Engineered headwaters can act as sources of dissolved organic matter and nitrogen to urban stream networks

Megan L. Fork, Joanna R. Blaszczak, Joseph M. Delesantro, James B. Heffernan

1Nicholas School of the Environment, Duke University, Durham, NC, USA; 2University Program in Ecology, Duke University, Durham, NC, USA; 3Department of Biology, Duke University, Durham, NC, USA; 4Curriculum in Environment and Ecology, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

Abstract

Improved management of urban stream water quality requires identification of sources contributing excess nutrients and organic matter. While soils and lawns are potential nonpoint sources characterized by large pools of carbon (C) and nitrogen (N), their hydrologic connectivity to streams is often low relative to impervious surfaces. In contrast, engineered headwaters (gutters and pipes) retain smaller pools of C and N, but efficiently process litter into dissolved organic matter and are highly connected to streams during storms. We found that engineered headwaters have the potential to provide more than enough dissolved C and N to account for streamflow fluxes during storms. This finding suggests that engineered headwaters can act not only as stormwater conveyances but as significant proximate sources of dissolved nitrogen and carbon derived from leaching of OM that is stored and processed between storms in these parts of the urban stream network.

Scientific Significance Statement

Streams that drain urban landscapes tend to have poor water quality caused in part by elevated concentrations of nutrients and organic matter (OM). Better understanding of which parts of the landscape contribute high nutrient and OM loads is necessary for effectively mitigating excess nutrients and biological oxygen demand in urban streams. Our work shows that engineered headwaters (i.e., roofs, roadside gutters, and subsurface pipes) are not merely stormwater conveyances but can also act as significant proximate sources of dissolved nitrogen and carbon derived from leaching of OM that is stored and processed between storms in these parts of the urban stream network.

Author Contribution Statement: MLF, JRB, JMD, JBH contributed to the conception of the problem and approach, as well as to data collection. JRB analyzed GIS data with input from JMD, JMD analyzed hydrologic data, and MLF analyzed data from field collections and the C budgets. MLF wrote the manuscript with contributions from the other authors.

Data Availability Statement: Data are available in the CUAHSI Hydroshare repository at http://www.hydroshare.org/resource/571afcb0bbbd14df995db3c472ca9dd3d.

Additional Supporting Information may be found in the online version of this article.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

This article is part of the Special Issue: Carbon cycling in inland waters

Edited by: Emily Stanley and Paul del Giorgio
As the footprint of urbanization increases worldwide, a growing number of streams are subjected to the pressures of draining urban landscapes (Walsh et al. 2005; Grimm et al. 2008). Excess nutrients and labile organic matter (OM) degrade water quality in urban streams and the downstream water bodies into which they flow by promoting eutrophication, harmful algal blooms, and hypoxia (Vitousek et al. 1997; Volkmar and Dahlgren 2006). High concentrations of dissolved organic matter (DOM) have a wide range of ecological and biogeochemical consequences (Prairie 2008; Solomon et al. 2015), and can also increase the cost of drinking water treatment by interacting with disinfection chemicals to form carcinogenic by-products (Chow et al. 2005). Effectively and efficiently managing water quality in urban streams and downstream waterbodies should start with identifying the sources that contribute to high nutrient and OM loads to urban streams.

There are several potential sources of nutrients and DOM to urban streams. Soils and fertilizer used on lawns are generally some of the largest pools of OM and nutrients in urban landscapes (Baker et al. 2001; Aitkenhead-Peterson et al. 2009). Soils underlying irrigated turfgrass in arid regions have been show to leach high concentrations of dissolved organic carbon (DOC) and nutrients (Steele and Aitkenhead-Peterson 2012). Nitrogen stored in soils and the application of fertilizer (a dominant N input to urban catchments) have been implicated as sources of the high nitrate concentrations characteristic of many urban streams (Groffman et al. 2004). While they may be large pools of C and N in urban catchments, soils and lawns may not be the most important contributors of these solutes to urban streams if the frequency and degree of their hydrologic connectivity to streams is relatively low as compared to impervious surfaces.

Engineered flowpaths such as stormwater pipes, roof gutters, and roadside gutters are another potential proximate source of nutrients and OM to urban stormwater. Despite storing smaller pools than those of lawns or soils, these ubiquitous components of urban landscapes may be important sources of nutrient and OM flux since they act as ephemeral headwaters that are highly connected to perennial streams during storms (Kaushal and Belt 2012). Litter that accumulates in these engineered headwaters is often protected from decomposition by short-circuiting infiltration in favor of runoff over and through OM pools that have collected and been processed in engineered headwaters.

