Hydrologic response to stormwater control measures in urban watersheds

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Abstract

Stormwater control measures (SCMs) are designed to mitigate deleterious effects of urbanization on river networks, but our ability to predict the cumulative effect of multiple SCMs at watershed scales is limited. The most widely used metric to quantify impacts of urban development, total imperviousness (TI), does not contain information about the extent of stormwater control. We analyzed the discharge records of 16 urban watersheds in Charlotte, NC spanning a range of TI (4.1 to 54%) and area mitigated with SCMs (1.3 to 89%). We then tested multiple watershed metrics that quantify the degree of urban impact and SCM mitigation to determine which best predicted hydrologic response across sites. At the event time scale, linear models showed TI to be the best predictor of both peak unit discharge and rainfall-runoff ratios across a range of storm sizes. TI was also a strong driver of both a watershed's capacity to buffer small (e.g., 1-10 mm) rain events, and the relationship between peak discharge and precipitation once that buffering

capacity is exceeded. Metrics containing information about SCMs did not appear as primary predictors of event hydrologic response, suggesting that the level of SCM mitigation in many urban watersheds is insufficient to influence hydrologic response. Over annual timescales, impervious surfaces unmitigated by SCMs and tree coverage were best correlated with streamflow flashiness and water yield, respectively. The shift in controls from the event scale to the annual scale has important implications for water resource management, suggesting that overall limitation of watershed imperviousness rather than partial mitigation by SCMs may be necessary to alleviate the hydrologic impacts of urbanization.

1 Introduction

Urbanization alters the response of river networks to hydrometeorological drivers, causing more frequent and intense floods (Leopold, 1968). This new flood regime causes more stream bank erosion, destroys habitat, and subsequently degrades stream ecosystem health (Paul and Meyer, 2001). Runoff generated during storm events is quickly concentrated in pipes and stream networks by stormwater drainage systems, which produce elevated peak flows and cause flooding and infrastructure damage. Additionally, urbanization can lead to rising or falling baseflow, which affects stream ecosystems by changing temperatures and nutrient cycling (Bhaskar et al., 2016). Stormwater control measures (SCMs) mitigate the impacts of urbanization by attenuating storm volumes, reducing peak discharges, accelerating groundwater recharge, and promoting evaporation (Roesner et al., 2001; Hamel et al., 2015). However, the capacity for SCMs to restore natural hydrologic regimes and stream ecosystem functions depends on both the extent of implementation within the watershed and the degree of impact from urbanization (Roesner et al., 2001; Hur et al., 2008; NRC, 2008; Roy et al., 2008; Burns et al., 2012).

Total imperviousness (TI), which is the fraction of the watershed area covered by an impervious surface, has often been used as a way to quantify the degree of urbanization. It is both integrative and easily measurable (Arnold and Gibbons, 1996). While the form of the relationship between stream degradation and TI is uncertain (e.g., linear or having a threshold after which degradation begins), it is well established that stream degradation does increase with TI (Schueler, 1995; May et al., 1997; Booth et al., 2002). As reviewed by Paul and Meyer (2001), TI increases runoff magnitude manifested as peak discharge, bankfull discharge, and runoff ratio at both event and annual time scales. The lag time between rainfall and runoff generation has also been shown to shorten with increasing TI (Espey et al., 1966; Leopold, 1968). In a review of urban streams in the U.S. Southeast, O'Driscoll et al. (2010) demonstrated that these hydrologic changes have cascading effects on stream ecosystems by altering channel geomorphology, reducing the ability of streams to retain and remove nutrients, and decreasing the abundance of intolerant macroinvertebrate taxa.

One criticism of TI as a metric for predicting stream response is that not all impervious surfaces are directly connected to drainage networks through surface conveyance channels or pipes. An example of a disconnected impervious surface is the rooftop of a building that is surrounded by vegetation on all sides. Effective imperviousness (EI) accounts for this important nuance in impervious surface connectivity and is defined as the portion of the watershed covered by impervious surfaces directly connected to the drainage network (Alley et al., 1980; Alley and Veenhuis, 1983; Shuster et al., 2005; Walsh et al., 2005). As with TI, EI is an integrative measure characterizing urbanization, however it is not as easily quantified because it requires information on the connectivity of impervious surfaces.

SCMs are designed to produce hydrographs that mimic pre-development conditions, therefore impervious surfaces mitigated by SCMs are assumed to be disconnected from the streams when computing EI (Walsh et al., 2005). SCMs take many forms (e.g. wet ponds, dry ponds, bioretention areas), but are generally hydrologically connected elements within the landscape that temporarily store and release water to the drainage network at a slower rate determined by the size and design of the SCM and its outlet structure. This process of water attenuation reduces peak flows, and increases lag times between precipitation and stormflow volumes (Horner et al., 2001; Villarreal et al., 2004; Hood et al., 2007; Jarden et al., 2015). However, the water balance of urban watersheds is often still perturbed, because of the leakage of imported drinking water through distribution pipes and decreased evapotranspiration, unless the SCMs include a significant water harvest or reuse component (Askarizadeh et al., 2015).

Accurately quantifying EI for large areas is time consuming and requires knowledge of roof downspout connections and pipe networks (Lee and Heaney, 2003). Therefore, simply distinguishing unmitigated impervious areas from mitigated ones may be a simple way to derive a watershed metric similar to EI. Here we propose an additional metric: unmitigated imperviousness (UI), which is the fraction of total watershed area occupied by impervious surfaces that are not mitigated by SCMs. The ratio of UI/TI, then, is the fraction of impervious area that is unmitigated by SCMs. This ratio is analogous to the directly connected impervious areas fraction (often abbreviated DC, DCI or DCIA) used in other studies (Lee and Heaney, 2003; Walsh et al., 2005; Walsh and Kunapo, 2009; Shields and Tague, 2014).

