urban-restored) and CC (urban-degraded) had the greatest mean annual baseflow (0.053 and 0.052 L/s·ha, respectively), though both were still more than 25% lower than that of the forested watershed with the lowest mean annual baseflow (SW3, mean = 0.072 L/s·ha). Variability in monthly baseflow was also greatest in the forested watersheds (Figure 2a), and the highest baseflow rates were observed in the largest forested catchments (SW1 and SALT3).

TABLE 2 Linear regression results describing the effect of impervious cover restoration status, and watershed area on the six hydrologic metrics and the first two principal components from the principal components analysis

	Estimates for model predictors				Model fit	
Response variable	Imp	Rest	Area	Imp * Rest	Adj R^2	*p* value
Baseflow	**−0.002***	0.01	**0.003***	−0.001	.50	.08
Threshold	**−0.08***	**29.9*****	**0.14***	**−0.68*****	.92	.0004
Frequency	**0.81****	**−67.3****	−0.37	**1.45***	.87	.002
Lag time	**−0.06***	1.48	**0.12****	−0.02	.68	.02
Flashiness	**0.04****	−1.37	0.01	0.03	.87	.002
Duration	**−0.19****	**14.5***	0.20	**−0.33***	.67	.03
PC1	**0.09*****	**−7.9****	−0.06	**0.18****	.88	.002
PC2	**0.06****	0.92	**−0.11***	−0.02	.72	.02

Note. Model coefficients in bold indicate a significance, given α = .05.

*$p < .05$.

**$p < .01$.

***$p < .001$.

Breakpoints for identifying *minimum runoff thresholds* were identified in nine of the 11 watersheds, indicating threshold hydrologic behaviour in response to rainfall (Figure 3a). The two watersheds that did not exhibit runoff threshold behaviour, CC and CH2, were both urban-degraded watersheds. Their rainfall-stage responses exhibited log-linear increases in runoff as a function of rainfall depth. For these sites, we used the smallest rainfall event that generated a runoff response as the minimum runoff threshold. Therefore, these two sites do not have confidence intervals associated with their runoff threshold (Figure 3a). Minimum runoff thresholds ranged from as high as 15 mm (CH1, urban restored) to as low as 0.52 mm (CC, urban degraded). Across the sites, thresholds declined with increasing impervious cover (Table 2, Figure 3a).

Centroid lag-to-peak times were significantly correlated with watershed area ($p < .002$); as lag time is well known to increase with basin area (Leopold, 1968) and the study sites spanned a fairly large range in area (Table 1), lag times were normalized by watershed area for the final regression analysis. As expected, area-normalized lag times declined with increasing impervious area (Table 2, Figure 2b), which is consistent with other studies that examined lag times and urbanization (Hood et al., 2007). The shortest lag times were observed at CH2 (urban-degraded; mean lag time = 1.6 min/ha, or 20.4 min) whereas the longest area-normalized lag times were measured at SALT1 (urban-restored; mean lag time = 5.8 min/ha, or 44.7 min for the area-normalized or raw mean lag time, respectively). Even after normalizing lag times for watershed area, it was still a significant predicator in the model ($p < .01$; Table 2) largely due to the high leverage of one site (SALT1; Figure 2b).

Average hydrograph duration ranged from 10 to 19 hr (Figure 3c). The shortest duration was observed at ML, an urban-degraded site, and the longest was observed at CH1, an urban-restored site. Forested watersheds had, on average, significantly longer runoff durations than did the urban-degraded watersheds ($p < .02$). Greater *runoff frequency* was observed with increasing impervious cover (Table 2). The percentage of rainfall events that generated a runoff response in the study watersheds ranged from 33% to 90% (27 to 69 of the 81 events during the 1-year period; Figure 3b), which translates into runoff events as frequently as every 5 days (CC, urban degraded) to 13 days (CH1, urban restored). Watershed area was significantly correlated with the *flashiness index* ($p < .01$); therefore each flashiness index value was normalized by site watershed area. We observed that area-normalized flashiness indices increased with impervious cover across the study area ($p < .001$; Figure 2c) with the highest mean flashiness index observed at CC (urban degraded) and the lowest index at SW3 (forested).