In this paper, we develop an annual carbon budget for the engineered headwater catchment comprised by a roof and calculate the contribution of engineered headwaters to event-scale fluxes of total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) from a small urban watershed in Durham, North Carolina. We characterized inputs, outputs, and transformations of carbon from the roofs of single-family homes. We used DOC and TDN concentrations in flow from roof downspouts, roadside gutters, storm water pipes, and catch basins (storm drain inlets with sumps that collect sediment and debris) to calculate the contribution of these engineered headwaters to stormwater solute fluxes from this urban catchment at the event scale. We hypothesized that engineered headwaters may be potentially important sources of dissolved carbon and nutrients derived from the decomposition of leaf litter in gutters and in catch basins.

**Methods**

We determined C budgets for the roofs of three single-family homes, measured storage of OM and TDN at locations throughout the engineered headwaters and measured event scale fluxes in a small urban watershed in Durham, North Carolina over the course of a year from November 2015 through November 2016. Our focal area for this study was a medium density neighborhood occupied mainly by single-family homes on quarter-acre (~ 1000 m²) or smaller lots. The 60 ha catchment is in the temperate U.S. Southeast, contains approximately 400 houses, has 39.4% impervious cover City of Durham Stormwater and GIS Services (2016), and considerable canopy cover (~ 60%, i-Tree Landscape v2.1.2) with mature willow oaks (Quercus phellos), originally planted in the 1930s, as the dominant canopy tree (Durham City-County Environmental Affairs Board 2015; Cooper et al. 2016).

We measured concentrations of DOC and TDN in stormwater for a total of nine storms: We collected stormwater from downspouts of three houses, three roadside gutters, three stormwater pipe outfalls, and the stream at the watershed outlet. A regression of sampled DOC concentration against rainfall prior to collection time showed no significant evidence of dilution over the majority of storms (for rainfall up to 22 mm; Supporting Information Fig. S3), despite a very brief first flush of DOC from roofs (Supporting Information Fig. S3). While first flushes are commonly observed in solutes and turbidity in urban stormwater (Sansalone and Buchberger 1997; Lee et al. 2002), accurately characterizing these requires specialized sampling (Lee et al. 2002). Because the first flush we observed was brief and because we saw no evidence of sustained dilution over storms, we used the mean seasonal concentration for stormwater draining from each infrastructure type (i.e., roof, road, etc.) multiplied by event rainfall volume to determine event-scale DOC flux (see Supporting Information).
Annual carbon budgets for the roofs of three single family homes

We measured areal rates of litterfall in the yards of five properties (for three of which roof C budgets were determined) and assumed that rates measured in baskets represented areal rates of litter input to roofs and roads (Supporting Information Fig. S1). Litter loading was estimated by multiplying planimetric roof area by measured areal litterfall rate. We estimated DOC inputs to roofs as the sum of contributions from throughfall and rainfall (see Supporting Information). Using summer aerial images (Google Earth V7.1.5.1557 2015), we estimated the proportions of roofs directly beneath tree canopy (Supporting Information Fig. S2) and used these proportions to determine the loads of DOC from throughfall vs. rainfall for each storm, multiplying by measured concentrations and the total rainfall volume for each roof.

To estimate the output of OM as particulate matter and decomposition to CO2, we conducted a litter decomposition experiment. We compared mass loss of senesced willow oak leaves from coarse polyethylene mesh and fine nylon mesh litter bags that were deployed in the roof gutters of five houses and inside five catch basins. We fit decay functions to the proportion of C remaining vs. time and multiplied by the measured C standing stock to infer the total mass loss from each roof or catch basin (Supporting Information Fig. S4). We assumed that mass loss from coarse litter bags was the sum of DOC loss, particulate OC loss, and decomposition to CO2, while the mass loss from fine litter bags was the sum of DOC loss and decomposition to CO2 only, allowing us to estimate particulate loss through downsputs. We independently measured DOC flux from roof gutters and storm-water pipes via grab sampling and were therefore able to determine decomposition to CO2 by difference.

The standing stock of C in roof gutters was assessed by measuring the C content of accumulated OM in a 50 cm length of gutter and multiplying this mass by the total gutter length of houses (see Supporting Information). Repeated measurements allowed us to quantify the change in C storage in gutters over the study period.