Because UI and EI contain additional information about connectivity and the role of SCMs, they may explain the difference in hydrologic response to rainfall between sites better than TI. However, neither contains information about treated pervious areas. Inclusion of the treated

pervious areas is important, particularly in residential urban and suburban environments, where lawns occupy on average 23% of the area (Robbins and Birkenholtz, 2003). During construction, lawns are compacted which reduces infiltration and contributes to excess runoff (Pitt et al., 2008). Hence, treating surface runoff from these pervious, but potentially runoff-yielding areas may mitigate peak flows. Therefore, quantifying the mitigated area (MA) of the watershed may prove to be useful for characterizing the benefits of treated pervious and impervious areas.

We hypothesized that if stormwater management is affecting urban hydrology, then metrics that include both urbanization and SCM mitigation will explain variation in hydrologic response variables across sites better than those that quantify either urbanization or SCM mitigation alone. Specifically, we predicted that MA, which accounts for potential storage of runoff from pervious and impervious surfaces in SCMs, would be most closely correlated with runoff volume. Also, we predicted that UI would best explain variation in peak discharge and record flashiness because it enumerates the potential for impervious surface runoff to bypass SCMs and flow efficiently to the stream. In addition, water resource managers seeking to limit the impacts of urbanization can use the metrics that best explain hydrologic response to SCM mitigation in a planning and policy development.

2 Site Descriptions

We examined 16 watersheds with SCMs in the Charlotte, North Carolina (35° 13' 36.9" N, 80° 50' 35.9" W) metropolitan region in the Piedmont physiographic province (Figure 1). Between 1971 and 2000, Charlotte's mean annual precipitation was 1105 mm and was distributed evenly across months. Over the same time period, the average daily temperature was 16.4°C annually,

and 5.4°C and 26.8°C for the months of January and July respectively (State Climate Office of North Carolina, 2013).

Of the 16 sites selected for hydrological analysis, streamflow was recorded at 12 of them by the United States Geologic Survey (USGS) (Table 1). These twelve sites had drainage areas ranging from 2.5 km² to 32.9 km² and were selected to span a range of urban development and SCM density. Little Sugar Creek drains Charlotte's city center and serves as an upper bound on urban development intensity in the city. Only 14% of the Reedy Creek watershed is developed (Table 1), and it was included as a control against any effects that watershed size may have on the results at Little Sugar Creek.

In addition to the 12 USGS sites, we included 4 smaller streams that were gaged as part of a larger study of the impacts of SCMs on multiple ecosystem services. Two of these four watersheds, UP1 (1.4 km²) and UL1 (1.5 km²), were adjacent to one another and are subwatersheds of Edward's Branch and Campbell Creek, respectively. The other two, SP1 (1.0 km²) and SL1 (0.15 km²), were drained by a tributary to Beaverdam Creek (BD4), which flowed into Beaverdam Creek downstream of a USGS gage used in this study. Changes to the hydrology and water quality during urbanization and contributions of SCM water to streamflow during storm events have been the topics of past studies at BD4 (Allan et al., 2013; Gagrani et al., 2014; Jefferson et al., 2015). We included these highly treated sites because they are smaller than watersheds typically gaged by the USGS. Also, EI can be estimated at this scale with a few simplifying assumptions, but is not practical for larger watersheds with complex engineered drainage networks. This allows us to use these sites to test the ability of other metrics to serve as a proxy for EI.

134 Drainage areas were calculated using the Hydrology Toolbox in ArcGIS (ESRI, Redlands, CA,
135 USA) with a 6.1 m (20 ft) digital elevation model (DEM). For the all sites, spatial data from the
136 City of Charlotte identifying the location of underground pipe networks was burned into the
137 DEM prior to automatic delineation. For the highly treated sites, we manually adjusted
138 watershed boundaries to incorporate additional knowledge of the underground storm sewer
139 networks from field visits, aerial imagery and stormwater pipe network data. These manual
140 adjustments were made at the small, highly treated sites because misidentification of watershed
141 area there could produce large relative errors when calculating metrics such as TI, EI, UI and
142 MA.

143 TI was determined from two spatial datasets: the first is a remote sensing land cover map
144 developed for the year 2012 by Mecklenburg County, and the second is a vector shapefile of
145 impervious surfaces used for stormwater taxation developed by the City of Charlotte. Tree
146 coverage was also derived from the Mecklenburg County land coverage map.

147 The location and extent of SCMs and corresponding drainage areas were taken from a database
148 compiled by the City of Charlotte Division of Storm Water Services, accessed upon its first
149 release in July 2015. This dataset was created from records kept by the City of Charlotte's
150 Division of Land Management in compliance with the city's post-construction stormwater
151 ordinances. The dataset is also linked to spatial data outlining the drainage area that each SCM
152 mitigates, which was determined using a combination of high-resolution topographic data and
153 site designs provided by developers in accordance with the post-construction ordinance. In
154 addition to the City's database, we used aerial photos available via Google Earth (Google Inc.,
155 2015) dating from 1993 to 2012 to identify any SCMs in the watersheds missing from the

database. We manually delineated drainage basins and calculated drainage area for these additional SCMs using pipe network data, aerial photos, and elevation data.

Only SCMs designed to add storage were included when determining SCM mitigated area, while conveyance SCMs (e.g. swales) were left out. A number of in-line ponds existed in Charlotte, but were not considered SCMs unless they were included in the City's pond rehabilitation program, which retrofits ponds with either an outlet weir, littoral zone vegetation, or both to provide water quantity and quality benefits. We used the spatial datasets of SCM mitigated area and TI to compute UI and UI/TI at all 16 sites.

We estimated EI at the highly treated sites only using the following simplifying assumptions: (1) all impervious surfaces within an SCM drainage area were considered to be not effective; (2) all hydrologically remote, disconnected impervious surfaces were considered to be not effective; (3) 100% of roads and parallel sidewalks drained by pipe networks leading directly to a stream were considered effective; (4) single-family residential rooftops with driveways tangent to an unmitigated road were assumed to be 50% connected on lots $\leq \frac{1}{4}$ acre and 33% connected on lots $> \frac{1}{4}$ acre, but the driveways were assumed 100% effective at both parcel classifications; and (5) other larger, multi-family residential and commercial buildings and associated parking lots were considered 80% connected. These assumptions were based on field observations and aerial photographs, and applying these assumptions produced land use specific EI estimates comparable to those of Alley and Veenhuis (1983) for 19 urban watersheds in Denver, CO, USA.