3.2 | Assessing the effects of the watershed restoration projects

We observed significant effects of watershed restoration implementation in minimum runoff thresholds, runoff frequency, and storm hydrograph duration. For these three metrics, the regression model coefficient for restoration status indicated a mitigation of the urbanization effect (Table 2). Minimum rainfall thresholds declined with increasing impervious cover, but sites implemented with restorations

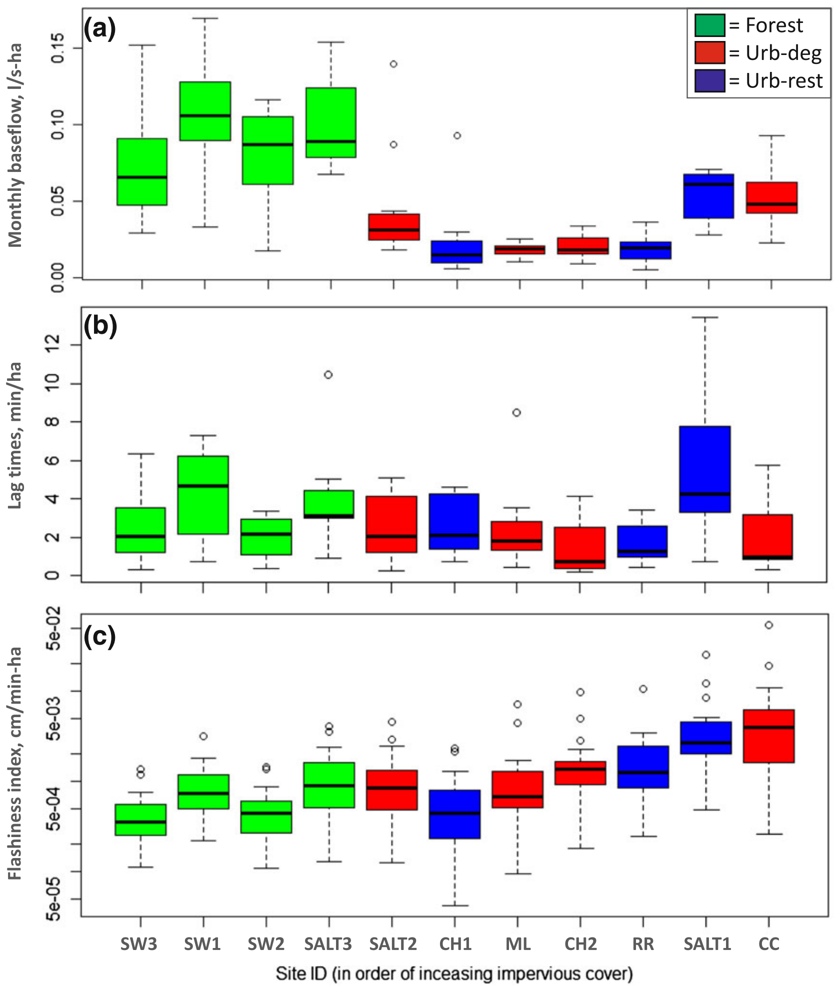

FIGURE 2 Boxplots for (a) baseflow normalized by catchment area (L/s·ha; n = 12), (b) centroid to peak lag time normalized by catchment area (min/ha; n = 7 events), and (c) flashiness index (cm/min·ha; n = 17) for the 11 watersheds. Flashiness index (cm/min·ha) is the mean rate of change (cm/min) for a hydrograph rising limb, normalized by the stream channel width–depth ratio and watershed area (ha). Sites are ordered from lowest to highest impervious cover and shaded by watershed type. See Table 1 for watershed impervious cover percentages

had, on average, higher thresholds than expected for their impervious surface area (Table 2). Similarly, these results indicate that the hydrological processes affected by restoration activities may lower runoff frequency and lengthen hydrograph durations. However, the interaction term between impervious cover and restoration status was significant for all three of these metrics. In each case, the interaction sign was in the opposite of the restoration coefficient, suggesting that the restoration effect diminished with increasing impervious cover. Figure 3 further illustrates that the restoration effect observed in these three metrics is likely driven by only one watershed (CH1).