Estimation of event C and N fluxes from engineered headwaters at the catchment scale

To estimate the total event-scale flux from roofs within the catchment, we began by converting mean event-scale fluxes measured for individual roofs into areal rates. Using 1 m resolution planimetric maps of catchment impervious surface City of Durham Stormwater and GIS Services (2016), we identified roofs within the catchment and then scaled fluxes of DOC and TDN to the total roof area calculated in ArcGIS 10.4. To estimate the total event-scale flux from road gutter sub-catchments and piped sub-catchments, a 1-m-resolution digital elevation model (DEM) based on 2016 LiDAR data from the 3D Elevation Program (U.S. Geological Survey 2016) was used to delineate the sub-catchments using Whitebox GAT “Montreal” v. 3.4.0 (Lindsay 2016). We assumed that only runoff from impervious surfaces contributed to each of our headwater sampling points (downspouts, roadside grates, and pipe outfalls) and calculated the impervious area for each sub-catchment. To estimate the DOC loading to impervious surfaces from throughfall and direct rainfall we used the average canopy cover in the catchment (i-Tree Cooperative 2016). Measured concentrations at the sub-catchment pour points during individual events were then used to determine areal rates of C and N loading to roads. Multiplying by total catchment road area gave us an estimate of their total contribution to the measured event flux at the pour point.

Results

Annual carbon budget for a roof

The main annual input of C to roofs was litterfall (10.03 ± 0.53 kg C) with another 2.49 ± 3.71 kg C entering as DOC in throughfall and rainfall (Fig. 1). Areal litterfall C inputs ranged from a midwinter low of 0.029 ± 0.038 g C m⁻² d⁻¹ up to 1.45 ± 0.66 g C m⁻² d⁻¹ in late autumn, with a secondary peak of 0.28 ± 0.24 g C m⁻² d⁻¹ in mid-spring, coincident with blossom fall and the year’s highest pollen counts.

Export of C via downsputs (as DOC: 5.42 ± 0.05 kg C, as POC: 0.616 ± 0.318 kg C) was the largest measured C loss from roofs. Assuming negligible processing of the DOM that enter roofs in rainfall and throughfall, we can calculate litter-derived DOC export as 291 mg DOC [g litter C]⁻¹, or 29% of litter C inputs.

Litter decomposition in roof gutters was best described by a two-component exponential decay model with slow and fast pools (Supporting Information Fig. S4). The slow proportion comprised 79.2% of the OM pool and the decay coefficient did not differ significantly from zero (i.e., no appreciable decomposition of the slow pool), while the fast component was 18.7% of the pool with a decay coefficient, k, of 0.044. In catch basins, litter decomposition was best described by simple exponential decay with a k of 0.00343. Decomposition to CO2 was a minor annual flux of C from individual roofs (0.202 ± 0.187 kg C) and catch basins (0.875 ± 0.545 kg C). Removal of C from gutters (by wind or gutter cleaning) was 6.10 ± 3.76 kg C, a value similar to total annual DOC export. We measured an average standing stock of 0.929 ± 0.153 kg C with a minor annual flux of C from individual roofs (1.45 ± 0.153 kg C) and catch basins (0.875 ± 0.545 kg C).

Longitudinal patterns of solutes through the continuum of engineered headwaters

Concentrations of DOC and TDN averaged 88.2 mg DOC L⁻¹ and 5.50 mg TDN L⁻¹ in road runoff and 83.0 mg DOC L⁻¹ and 4.56 mg TDN L⁻¹ in pipe outfalls, with both locations significantly higher than stream concentrations (DOC: p-values < 0.001 and = 0.002, respectively; TDN: p-values < 0.001 and < 0.024, respectively, Fig. 2). DOC and TDN concentrations ranged from minima of 2.94 mg DOC L⁻¹ and 0.114 mg TDN L⁻¹ in...
roof outflow to as high as 436.4 mg DOC L\(^{-1}\) and 31.1 mg TDN L\(^{-1}\) in road runoff. DOC concentrations in road runoff were also significantly higher than in roof gutter outflows \((p = 0.039)\). We observed higher concentrations of DOC and TDN in spring vs. other times of year \((p < 0.001)\) for both DOC and TDN. These high concentrations of DOC and TDN in mid-spring coincide with blossom fall and the year’s highest pollen counts.

**Estimated event-scale fluxes of stormwater and solutes from the urban catchment**

We measured fluxes of water, chloride, DOC, and TDN at the catchment outlet for six storms and estimated the contributions of components of the engineered headwater to these fluxes (Fig. 3; Supporting Information Table S1). In general, we found that the rainfall that falls on connected roofs and roads in the catchment can account for an average of 85% of streamflow across a range of storm magnitudes (Fig. 3; Supporting Information Table S1).