3 Data and Analysis

3.1 Data Sources

At the highly treated sites, a period of approximately one year (2011-2012) was used for hydrologic analysis. The period was slightly different for each site, running from 6/21/11 to 5/1/12 at UP1, 6/20/11 to 6/20/12 at UL1, 9/27/11 to 9/27/12 at SP1 and 8/18/11 to 8/18/12 at SL1. These time periods were chosen to include dates of stormwater quality sampling done as part of a companion study. At the USGS sites, the 2012 water year was selected for analysis, as it is the water year that corresponds best with the records selected at the highly treated sites.

Data from Charlotte Douglas Airport (station ID: KCLT, downloaded from <http://www.ncdc.noaa.gov/cdo-web/>) indicated that the 960 mm of water fell during the 2012 water year, which was the 25th percentile of total annual precipitation on the station's 72-year record.

For the USGS sites, approved instantaneous discharge data, measured at 15-minute intervals, were downloaded from the USGS National Water Information System (<http://nc.water.usgs.gov/char/streamflow.html>). At the highly treated sites, we recorded stream stage at 10-minute intervals using a 730 Bubbler Module Sensor attached to an ISCO autosampler (Teledyne Technologies Inc., Thousand Oaks, CA, USA). We developed stage-discharge relationships for each site using a HEC-RAS (US Army Corps of Engineers) hydraulic model built from cross sectional geometry data collected at approximately 1.5 m longitudinal intervals. The modeled Manning's roughness coefficient for the channel banks was calibrated to match four to five high storm flow observations collected using velocity-area and dilution gaging methods (USGS, 1982). For calibrating Manning's roughness in the channel at low flows, the total unit stormflow volume contributed from flows less than the 90th percentile discharge value was calibrated to be within $\pm 10\%$ of the observed annual unit discharge from nearby gages over

the same period. The USGS gage at Edward's Branch was used for calibration of low flows at UL1 and UP1, since the watersheds are adjacent and have similar land use and stormwater infrastructure. The USGS Edward's Branch gage was located 0.4 km downstream from UL1. For the two suburban sites, the record for low-flow calibration was compiled from a capacitance water level record combined with a stage-discharge rating curve by Gagrani et al. (2014) for the BD4 watershed.

We used 5-minute precipitation data from 31 rain gages in the USGS National Water Information System (NWIS) (<http://nc.water.usgs.gov/char/raingage.html>) to construct composite precipitation records for each watershed using the Thiessen method (Thiessen, 1911) (Figure 1). The number of gages used to create the area-weighted composite record at a given site ranged from 1 to 8.

3.2 Hydrologic Variables Considered

To characterize the hydrologic response, we first developed a procedure to identify individual storm events. We modified the constant line separation method developed by Hewlett and Hibbert (1967) to separate stormflow from baseflow and to define the end of a hydrologic event (Figure 2). This method was originally applied in forested watersheds to separate stormflow from baseflow, but because response times are considerably faster in urban streams, we decreased the slope of the separation line to $3.3 \times 10^{-5} \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2} \text{ hr}^{-1}$ based on observations of a subset of individual events at each site. We defined the initiation of an event as the time of the first positive hydrograph slope during a 60-minute period that exceeded the slope of the hydrograph separation line. We determined the end of the event as the time when the separation line intersected the hydrograph. Of all hydrologic events identified, we retained only events in which total precipitation (PPT_E) exceeded 2.54 mm (0.1 in) for analysis. While other hydrograph

separation methods using digital filters exist (Lyne and Hollick, 1979; Eckhardt, 2005), these methods are not designed to determine the start and end of individual storm events at a sub-daily time step.

Using the discharge and precipitation data, we derived several metrics of event-scale hydrologic response. First we calculated the rainfall-runoff ratio as shown in Eq. 2:

$$Runoff\ Ratio = \frac{V/A}{PPT_E} \quad (Eq. 2)$$

where V is the total stormflow volume [L^3] above the separation line (Figure 2), A is the watershed area [L^2], and PPT_E is the total event precipitation [L]. PPT_E was the sum of all rain falling during the defined hydrologic event and any rain that had fallen 1.5 h prior to the event. Using this 1.5 h time window, pre-event precipitation accounted for <10% of total event rainfall for 75% of events analyzed.

We defined peak discharge as the largest instantaneous discharge value during the hydrologic event and normalized it to watershed area to allow for comparisons across sites. We calculated a “response rate” using the slope of a log-transformed linear model of peak discharge vs. maximum 60-minute precipitation intensity (I_{60}). This precipitation metric was chosen over PPT_E and the maximum 15-minute precipitation intensity as it produced the highest R^2 values at 9 of the 16 sites. We also estimated the amount of storage within the watershed as the threshold of precipitation above which streamflow responds more rapidly to rainfall (Loperfido et al., 2014). We calculated this as the breakpoint in slope of piecewise linear models between peak discharge and total precipitation using the “segmented” package in R (R Core Team, 2013). For

computation of these breakpoints only, precipitation events with PPT_E less than 2.54 mm were also included.

In addition to these event-specific metrics, we computed two metrics to describe hydrologic behavior over longer timescales. We computed the annual water yield ratio as the slope of the regression line fit between cumulative daily flow depth and cumulative daily precipitation. Additionally, we calculated the percent of time the instantaneous discharge was above the mean value to characterize flashiness, a metric that can be used to describe the regime of hydrologic disturbances to stream ecosystems and is also tied to ecosystem biological integrity (Booth et al., 2004; Cassin et al., 2005; Burns et al., 2015).

3.3 Statistical Analysis

We used the software R (R Core Team, 2013) to perform all statistical analyses and all results reported as significant are within 95% confidence unless otherwise indicated. To determine trends across sites, we fit both linear and log-transformed linear models through the hydrologic response variables using the eight watershed metrics (Table 2). The watershed metric producing a univariate model with the highest performance determined by R^2 was deemed the primary control on hydrologic behavior across sites. Only univariate models were tested because the site factors were highly correlated (Table 3) and using two or more of these variables would introduce multicollinearity. Instead, we performed a correlation analysis between the residuals of the linear models and each of the remaining watershed metrics to identify secondary controls. All correlations were quantified using the Pearson product-moment correlation coefficient (R).