3.3 | Correlation among hydrologic metrics

Not surprisingly, several of the hydrologic metrics were correlated with one another (Table 3). Minimum runoff thresholds were highly correlated with runoff frequency, because streams draining watersheds with lower runoff thresholds will exceed their storage capacity and respond to rainfall events more frequently. The strong correlation between storm hydrograph duration and the flashiness index may reflect the shifts in runoff delivery processes within the watersheds as they are urbanized. Storm sewers systems extend the drainage network upstream into the watershed above stream channels, and the low roughness of pipes creates short travel times within these efficient drainage networks. The resulting hydrographs are thereby short in duration, with steep rising limbs indicating much greater rates of change (and, presumably, greater peak discharges). These four metrics (minimum runoff thresholds, runoff duration, runoff frequency, and flashiness index) collectively describe changes in available hydrologic storage and the resulting changes in the runoff hydrograph. Interestingly, none of these storm-event-based metrics were significantly correlated with mean annual baseflow, which suggests the storm hydrograph metrics and the baseflow metric may indeed be capturing different hydrological processes at different scales (e.g., short-term event scale processes vs. longer term storage processes).

3.4 | Principal components analysis

We used a PCA to clarify redundancy in the metrics and identify those with high potential to explain overall differences in hydrologic responses among the 11 watersheds. The first two components of the PCA explained approximately 87% of the total variability in the overall dataset (Figure 4). The first principal component (PC1) explained 60% of the variance, and the four storm-event-based metrics discussed above were all highly loaded onto this component (Table 4). Runoff frequency explained the greatest amount of variance within this component. Principal component 2 (PC2) explained 27% of the overall variance, and mean annual baseflow and lag times loaded highest on this component (Table 4). In general, the forested

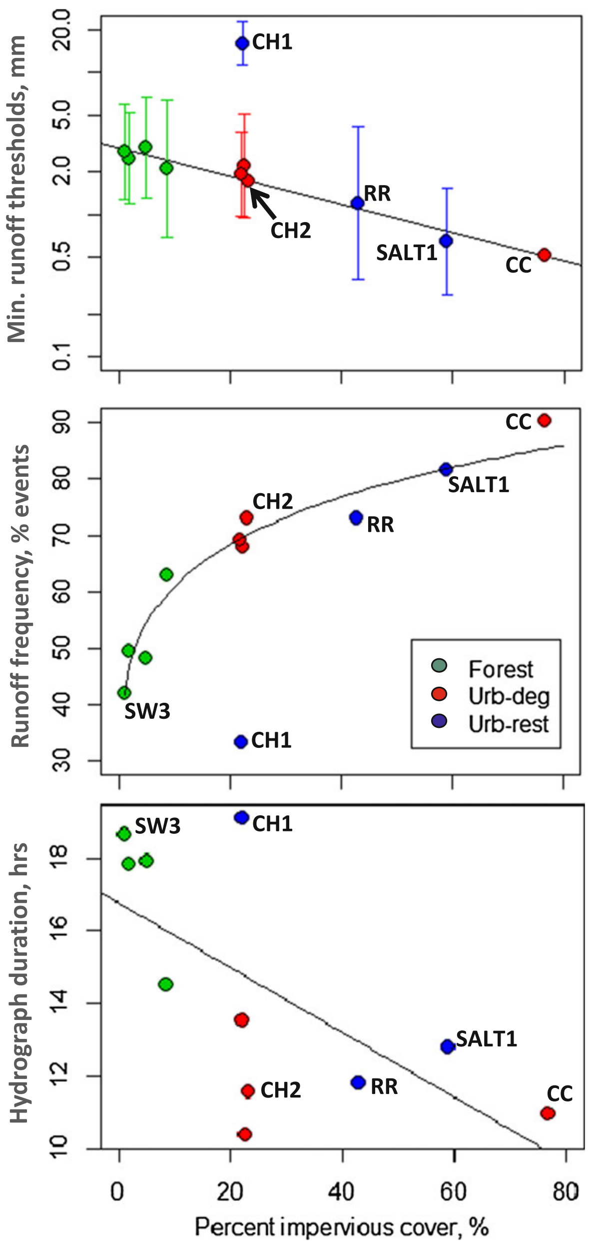

FIGURE 3 Percent impervious cover versus (a) minimum runoff thresholds (mm rain), (b) runoff frequency (percentage of rainfall events), and (c) mean duration of runoff events (hr). For minimum runoff thresholds, whiskers indicate 5th and 95th percentile confidence intervals for thresholds identified through a breakpoint analysis