Mass flux for an average storm at the catchment outlet was 33.4 ± 30.4 kg Cl\(^-\), 51.9 ± 25.3 kg DOC, and 2.42 ± 1.70 kg TDN. On average, areal chloride fluxes from roofs were 26.1 ± 24.9 mg Cl\(^-\) mg\(^{-2}\), areal DOC fluxes were 580 ± 630 mg C m\(^{-2}\), and areal TDN fluxes were 41.2 ± 46.1 mg N m\(^{-2}\), with high variability resulting from variation in event magnitude. Scaled to total roof area in the catchment, the average event-scale yields were 2.2 ± 2.1 kg Cl\(^-\), 48.8 ± 52.9 kg C, and 3.5 ± 3.9 kg N from roofs (Supporting Information Table S1). However, it has been estimated that only 11% of roofs in this neighborhood have direct hydrologic connections to impervious flowpaths (Miles 2014), so their actual contribution to solutes loads in stream stormwater is likely much lower; in an average storm, we estimate directly connected roofs contribute 0.74% ± 0.65% of the chloride flux, 10.0% ± 8.6% of the DOC flux, and 14% ± 15% of the TDN flux to the stream (Fig. 3).

Solute fluxes through roadside gutters (pour points of the next largest catchments we considered, and in which connected roofs are nested) were 57.1 ± 66.8 mg Cl\(^-\) m\(^{-2}\), 938 ± 877 mg C m\(^{-2}\), and 67.1 ± 83.5 mg N m\(^{-2}\) on average. These scale to fluxes of 9.5 ± 11.4 kg Cl\(^-\), 157 ± 146 kg C, and 11.2 ± 14.3 kg N from all roads during the average storm, or 12% ± 13% of chloride, 306% ± 202% of DOC and 430% ± 441% of TDN event-scale fluxes in streamflow (Fig. 3; Supporting Information Table S1).

We assumed that 10% of roof area plus 100% of road area comprised all of the directly connected impervious area contributing runoff to the stream, but that OM stored in the subsurface pipe system (including catch basins) may contribute additional solutes to flux through the catchment outlet. Total event-scale fluxes through storm drain outlets (downstream of roofs and roads) averaged 193 ± 408 kg C and 11.9 ± 35.0 kg N, making up 323% ± 299% of DOC and 387% ± 380% of the average event-scale fluxes in streamflow.

**Discussion**

**Engineered headwaters can be disproportionate sources of dissolved organic material**

We measured the fluxes and transformations of OM in an urban catchment Figure 4 and found that engineered
headwaters are major sources of C and N to the stream during storms. Litter that falls onto impervious surfaces accumulates in catch basins and gutters and is processed into readily-mobile DOM between storms (Hobbie et al. 2014). These areas then become source areas of DOC and nutrients when they are connected to the stream by ephemeral flow (Hobbie et al. 2014; Bratt et al. 2017). We found that about one third of C that enters roof gutters as leaf litter exits as DOC through downspouts, and in some cases these downspouts are routed directly to roads and that can drain quickly to streams. In addition, we estimated that engineered headwaters emit more than enough DOC and TDN to account for stormflow fluxes.

We estimate that roofs contribute element fluxes disproportionately higher than their areal coverage in the catchment. Although roofs represent only 14.1% of the land cover in this catchment, they would have the potential to contribute up to 100% of the average stormflow DOC load if (1) all roofs allowed litter to collect in gutters and (2) were directly connected to the impervious flowpaths (Supporting Information Table S1). In fact, parcel-scale BMPs such as cisterns, rain gardens, and simple routing of gutter outflows over vegetated lawns (downspout disconnections) decrease the contribution of roof-derived stormwater to streams (Dietz 2007; Loperfido et al. 2014; Miles 2014).