We computed 6 percentiles (10th, 30th, 50th, 70th, 90th and 99th) for peak discharge and runoff ratio at all 16 sites. We then performed the linear modeling procedure outlined above on all

these percentile values (6 models per variable, each with n=16) to characterize the primary and secondary control across the entire range of event scale observations, rather than just characterizing the mean or median. Performing this analysis across the distribution of hydrologic variables allowed us to identify which watershed factors controlled hydrologic response under varying antecedent moisture, temperature, and precipitation characteristics, which contribute to the variability within each site.

4 Results

4.1 Watershed metrics

All of the watersheds metrics considered characterized either the intensity of urbanization, SCM mitigation or both (Table 1), and several of them correlated with each other (Table 3). The level of urbanization, quantified by TI, spanned from 4% to 51%. Mitigated Area (MA) ranged from 1.3 to 89%, but only three sites (all from the highly treated sites group) had MA values > 20%. EI, computed at only the 4 highly treated sites, ranged from 0.2% at SL1 to 41% at UL1. UI ranged from 0.48% to 52%. UI was very strongly correlated with EI (Table 3), which indicates that it can serve as a suitable replacement for EI if SCMs are assumed to convert effective impervious areas into non-effective ones. UI and TI were also strongly correlated, and UI averaged 77% of TI. TI and tree coverage were moderately negatively correlated.

4.2 Runoff Ratios

For the analysis period, across 16 sites, we identified a total of 737 hydrologic events with precipitation ≥ 2.54 mm. Of the eight watershed metrics, TI was the best predictor of the 10-90th percentile runoff ratios, and runoff ratios increased with increasing TI (Figure 3a, Table 4). No significant relationship was produced for 99th percentile storms, which were highly variable.

286 Additionally, the coefficient of variation of runoff ratios decreased with increasing TI ($R^2=0.57$,
287 $p<0.001$). Significant linear models were also identified for the 30th-90th percentile runoff ratios
288 using UI as the independent variable, and for the 10th-90th percentiles using tree coverage
289 fraction. Runoff ratios increased with increasing UI and decreased with increasing tree cover.
290 These models had lower explanatory power (R^2) than the TI models. No significant relationships
291 were identified for any runoff ratio percentile versus MA, SCM density or UI/TI.

292 To identify secondary controls on the 10-90th percentile runoff ratios, we correlated the residuals
293 of the runoff ratio-TI models with the remaining site metrics. Residuals were most strongly
294 correlated with the ratio of UI/TI (i.e., the percentage of impervious area that was unmitigated by
295 SCMs). All correlations were negative ($-0.46 \leq R \leq -0.63$), which indicated that sites with a higher
296 ratio of unmitigated imperviousness to total imperviousness had higher runoff ratios (Figure 3b).

297 **4.3 Peak Discharge**

298 Across all events and watersheds, simple linear regression models show peak discharge to be
299 most strongly predicted by TI at all percentiles (Figure 4a, Table 4). In addition, significant
300 models with lower explanatory power (R^2) were identified for UI (10th – 70th percentiles) and
301 tree coverage (10th – 90th percentiles).

302 Correlation with the residuals of the peak discharge-TI models identified multiple secondary
303 controls, changing with event size. Watershed area was identified as the strongest secondary
304 control for smaller peak flows (10th-50th percentiles, $R < -0.53$, shown in Figure 4b). Larger peak
305 flows (70th and 90th percentiles) were inversely correlated to SCM density ($R=-0.414$ and -0.594 ,
306 respectively, Figure 4c), and the 99th percentile was best correlated to the tree coverage

($R=0.556$, Figure 4d). However, the correlations for the 70th-90th percentiles were strongly leveraged by one point.

Despite the shifting secondary control, when plotted against watershed area, the peak flow-TI residuals for all percentiles generally declined as area increased (Figure 4b). This indicated that as watershed size shifted from small to large, the TI model shifted from under-predicting to over-predicting peak discharge. However, below 2 km², the trend was reversed, potentially due to the high level of SCM mitigation at the small, highly treated sites.

4.4 Peak Discharge Response to Precipitation Across Sites

Two record-long metrics were used to characterize the form of the relationship between peak discharge and precipitation characteristics. First, we defined the discharge response rate as the slope of the linear model of peak discharge (log-transformed) and I_{60} . This site-specific variable ranged from 0.59 at Gar Creek to 1.65 at Briar Creek Trib. As with the event scale metrics, the primary site factor that best predicted this variable across sites was TI ($R^2=0.54$, $p=0.001$, Figure 5). Significant, but weaker linear models were also observed between the response rate and UI.

The second metric describing the relationship between rainfall and peak discharge was the breakpoint in the slope of a linear model of peak unit discharge and PPT_E . Examples of this break in slope are shown for sites at the opposite ends of the urbanization spectrum. Figure 6a shows that Gar Creek, with 4% TI, had a flatter slope between 0 and 12 mm of rain, above which the stream responded at a higher rate. Little Sugar Creek, with 54% TI, shifted at precipitation levels as low as 1 mm (Figure 6b). Our data showed that with increasing TI, runoff generation and streamflow response occurred during smaller rain events (Figure 6c). There was a downward trend in the breakpoint as TI increased. Determining the primary site metric

controlling the breakpoints across site was difficult, as a number of sites did not exhibit a significant breakpoint (Figure 6c). Using subsets of the data based on breakpoint significance, TI consistently showed the strongest correlation with the breakpoint.

4.5 Annual Metrics

Two annual hydrologic metrics (water yield and time above mean) were also computed. Of all eight site metrics tested, water yield was most strongly correlated with tree coverage ($R^2=0.53$, $p=0.002$) (Figure 7a). TI and UI also produced significant linear models, but with poorer performance.