watersheds clustered on the low end of PC1 and PC2, whereas the urban-degraded watersheds clustered at the upper end of PC1 and PC2 (Figure 4). The urban-restored watersheds varied widely in their overall placement along PC1 and PC2, indicating variable effects of watershed restoration on the hydrological metrics across the three sites. Impervious cover was significantly related to both PC1 and PC2 scores, indicating that impervious cover may explain the majority of the variance in the combined metrics. We also observed a positive restoration effect (as seen in thresholds and runoff frequency), as well as a significant interaction between restoration and impervious cover for PC1 scores. Finally, watershed area was correlated with PC2 scores.

TABLE 3 Correlation matrix for the six hydrologic metrics

	Baseflow	Threshold	Frequency	Lag time	Flashiness
Threshold	−0.05				
Frequency	−0.26	**−0.90*****			
Lag time	0.47	−0.18	0.07		
Flashiness	−0.23	**−0.82****	**0.92*****	0.21	
Duration	0.50	**0.71***	**−0.91*****	0.11	**−0.77****

Note. Correlation coefficients in bold indicate a significance, given α = .05.

*p > .05.

**p > .01.

***p > .001.

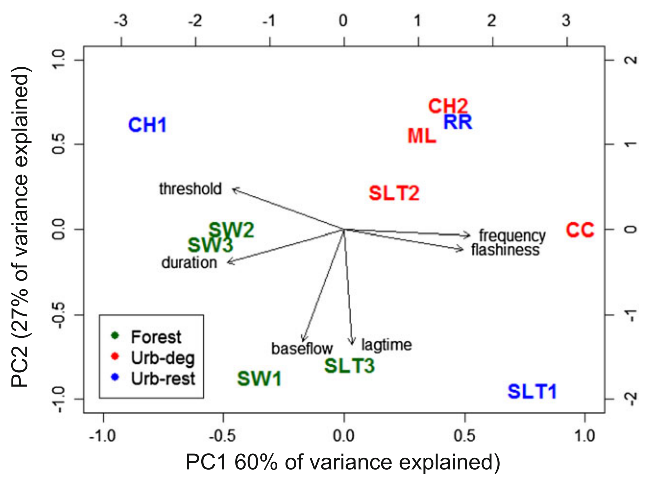

FIGURE 4 Results of a principal component analysis on the six hydrological metrics. Black arrows indicate how the metrics load on PC1 (x axis) and PC2 (y axis). Individual sites are indicated by their site ID (Table 1)

4 | DISCUSSION

Uncontrolled urban stormwater is a pervasive global issue, but the extent to which this problem has been addressed varies dramatically among regions. Source control approaches have been advocated for and used in Australia (Hamel et al. 2013), with the goal of capturing urban runoff near its origin through the use of infiltration-based systems distributed throughout the watershed. In Europe, the Water Framework Directive raised awareness of the need for new approaches mitigating the impacts of stormwater runoff (CEC, 2000). However, Perales-Momparler and others (2015) have identified barriers to the widespread adoption of sustainable urban stormwater management practices in the Mediterranean. In the United States, the implementation of green infrastructure to manage stormwater has been widely encouraged (https://www.epa.gov/green-infrastructure). In the mid-Atlantic United States, decisions regarding approaches to manage stormwater are driven by total maximum daily load requirements to reduce nitrogen, phosphorus, and sediment loading into Chesapeake Bay (EPA, 2011), and these RSCs are among the approved BMPs for which jurisdictions can receive water quality credits. However, much remains unknown

TABLE 4 Loadings for the first two principal components

Metric name	PC1	PC2
Baseflow	−0.17	**−0.66**
Threshold	−0.47	0.24
Frequency	**0.52**	−0.03
Lag times	0.03	**−0.68**
Flashiness	0.49	−0.12
Duration	−0.49	−0.19

Note. Variables in bold have loadings greater than 0.5.

about their performance, and this study is an important contribution to understanding their role in altering hydrological processes in urban watersheds.