The fluxes of DOC and TDN we estimate from roads exceed the fluxes measured in the stream (Fig. 3). While source limitation during very large storms (see Supporting Information) may account for some of this discrepancy, retention of DOC and TDN within the stormwater infrastructure and infiltration of stormwater from leaky pipes into the urban groundwater system (Fork 2017) likely play roles in retaining nutrients and DOM in runoff from impervious surfaces. We suggest that this pattern of high DOC and TDN fluxes from engineered

**Fig. 2.** Concentrations of DOC and TDN measured during stormflow at different types of infrastructure, arranged longitudinally, in an urban catchment in Durham, North Carolina.
headwaters may hold wherever canopy cover over impervious surface is high, as observed by Janke et al. (2017). The event-scale mass fluxes we measured in this study indicate a high potential for engineered headwaters to influence catchment-scale organic matter fluxes. If we assume that DOC concentrations in the measured storms (Supporting Information Fig. S5) are representative of DOC dynamics in the 99 storms $>1$ mm during our study period and that the periodic baseflow samples are representative of interstorm conditions, the annual areal flux from our 60 ha catchment would be $173 \pm 89$ kg DOC ha$^{-1}$. This is considerably higher than the annual export of DOC from forested watersheds throughout the eastern U.S. (Raymond and Saiers 2010), but similar to the DOC yield that would be predicted for the highly urban Anacostia watershed near Washington, D.C. given the 1518.9 mm of rainfall during our study period (Smith and Kaushal 2015). By design, engineered headwaters have high hydrologic connectivity to streams, and lack mineral soils that could contribute to sorption and storage of DOM (Jardine et al. 1989; Kaiser and Guggenberger 2000). The result is high yields of soluble material from litter that falls on engineered headwaters Figure 4, and potentially disproportionately contributions to catchment scale fluxes.

Further evidence of the importance of engineered headwaters as source areas of C and N to urban streams is the rapid increase in stream concentrations of DOC and TDN which remain elevated during storms (Supporting Information Fig. S6), when impervious surfaces become hydrologically connected to the stream. Such behavior has been observed for DOC in other urban catchments (Hook and Yeakley 2005; Smith and Kaushal 2015) and suggests that expansion of the stream network during storms connects new sources of DOC and TDN located in engineered headwaters. These findings do not support a model of impervious surfaces as mere connectors of biogeochemical sources to streams, but rather that these flowpaths are also sources, sinks, and reactors that act as control points for watershed exports (Bernhardt et al. 2017). The role of gutters and pipes

---

**Fig. 3.** Comparisons of water (A) and solute (B–D) fluxes for catchment-scale estimates of runoff from engineered headwaters and in streamflow measurements for seven storms. Estimates of fluxes from roof runoff assume that 10% of the total roof area in the catchment is directly connected to impervious flowpaths, while we assume 100% hydrologic connectivity for roads. Stormwater pipes do not contribute additional water runoff (because they drain surface infrastructure already considered in our roof and road estimates), but they do storm OM in catch basins and can therefore be additional sources of solutes (B–D).
and indeed, their design) in concentrating and routing precipitation from impervious landscape patches to stream channels is well known. However, prevailing conceptual models have implicitly or explicitly ascribed to pipes the role of simply connecting the sources of OM and nutrients to streams and have not recognized these landscape elements as bioreactors able to process litter into DOM (but see Hobbie et al. 2014; Bratt et al. 2017). While the loads of OM stored in the engineered headwaters may be smaller than those in lawns and soils, these areas can store readily mobilizable OM and have the potential to be important proximate sources of dissolved OM and nutrients to streams during storms. This is likely to be true in regions and neighborhoods with high deciduous canopy cover contributing leaf litter to engineered headwaters such as older neighborhoods in the Midwest and Piedmont, but may be less important in neighborhoods that are newer (Lowry et al. 2012), of lower socioeconomic status (Schwarz et al. 2015), or in other regions where tree canopy is more sparse.

**Implications for urban stream management**

Gutter cleaning and street sweeping are potentially significant pathways of OM removal from the headwater stream network. Previous research has shown that more dense tree
canopy is associated with higher nutrient loads in urban streams (Janke et al. 2017), and that street sweeping can significantly reduce export (Hobbie et al. 2014; Selbig 2016) of N and P during storms, but weather conditions may decrease the effectiveness of this nutrient removal pathway (Bratt et al. 2017). The effects of litter removal may be especially beneficial in terms of controlling P export to urban waterways (Hobbie et al. 2014; Selbig 2016), and targeting for P may also yield benefits in terms of C and N. Yard waste collections may also be a significant vector of nutrient and OM from the catchment (Templer et al. 2015), but litter that falls on lawns and gardens may have lower relative connectivity to streams than litter falling on impervious surfaces.