The second annual metric considered was the fraction of time the hydrologic record spent above the mean discharge. This metric is an indication of flashiness with low values representing rapid watershed response (e.g., higher peaks and shorter duration). The time above mean ranged from 7.1% at Edwards Branch to 31% at SP1. UI was the best predictor of time above mean across all sites (Figure 7b, $R^2=0.60$, $p=0.005$), and TI also produced a significant, but less explanatory model. In search of secondary controls, no watershed metrics were strongly correlated ($|R| < 0.45$) with the primary model residuals.

5 Discussion

5.1 Total imperviousness controls event scale response

At the event scale, TI was the dominant control on a range of hydrologic response metrics at 16 sites in Charlotte, NC that spanned a range of imperviousness and mitigation by SCMs. Regression analysis demonstrated that TI was best of a suite of spatially integrated, watershed-scale metrics at describing the variance of storm event runoff ratios. Additionally, a watershed's ability to store small rain events, quantified by a breakpoint in slope between total precipitation

and peak discharge, was also tied best to TI. These results are in alignment with other hydrologic effects of urbanization, including a loss of watershed recharge and storage (Booth 2002) and decreased evaporation and transpiration with loss of vegetation (Grimmond and Oke, 1999). Lower storage capacity would lead to more frequent flooding events, and therefore alter disturbance regimes in stream ecosystems. Additionally, TI had the strongest statistical control on both the distributions of peak discharge across sites and the rate of response of peak discharge to rainfall once initial storage (i.e., breakpoint) had been exceeded. These results add to an increasing body of evidence of urbanization, measured by TI, causing increased surface runoff and drainage efficiency (Shuster et al 2005). This is also demonstrated by the negative correlation ($R=-0.75$) between TI and each site's coefficient of variation of runoff ratios.

Other metrics like UI and tree coverage fraction frequently produced significant linear regression relationships at our study sites, but the strength of these was consistently less than those produced by using TI. Many studies have shown the relationship between hydrologic response and TI (see reviews by Arnold and Gibbons, 1996 and Shuster et al., 2005). However, modeling studies that considered both TI and EI (EI is assumed to be analogous to UI if SCMs operate as designed), found EI to be either a better metric than TI or an important control when modeling hydrologic response to rainfall (Lee and Heaney, 2003; Guo, 2008; Dewals et al., 2012; Shields and Tague, 2014). In the watersheds in our study, TI best explained event scale hydrology across sites, indicating that TI is the single best metric for quantifying impacts of urban development on storm runoff delivered to streams.

5.2 Secondary controls on event scale hydrology

An analysis of residuals of the linear models between event hydrologic variables and TI was performed to identify secondary watershed controls. Analogous to the fraction of directly

connected impervious surfaces (e.g., Shuster et al., 2005; Walsh et al., 2005; Shields and Tague, 2014), UI/TI was the dominant secondary control of runoff ratios. In our 16 watersheds, the correlation between the residuals and UI/TI was negative, so that for a given TI, runoff ratios decrease as the proportion of untreated impervious increases. Counterintuitively, this suggests that as a higher percentage of TI is treated by SCMs (i.e., UI/TI decreases), runoff ratios actually increase for given a level TI. Actual event runoff ratios were also weakly negatively correlated to UI/TI (R ranging from -0.10 to -0.24 across the percentiles). We postulate that this effect is a result of different ages and styles of infrastructure within the SCM catchments than in areas with untreated imperviousness. In areas with high density of SCMs, development is likely newer, with less secondary permeability of pavement (Wiles and Sharp, 2008) and fewer joints and breaks in drainage pipes. Areas with SCMs may also be more likely to have a higher density of drainage pipes and curb and gutter systems, than in areas without SCMs, where informal drainage (e.g., roads without curbs) may be more prevalent (Walsh et al., 2012). Together or separately, these differences result in greater drainage efficiency of stormwater runoff to SCMs in newer developments, producing the higher runoff ratios observed in this study. The presence of a SCM may even spur greater connectivity of impervious surfaces because of the perception that the SCM will mitigate the effects of the runoff.

Although peak discharge did not have a consistent, dominant secondary control across the percentiles considered, watershed area was the most prevalent. The trend, as shown in Figure 4b was that as watershed area increases, the residuals decrease (i.e., peak discharge for a given TI decreases as area increases). This finding is consistent with peak attenuation due to channel and floodplain storage during flood routing (Bedient et al., 2002). It may also be attributable to non-uniform rainfall (both spatially and temporally) in larger watersheds, where isolated convective

thunderstorms may produce high rain intensities in a small area while the rest of the watershed receives little or no precipitation. This finding contrasts with that of Galster et al. (2006) who observed a positive linear relationship between peak unit discharge and area. Galster et al. (2006) tracked a single event downstream within the channel network and attributed the observed relationship to downstream increases in TI, which does, however, agree with our findings of TI as a primary control. Despite our observed trend of decreasing peak unit discharge residuals with increasing area, in the smallest watersheds ($<2 \text{ km}^2$) with the highest SCM treatment, the residuals are negative compared to positive residuals in slightly larger watersheds ($2\text{-}5 \text{ km}^2$) with lower SCM treatment. The effects of flood routing and spatial variation in rainfall should be small over this range of scales, so the difference between the highly treated and less treated watersheds implies that SCM mitigation may be a tertiary control on peak discharges across sites.

5.3 Tree coverage and SCM mitigation predict annual hydrologic response

While processes associated with impervious coverage were found to dominate the hydrology at the event scale, at the annual scale, tree coverage and stormwater mitigation of impervious surfaces have a larger impact. The water yield fraction across sites was best explained by tree coverage, as a linear relationship showed lower water yield as tree coverage increased (Figure 7a). An urban forest canopy can increase transpiration, interception and subsequent evaporation (Nowak and Dwyer, 2007). This is inconsistent with the finding for runoff ratios at the event time scale, which were best explained by TI. TI is approximately the complement of total vegetation (i.e., total vegetation coverage = tree coverage + lawn coverage $\approx 1 - \text{TI}$). At the event time scale, fresh rainfall is available for transpiration by both shallow-rooted lawns and deep-rooted trees, so TI may best represent plant access to water for transpiration. However, at

longer time scales, tree coverage may better represent vegetative effects on hydrology than TI because trees have deeper rooting systems than grasses that allow them to transpire groundwater between rain events when the water table is lowered. The increased transpiration of urban trees compared to urban grasses was demonstrated by Shields and Tague (2014), where simulations of suburban and urban residential neighborhoods in semiarid Santa Barbara, California showed live oak consistently transpired more water per unit vegetated area than local grasses.