A primary goal of this study was to develop stage-based metrics that could detect the hydrological effects of urbanization. The linear regression results indicate that all hydrological metrics in the study were sensitive to urbanization. Mean annual baseflow, minimum runoff thresholds, lag times, and runoff event duration all decreased with increasing impervious cover, while runoff frequency and flashiness increased. Although changes in baseflow in response to urbanization are complex (Bhaskar et al., 2016; Price, 2011), lower mean annual baseflow observed in the urban streams is consistent with other studies conducted in the humid Eastern United States (Rose & Peters, 2001). Minimum runoff thresholds quantified in this study are within the range of thresholds observed in other urban watersheds. Loperfido and others (2014) identified thresholds for urbanized mid-Atlantic watersheds ranging from 7.5 to 11 mm, though these watersheds were larger in size (110–700 ha). In smaller urban watersheds, Hood and others (2007) measured minimum runoff thresholds ranging from 0.9 to 6.0 mm. Declining runoff hydrograph durations with increasing urbanization has also been documented in several U.S. metropolitan regions (Hopkins et al., 2015). Increased runoff frequency and flashiness indices with impervious cover have been documented elsewhere in the United States as well as globally (Hopkins et al., 2015; Nagy, Lockaby, Kalin, & Anderson, 2012; Roy et al., 2005; Schoonover, Lockaby, & Helms, 2006; Trudeau & Richardson, 2016). Lag times have also been reported to decrease with increasing impervious cover in other systems globally (Yao, Chen, & Wei, 2016).

We observed a significant effect of the watershed restoration projects on runoff frequency, minimum runoff thresholds, and runoff hydrograph duration (Table 2). However, these effects were largely driven by only one urban-restored watershed (CH1; Figure 3a, 3b, and 3c). The significant interaction between restoration status and impervious cover for these three metrics (Table 2) suggests the relative benefits of watershed restoration declines in watersheds with greater urbanization. Collectively, these results suggest that only the restoration in the CH1 watershed may be effectively altering hydrological processes within the watershed. We postulate that this type of restoration project is best suited to function well in a primarily suburban, small watershed, such as CH1 (22% impervious, 5 ha in size).

4.1 | Factors affecting hydrologic processes within the watershed restoration projects

The ability of watershed restoration projects to mitigate the effects of urbanization may be constrained by characteristics of both the natural environment (soils, topography, and geology) and built environment (development age and intensity, and storm sewer configuration), a concept known as watershed capacitance (Miles & Band, 2015). The sites in this study are within close proximity to each other (within a 5-mi radius) and, in general, have similar geology, topographic relief, and soils. The urban-restored watersheds vary, however, in their percent impervious cover, storm sewer connectivity, and size of the contributing area. These differences may influence the types of hydrological processes that each restoration project supports, such as infiltration and detention/storage, as well as the relative magnitude of the effects these processes have on patterns that we monitored in the downstream channel.

The design for this type of restoration project is explicitly tied to the impervious cover and contributing area of the watershed (MDE, 2009), so all of these restorations should be able to accommodate the volume of runoff generated in its watershed from a 1-in., 24-hr event. If this was the case, one would assume a similar performance across the sites. However, these results suggest a diminished benefit with increasing impervious cover. For example, a recent study in North Carolina documented the hydrologic performance of an RSC in a Coastal Plain watershed similar in size to the CH1 watershed in our study (5.2 ha) but with about half the impervious cover (12.3% vs. 22% at CH1). The restoration at the NC site completely infiltrated runoff from rainfall events as large as 45 mm (Cizek, 2014). CH1, in comparison, only infiltrated runoff completely for events as large as 15 mm. The restoration in the RR watershed (40% impervious) only retained runoff for events smaller than 1.2 mm on average (Figure 3a). SALT1 (50.7% impervious) performed even worse for retaining runoff. This clearly shows that greater impervious cover limits the ability of these restoration projects to completely capture stormwater runoff for even small rainfall events well within the design criteria. These findings corroborate a recent modelling study in Singapore, which documented decreased performance of a bioretention structure as impervious cover increased within its contributing area (Palanisamy & Chui, 2015).

