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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 (4.1–54%) and area mitigated with SCMs (1.3–89%). 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., 2013). 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.

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(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 predevelopment 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., 2016). 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 were 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 (Fig. 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 km^2 to 32.9 km^2 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 km^2) and UL1 (1.5 km^2), were adjacent to one another and are subwatersheds of Edward's Branch and Campbell Creek, respectively. The other two, SP1 (1.0 km^2) and SL1 (0.15 km^2), 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.

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

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