We characterized stream flashiness as the fraction of time the hydrologic record spent above its mean discharge. Low values of this metric occur if the flow distribution is skewed up towards fewer, larger events and this is indication of the intensification of the hydrologic response to precipitation. A previous study demonstrated that increased urbanization, as measured by TI, lead to decreases in the time spent above the mean (Booth et al., 2004). In this study, a similar relationship between the time above mean and TI existed, but UI, the fraction of watershed area covered by impervious surfaces not mitigated by SCMs, was a stronger predictor. We attribute this to SCM design, which both delays the release of stored runoff from impervious surfaces and can promote local infiltration and groundwater recharge (Roesner et al., 2001; CMSWS, 2013). Localized infiltration in SCMs can lead to increased baseflow, which causes hydrologic records to spend more time above the mean discharge (Hamel et al., 2013; Bhaskar et al., 2016).

However, a vast majority of the SCMs in this study were retention ponds and wetlands which designed with liners to limit infiltration (CMSWS, 2013). Therefore, we attribute this result to attenuation of surface water in SCMs rather than elevated infiltration. Jefferson et al. (2015) used isotopic hydrograph separation to show that SCMs surface outflow contributes disproportionately high amounts of runoff to streamflow during hydrograph recession relative to their drainage area. Our results, in combination with the goals of SCM design and observations

of Jefferson et al. (2015), explain why UI, which implicitly incorporates SCM mitigated impervious surfaces, outperforms TI at predicting stream flashiness because SCMs temporarily retain surface runoff. Together, results of annual hydrologic variables indicate that management strategies like tree planting and mitigating impervious areas can reduce total water runoff and decrease hydrologic record flashiness.

5.4 Why was our hypothesis wrong? Highlighting topics for further research

We hypothesized that metrics incorporating both the extent of urban impact and mitigation with stormwater control measures (i.e., UI and MA), would better predict hydrologic variables than those quantifying urbanization or SCM mitigation alone. This hypothesis implied that SCMs are affecting storm event runoff. However, at the event-scale, TI produced the strongest relationships. We propose four possible explanations for these unexpected results: (1) the signal produced by the distribution of SCM mitigation was insufficient to overcome the signal from imperviousness, (2) these metrics do not incorporate necessary information on spatial arrangement of both impervious surfaces and SCMs, (3) TI is actually a better predictor than EI of the suite of hydrologic behaviors studied here and (4) SCMs are unable to reverse the connection between urban surfaces and streams formed by storm drainage pipes (i.e., some mitigated impervious surfaces are still effective). These possible explanations highlight needs for future research.

The sixteen sites span a range of urbanization and SCM mitigation that reflects current practices in Charlotte, NC. The population of Charlotte grew by 14% between 2007 and 2014 (United States Census Bureau, downloaded at: <http://factfinder.census.gov/>), and this growth has coincided with urban development under stormwater post-construction ordinances implemented in 2007. This extensive, regulated development makes Charlotte a city with a relatively high

level of SCM mitigation. However, while the range of mitigated area at the sites considered in this study is broad, it is skewed toward sites with less mitigation, which may not be sufficient to compensate for the impacts of urbanization at the watershed scale.

To investigate the sensitivity of our analyses to the influence of including a single very small, highly mitigated watershed (SL1), we repeated the analysis without SL1. This analysis showed that TI was still the best predictor of the distributions of runoff ratios and peak discharges, the breakpoint in slopes of the relationship of peak discharge vs. PPT_E , and discharge response rates. Similarly, tree coverage remained the best predictor of total water yield. The only result that changed was that TI slightly outperformed UI ($R^2 = 0.58$ and 0.54 , respectively) at predicting the time above mean. Since the results were mostly unchanged, we assert that these 15 sites may not have enough SCM mitigation to override the signal of urbanization. This is similar to results from studies in Cincinnati, OH on the effects of implementing rain gardens and rain barrels, which are more distributed forms of stormwater management. The authors found that partial mitigation (which reduced EI by ~9%) made small, but detectable changes to hydrology, however, these changes were not enough to effect stream biota (Shuster and Rhea, 2013; Roy et al., 2014).

Secondly, while one of the strengths of the metrics we chose is that they are easily computed and readily incorporated into policy, their simplicity renders them blind to spatial arrangement. Our analysis was not able to address proximity of impervious surfaces to one another or to the watershed outlet. In a modeling study, Corbett et al. (1997) found that although clustering impervious surfaces did not change event-scale rainfall-runoff ratios compared to scenarios with distributed impervious surfaces, it did increase peak flows. Other modeling study showed that runoff volumes increased (Zhang and Shuster, 2014) and peak discharge decreased (Yang et al.,

2011) as the average hydrologic distance between impervious areas and the outlet decreased. These studies highlight complexity of the interaction between impervious area distribution and stormwater hydrology. Similar information is lacking with regard to the location of SCMs that could also have significant effects on runoff timing and volume. At four sites in the Mid-Atlantic United States, Loperfido et al. (2014) showed that many small, distributed SCMs increased baseflow, increased precipitation-peak discharge breakpoints, and decreased extreme event runoff volumes more than a site with larger, more centralized SCMs. This shows that metrics like TI, UI, and MA may be missing important information about the spatial arrangement of both urban surfaces and SCMs.

Our hypotheses may also have been incorrect because one of two assumptions made in our theoretical framework was invalid. The first assumption was that EI is a better predictor of urban event scale hydrologic response than TI because it accounts for both impervious surfaces and their connectivity. There is a strong theoretical basis for EI as a predictor of urban hydrologic response (Shuster et al., 2005), and numerous modeling (Lee and Heaney, 2003; Guo, 2008; Dewals et al., 2012; Shields and Tague, 2014) and ecological studies (Walsh et al., 2005; Walsh and Kunapo, 2009) have demonstrated the importance of including connectivity. However, no empirical studies known to the authors have actually demonstrated the predictive power of EI with respect to hydrologic response.