The spatial placement of these watershed restoration projects is often constrained by surrounding landscape characteristics (e.g., existing development if the projects are retrofits). As such, their location within the larger landscape may control the types of hydrological processes that the project itself can support. For example, in SALT1, much of the watershed has been developed, and likely constrained watershed restoration projects to its riparian zone and floodplain (Figure 1 inset). As a result, the SALT1 restoration design relies on lateral surface storage in the floodplain rather than the upland vadose zone as with the CH1 and RR restoration projects. Water table depths may control the partitioning of the two primary mechanisms for increasing storage through this design: either through surface storage in large pools (which enhances surface detention) or through subsurface storage in the seepage bed and surrounding vadose zone (which enhances infiltration and potentially groundwater recharge). Lowland

Coastal Plain streams are often groundwater discharge zones (Bachman, Lindsey, Brakebill, & Powars, 1998), and as such, water tables are typically shallow in the floodplain. With limited infiltration potential, surface detention may be the dominant hydrological process within the restoration practice at SALT1. Seasonally elevated groundwater levels have been documented within the seepage bed of another RSC in North Carolina (Cizek, 2014), so it is possible this process may be occurring at our sites as well. This process can impact other infiltration-based stormwater management practices; for example, the effects of groundwater tables on bioretention performance were documented in a recent modelling study in a tropical watershed (Chui & Trinh, 2016).

In contrast, the restoration project in the CH1 watershed has subsurface storage zones that are presumably well above the regional groundwater table, thereby providing the opportunity for infiltration and subsurface storage. Although we did observe evidence of enhanced runoff infiltration within the project in the CH1 watershed, mean annual baseflow in its stream channel is significantly lower than that of all the forested reference streams (Figure 2a). Furthermore, a Student's *t* test of monthly baseflow measurements between CH1 and CH2, which is an urban un-restored catchment immediately adjacent to CH1 (Figure 1), shows no difference in mean annual baseflow between the two sites ($p = .83$; Figure 2a). The CH2 watershed is very similar to CH1 watershed in terms of catchment area, impervious cover, age of development, geology, and topography (Table 1). However, it has not been implemented with an RSC. Both of these findings suggest that the infiltrated runoff is not recharging longer term storage zones that supply baseflow to the stream. This could be because concentrated infiltration from the restoration project occurs near the channel head rather than in the upper portions of the watershed. Alternatively, it is possible that enhanced recharge from infiltrated runoff could be elevating baseflow downstream of the monitoring stream reach. However, long hydrograph durations observed at this site (Figure 3), may indicate that the restoration project merely extends the release of runoff into the downstream channel rather than converting it to groundwater recharge.

Restoration effectiveness could also be influenced by characteristics of the storm sewer network and catchment area. Besides being more developed, the RR watershed also had a larger contributing area (Table 1), and a more connected storm sewer network than CH1 (Figure 1 inset). In the PCA, the RR watershed clustered with the other urban-degraded watersheds (Figure 4), suggesting that no hydrological processes were enhanced by the restoration project. One explanation for the poor performance at this site is the storm sewer network delivers runoff too effectively, thereby overwhelming the restoration project. Extensive storm sewer networks can increase a watershed's effective impervious cover (e.g., directly connected impervious area, or DCIA), which is the amount of impervious surfaces that are directly connected via surface or subsurface flowpaths to the stream channel (Roy & Shuster, 2009). Studies have shown that DCIA is a better predictor than total impervious area of the effects of urbanization on stream ecosystems (Hatt, Fletcher, Walsh, & Taylor, 2004). For example, a modelling experiment in China showed greater dependence of storm-event lag times on DCIA rather than on total impervious area (Yao et al., 2016). Indeed, the shortest lag times in our study were observed at the RR watershed (Figure 2b), suggesting that high DCIA exists in this watershed from the extensive storm sewer network. These extensive drainage networks facilitate the delivery of runoff into the restoration, which may reduce its ability to capture runoff given the finite infiltration rates of the seepage bed material (composed of fine sand), especially during rain events with high rainfall intensities. When coupled with high DCIA, larger contributing areas (as with the RR watershed) may exacerbate this issue as well.

4.2 | Applications for future studies on watershed management and restoration

One of the goals of this study was to identify metrics that could be relatively easily measured at many watersheds (including populations of reference watersheds) to improve our understanding of how urbanization and watershed restoration projects manipulate the routing, storage, and release of runoff from watersheds. Two metrics, runoff frequency and mean annual baseflow, respectively load highly on the first two principal components of the PCA (Table 4). The first metric, runoff frequency, describes the resultant change in runoff delivery to the stream channel from decreased watershed storage. Runoff frequency was highly correlated with three other metrics, including minimum runoff thresholds, which is a more robust metric for quantifying watershed storage (Table 3). The runoff frequency metric captures changes in rainfall–runoff partitioning from both urbanization and restoration but could be measured over a shorter period than this study (3–6 months rather than the 1-year period used in this study). Runoff frequency captures an ecologically relevant facet of the flow regime, as more frequent high flows have been linked to lower biodiversity in headwater steam ecosystems across the globe (Roy et al., 2005; Walsh et al., 2016). Runoff frequency is used to quantify retention capacity, a metric proposed in Australia to assist managers with achieving the goal of restoring the flow regime to predevelopment conditions through improved stormwater management (Walsh et al., 2009).

The second metric, mean annual baseflow, captures the level to which rainfall is partitioned into longer term storage, beyond any short-term storage that may occur immediately following a runoff event. We suggest that these two metrics in tandem can initially assess the effectiveness of watershed restoration projects in restoring hydrological processes pertaining to watershed storage (Figure 5). If the hydrological processes supporting watershed storage were fully restored, one would observe both decreased runoff frequency from enhanced infiltration of runoff and increased baseflow from percolation of that infiltrated runoff into long-term subsurface storage. We did not observe these combined processes occurring in any of the restored watersheds (Figure 5), suggesting that this particular design, which concentrates the infiltration of runoff adjacent to the stream channel, does not effectively restore all hydrological processes lost through urbanization. Alternatively, approaches that emphasize decentralized stormwater infiltration throughout the watershed, such as green infrastructure (Jarden et al., 2016), may be more successful at restoring overall watershed hydrologic function, because distributed infiltration more closely mimics the natural distribution of storage zones in undisturbed, forested landscapes. Indeed, a recent modelling study predicted significant restoration of baseflow with the

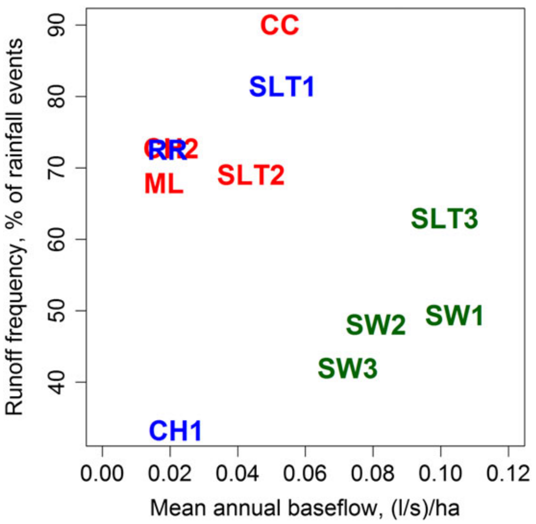

FIGURE 5 Relationship between area-normalized mean annual baseflow and runoff frequency

implementation of distributed bioretention basins across an urbanized watershed in Singapore (Trinh & Chui, 2013). Moreover, the addition of distributed infiltration-based management practices in upland regions could potentially improve the effectiveness of these RSC practices in heavily urbanized watersheds, as decentralized stormwater management may reduce the volume and rate of runoff entering the restoration structures.