The second assumption is that because SCMs are designed to replicate the hydrology in an undeveloped watershed (i.e., meet pre-development conditions), mitigated impervious surfaces are no longer directly connected and therefore not effective (suggested by Walsh et al. (2005)). However, this assertion requires that SCM design standards address all of the changes to flow regimes from urbanization, which some argue is not the case in practice (e.g., Burns et al., 2012;

Askarizadeh et al., 2015). Additionally, the performance of a SCM may vary based on SCM type, design approach, age or a combination of these factors. For example, in-line ponds may provide flow control and water quality benefits for smaller events, but larger events or events in wet antecedent conditions pass through with little retention. Because these ponds are directly on the stream network, they typically mitigate much larger areas than those closer to the ridgeline. This is further complicated because policies that specify SCM design, and therefore performance, vary both across political districts and in the same district through time. If in-line ponds or other SCMs underperform, this will lead to a misrepresentation of metrics like MA, UI and EI. The opposite effect may also be true: in-line ponds that we have ignored from our analysis, along with SCM approaches that provide small amounts of storage such as swales and infiltration trenches, may be affecting the hydrological signal. A potential improvement to these problems is to base the metrics of SCM mitigation on their performance or quality. However, quantifying “quality” in the face of varying design standards and watersheds is challenging. Indeed, this variability of performance is demonstrated by the wide range of volume reduction reported by the International Stormwater Best Management Practice Database (Geosyntec Consultants and Wright Water Engineers, 2011). Finally, it is possible that the effects of a fully functioning SCM on local hydrology do not translate to the watershed scale where multiple SCMs influence streamflow at different times.

6 Conclusions and Implications

The purpose of this study was to test whether or not watershed metrics characterizing both urban development and mitigation with SCM were better able to explain variation in hydrology across sites than those quantifying urbanization or mitigation alone. We analyzed hydrologic regimes for 16 urban watersheds with stormwater control measures in Charlotte, NC. Total

imperviousness, a metric characterizing only urbanization with no information about SCMs, was the best predictor of storm event hydrologic variables including rainfall runoff ratios, peak discharge, the ability of watersheds to buffer small rain events, and the rate of response between peak discharge and precipitation once that buffering capacity has been exceeded. Watershed metrics that included SCM mitigation were only found to be secondary or tertiary controls on hydrologic behavior at the event scale. These data indicate that SCMs implemented at the levels observed are not significantly affecting event hydrology at the watershed scale.

Annual hydrologic behavior, however, was best correlated to metrics other than TI. The total water yield was best related to the fraction of tree coverage, potentially because trees can transpire deeper groundwater between rain events. The time the discharge record spent above mean, a measurement of streamflow flashiness, was best related to unmitigated impervious area, indicating that SCMs may affect baseflow recession at time scales longer than a single event, as defined in this study.

Despite intense efforts to mitigate stormwater runoff through SCMs in newly developed areas and opportunistically through retrofits in older developments, our analysis demonstrates that these investments have not paid off in terms of storm event scale hydrologic response at the watershed scale. Therefore, unless different results are produced by future empirical studies either at sites with a broader range of SCM mitigation (e.g., 20-80%) or that incorporate SCM performance, TI is the watershed metric that policy makers should use to manage watersheds to mitigate impacts to streams. Tree planting may be a desirable management strategy for reducing total runoff, while SCM mitigation of impervious surfaces is a strategy that may reduce hydrologic flashiness on longer time scales by extending baseflow recession.

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704 Table 1: Extent of urban development and SCM mitigation for the 16 analyzed watersheds.

USGS ID	Site Name	Drainage Area (km ²)	Total Imperviousness (TI) [%]	Effective Imperviousness (EI) [%]	Untreated Imperviousness (UI) [%]	Unmitigated Impervious Fraction (UI/TI) [%]	Mitigated Area (MA) [%]	SCM Density [/ km ²]	Tree Coverage [%]
--	SL1	0.15	24	0.2	0.48	2.0	89	20.4	16
--	SP1	1.01	14	5.4	7.4	53	16	2.0	49
--	UL1	1.44	43	28	41	95	16	3.5	41
--	UP1	1.45	27	7.7	12	44	48	3.4	59
214643820	Edwards Branch	2.51	43	--	29	67	28	2.0	45
214645080	Briar Creek Trib.	3.11	32	--	31	97	1.3	0.96	56
2146470	Little Hope Creek	6.81	42	--	39	93	5.5	1.5	50
214297160	Beaverdam Creek	9.62	8.6	--	6.9	80	4.0	1.2	66
214266080	Gar Creek	9.79	4.1	--	4.0	98	1.3	0.10	67
214642825	Briar Creek	13.4	34	--	31	91	5.8	2.2	40
2142914	Gum Branch	13.9	23	--	20	87	10	1.9	50
2146315	Taggart Creek	14.0	37	--	30	81	12	2.9	46
2146562	Campbell Creek	14.7	37	--	29	78	17	2.6	49
2146211	Irwin Creek	15.4	32	--	27	84	9.0	2.1	47
2146409	Little Sugar Creek	31.5	54	--	52	96	3.2	1.5	36
212430293	Reedy Creek	32.8	12	--	11	92	2.9	0.73	61

Table 2: Separated into three sections by horizontal bars. The top section contains the abbreviations and computation methods of the metrics used to characterize the extent of urban development and SCM mitigation in the 16 watersheds. The middle section contains abbreviations and descriptions of the precipitation metrics used in the hydrologic analysis. The bottom section lists the hydrologic variables chosen to characterize each site's hydrologic regime at the event and annual time scales.

Abbreviation/Name	Metric	Unit
<i>Watershed Characteristics</i>		
Area	Total watershed area	km ²
TI	Total imperviousness (total impervious area / total area)	%
UI	Unmitigated imperviousness [(TI – Mitigated impervious area) / total area]	%
EI	Effective imperviousness (directly connected impervious area/ total area)	%
UI/TI	Fraction of impervious area unmitigated (UI/TI)	%
MA	Mitigated Area (SCM mitigated area / total area)	%
SCM Density	(Total number of SCMs in the watershed / total area)	SCMs km ⁻²
Tree Coverage	Fraction of watershed covered by trees (forested area / total area)	%
<i>Precipitation Magnitude and Intensity</i>		
PPT _E	Total event precipitation	mm
I ₁₅	Maximum fifteen-minute precipitation intensity	mm hr ⁻¹
I ₆₀	Maximum sixty-minute precipitation intensity	mm hr ⁻¹
<i>Storm Event Hydrologic Variables</i>		
Runoff ratio	Fraction of rainfall runoff during an event (quick-flow runoff volume / PPT _E)	unitless
Peak discharge	Maximum instantaneous unit discharge during each event	m ³ km ⁻² s ⁻¹
<i>Peak Flow Response to Precipitation</i>		
Peak response rate	Slope of linear model between the logarithm of peak discharge vs. I ₆₀	m ³ km ⁻² s ⁻¹ / mm hr ⁻¹
Breakpoint	PPT _E value where there is a break in slope between peak discharge and PPT _E	mm
<i>Annual Hydrologic Variables</i>		
Water yield	Annual fraction of precipitation leaving watershed as streamflow	mm/mm
Time above mean	Percentage of time discharge was above mean annual discharge	%

712 Table 3: Correlation matrix of 8 site metrics considered in this analysis. Values in the table are
 713 Pearson's product moment correlation coefficient (R). EI correlations are only for the four
 714 highly treated sites, while the rest are for all 16 sites.

	Area	TI	UI	EI*	MA	Tree Coverage	SCM Density	UI/TI
Area	1.00	0.07	0.27	0.64	-0.48	0.12	-0.34	0.49
TI	0.07	1.00	0.91	0.87	-0.01	-0.51	-0.01	0.18
UI	0.27	0.91	1.00	1.00	-0.41	-0.23	-0.34	0.56
EI*	0.64	0.87	1.00	1.00	-0.65	0.24	-0.51	0.93
MA	-0.48	-0.01	-0.41	-0.65	1.00	-0.63	0.91	-0.94
Tree Coverage	0.12	-0.51	-0.23	0.24	-0.63	1.00	-0.76	0.52
SCM Density	-0.34	-0.01	-0.34	-0.51	0.91	-0.76	1.00	-0.82
UI/TI	0.49	0.18	0.56	0.93	-0.94	0.52	-0.82	1.00

715

716 Table 4: Best linear models for predicting the 10th, 30th, 50th, 70th, 90th and 99th percentile
 717 rainfall-runoff ratios and peak unit discharge (log-transformed) using only a single site metric.
 718 Only significant models ($p < 0.05$) with the highest R^2 are reported. This table describes the linear
 719 models shown in Figures 2(a) and 3(a).

Percentile	Rainfall-runoff ratio			Peak unit discharge		
	Metric	R^2	Slope	Metric	R^2	Slope
10	TI	0.76	0.32	TI	0.76	7.8
30	TI	0.75	0.41	TI	0.83	7.8
50	TI	0.74	0.47	TI	0.87	8.1
70	TI	0.72	0.51	TI	0.82	7.3
90	TI	0.43	0.43	TI	0.63	5.8
99	--	--	--	TI	0.45	5.6

720

Figure Captions: Hydrologic response to stormwater control measures in urban watersheds

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Keywords: stormwater management; urban hydrology; impervious surfaces; runoff mitigation; best management practices

Figure Captions

Figure 1: Map of 16 watersheds analyzed in the Charlotte, NC region. The dense cluster of impervious area in the southern portion of the Little Sugar Creek watershed is the city center.

Figure 2: Example of modification to Hewlett and Hibbert (1967) constant line separation method used to define the beginning and end of storm events storm events, and to separate stormflow from baseflow for runoff ratio calculation. Example shown is for the first hydrologic events of the 2012 calendar year from Little Sugar Creek.

Figure 3: Panel (a) plots all observations of event rainfall-runoff ratios vs. TI. The solid lines represent significant linear relationships at selected percentiles, indicated by the color in the legend. Panel (b) shows the residuals of each of the linear models in (a) vs. the percentage of

unmitigated impervious area. Generally, sites with less mitigated imperviousness have a higher runoff ratio, after discounting the effect of total TI.

Figure 4: Panel (a) plots all observations of event peak unit discharge vs. TI. The solid lines are significant linear relationships at selected percentiles, indicated by the color in the legend. Panel (b) shows the residuals of all of the linear models in (a) vs. watershed area. The residuals of the 10th-50th percentiles were most strongly correlated to watershed area. Generally, the residuals decrease as watershed area increases, however the smallest sites deviate from this trend. Panel (c) shows the residuals of the 70th and 90th percentile linear model vs. SCM density, as this produced strongest correlation, although it was heavily leveraged by one site. Panel (d) shows the residuals of the 99th percentile model vs. tree cover, which produced the strongest correlation.

Figure 5: Peak discharge response rate vs. TI. This value was computed as the slope of a linear model constructed between peak discharge and maximum 60-minute rainfall intensity at each site. This plot shows that the sensitivity of peak discharge to equivalent forcing from precipitation increases as TI increases ($R^2 = 0.53$ $p = 0.001$).

Figure 6: Panels (a) and (b) give examples of breaks in the slope of log-transformed peak discharge vs. log-transformed PPT_E at the lowest TI site, Gar Creek (a), and highest TI site, Little Sugar Creek (b). The dashed, vertical lines run through the breakpoints for clarity. Panel (c) shows that as TI increases, the breakpoints decrease indicating a more sensitive response to rainfall and therefore a loss in watershed storage. Different symbols are used to show different levels of statistical significance, and sites with $p > 0.20$ are plotted as open circles near the x-axis to indicate no change in slope, and therefore no storage. The point for UL1 is left hollow despite

44 being significant ($\alpha < 0.15$) because the slope decreases at this breakpoint at this site, rather than
45 increases.

46 Figure 7: (a) Annual water yield fraction decreased with increased tree coverage ($R^2 = 0.52$, $p =$
47 0.002), and (b) time above mean decreased with increased UI ($R^2 = 0.60$, $p < 0.001$).

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6