Urban regions around the world are now focusing on minimizing the impact of stormwater runoff on urban stream ecosystems (CEC, 2000; Jia et al., 2015), prompting the need to implement more effective approaches to managing stormwater. Although our study focused on an emerging BMP type currently only implemented in the mid-Atlantic United States, our methods could be used in a variety of settings to assess any stormwater BMP or watershed restoration practice. Moreover, this approach can be used also provide important information to corroborate modelling study results (Chui & Trinh, 2016; Palla & Gnecco, 2015). There are some limitations on the level of assessment that can be achieved through the use of stage-based metrics; for example, careful use of stage data is required for comparability across sites, given differences in hydraulic geometry and velocity–discharge relationships. However, important patterns in the relative hydrologic responses in watersheds with different stormwater management strategies can be detected using this approach.

5 | CONCLUSIONS

We used a suite of hydrological metrics to evaluate changes in watershed hydrologic responses due to urbanization and subsequent watershed restoration practices. This multimetric analysis, which leveraged both discrete discharge and continuous stage-rainfall monitoring data, revealed lower watershed storage, short duration hydrographs, flashier flow regimes, and greater runoff frequency with increasing urbanization. Infiltration-based watershed restorations showed limited success in modulating the hydrological effects of urbanization. Although one restored watershed demonstrated significantly enhanced infiltration of stormwater runoff, its mean annual baseflow remained low, indicating that enhancing infiltration and storage proximal to the channel head does not restore long-term storage and stream baseflow. Variable hydrological responses among the three restored watersheds were likely influenced by watershed characteristics, including level of imperviousness, watershed size, and extent of the storm sewer network. We identified two metrics in particular that are easily quantified in many watersheds over a relatively short period: (a) runoff frequency, which captures rainfall–runoff dynamics, and (b) baseflow discharge, which quantifies release of water from long-term storage. Restoration actions designed to restore watershed hydrologic processes should ideally be addressing both short- and long-term storage of rainfall, and these two metrics seem to capture these hydrological processes. This approach could be used by resource managers to gain a better understanding of how management practices affect watershed hydrological processes.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S1-I: Detailed descriptions of the upland BMPs present in the study area (n = 49), including BMP type, date built, drainage area, its assumed runoff reduction, and the estimated treated drainage area. Upland BMPs built before 2000 were assumed to have tier 1 (lower) runoff reductions, and those built after 2000 were assumed to have tier 2 (higher) runoff reductions. Estimated runoff reductions derived from Chesapeake Stormwater Network (2004).

Table SI-II: Summary table describing BMP implementation in each of the 11 watersheds. Area treated by upland BMPs were calculated by applying each BMPs runoff reduction to their drainage area and summing up the treated areas for all BMPs within a watershed.

Figure SI-1: Total percent impervious cover vs untreated percent impervious cover for the 11 watersheds, after accounting for upland BMPs. Black line denotes a 1:1 relationship.

Figure SI-2: Boxplots of the change in stage during the 81 rainfall events across the 11 watersheds. A change in stage was calculated by subtracting the average stage for 1-hour prior to the start of the event from the peak stage during the rainfall event.

Figure SI-3: Two example piecewise regressions for an urban-degraded site (CH2; **A**) and an urban-restored site (CH1; **B**). Each point represents a rainfall event. Arrows indicate the breakpoints identified in the analysis; the rainfall depth at that breakpoint is the minimum runoff threshold.

Figure SI-4: Effect of variable minimum inter-event time (MIT) on the characteristics of the population of events defined by the MIT (Carriage Hills = CH1; Riva Rd = RR). (**A**) Number of rainfall events defined for the two rain gages vs length of MIT, hrs. (**B**) Frequency histograms of rainfall events for variable MITs at the Carriage Hills precipitation station.

Figure SI-5: Rainfall totals for the final 81 events defined by the 5-hour MIT for the Carriage Hills (CH1) and Riva Rd (RR) rain gages. $R^2 = 0.97$; $p < 0.001$.

Figure SI-6: Rainfall characteristics of the rainfall events used for the hydrometric analysis in the study. (**A**) Frequency histogram showing the distribution of different sized rainfall events. Note that the x-axis is not fully extended to show the largest rainfall event during the monitoring period (95 mm, August 13, 2014); (**B**) An exceedance probability plot for the 81 rainfall events according to their total rainfall depth.

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