Interventions that remove CPOM from these highly connected headwater flowpaths (e.g., cleaning of catch basins, street sweeping) or that disconnect gutters from streams (e.g., rain gardens, downspout disconnection) may be effective solutions to mitigate nutrient loads delivered to urban streams in stormwater and provide management options when more typical BMPs such as retention/detention ponds can’t be retrofitted into existing developments. These interventions are becoming increasingly common non-structural BMPs implemented by municipalities (City of South Lake Tahoe 2013; Donner et al. 2015). State, municipal, and community groups encourage and credit interventions managed by individual homeowners such as downspout disconnection and rainwater harvest in this catchment (NC Rules Review Commission 2011; City of Durham Stormwater and GIS Services 2015). On the municipal scale, removal of OM from roadside gutters and storm drains are currently being considered as creditable nutrient reduction strategies by the NC Department of Environment and Natural Resources.

**Implications for catchment science**

Catchment-scale budgets have been used as a tool to understand how landscapes transport, retain, and transform elements and OM (Bornmann and Likens 1967; Fisher and Likens 1972; McDowell and Likens 1988; Schlesinger and Bernhardt 2013) and can provide insight about the internal processes regulating elements in catchments where loading, soils, and hydrologic connectivity are relatively homogenous. Such an approach can be especially enlightening when paired catchments can be compared (e.g., Johnson and Swank 1973; Martin et al. 2000). However, “black boxing” the catchment as an individual unit may impede mechanistic understanding or inference in systems characterized by high spatial heterogeneity in sources and transport of the element(s) of interest. Disparities in surface hydrologic connectivity can cause significant differences in the potential vs. actual importance of source areas of OM and nutrients in stormwater to streams (Miles and Band 2015).

Here, we applied a nested catchment mass balance approach that allows us to determine the importance of discrete urban landscape elements as source areas and flowpaths. Although urban soils and lawns have high potential loads of C and N to urban streams, their actual contribution to catchment-scale flux in this system appears to be less important than engineered headwaters that have smaller loads but often greater hydrologic connectivity to the surface stream. The most valuable applications of this approach will be in catchments that feature heterogeneity in the source concentrations in patches or in the degree of connectivity to the stream network, as is likely to be common in urban catchments (Hook and Yeakley 2005; Miles and Band 2015) and other landscapes (McGlynn and McDonnell 2003; Laudon et al. 2011; Herndon et al. 2015). Applying this nested catchment mass balance approach to formerly overlooked but relatively bounded subsystems like engineered headwaters can help provide mechanistic understanding of sources and transport of chemical constituents in urban catchments.

**References**

Aitkenhead-Peterson, J. A., M. K. Steele, N. Nahar, and K. Santhy. 2009. Dissolved organic carbon and nitrogen in urban and rural watersheds of south-central Texas: Land use and land management influences. Biogeochemistry 96: 119–129. doi:10.1007/s10533-009-9348-2

Baker, L. A., D. Hope, Y. Xu, J. Edmonds, and L. Lauver. 2001. Nitrogen balance for the Central Arizona-Phoenix (CAP) ecosystem. Ecosystems 4: 582–602. doi:10.1007/s10021-001-0031-2

Bernhardt, E. S., J. R. Blaszczyk, C. D. Ficken, M. L. Fork, K. E. Kaiser, and E. C. Seybold. 2017. Control points in ecosystems: Moving beyond the hot spot hot moment concept. Ecosystems 20: 665. doi:10.1007/s10021-016-0103-y

Bornmann, F. H., and G. E. Likens. 1967. Nutrient cycling. Science 155: 424–429. doi:10.1126/science.155.3761.424

Bratt, A. R., J. C. Finlay, S. E. Hobbie, B. D. Janke, A. C. Worm, and K. L. Kemmitt. 2017. Contribution of leaf litter to nutrient export during winter months in an urban residential watershed. Environ. Sci. Technol. 51: 3138–3147. doi:10.1021/acs.est.6b06299

Chow, A. T., S. Gao, and R. A. Dahlgren. 2005. Physical and chemical fractionation of dissolved organic matter and trihalomethane precursors: A review. J. Water Supply Res. Technol. AQUA 54: 475–507.

City of Durham Stormwater and GIS Services. 2015. State of Our Streams: 2015.

City of Durham Stormwater and GIS Services. 2016. Impervious areas, paved areas.

City of South Lake Tahoe. 2013. City of South Lake Tahoe Pollutant Load Reduction Plan.

Cooper, G., A. Liberti, and M. Asch. 2016. Replanting Durham’s urban forest. Duke Univ.

Dietz, M. E. 2007. Low impact development practices: A review of current research and recommendations for
future directions. Water Air Soil Pollut. 186: 351–363. doi:10.1007/s11270-007-9484-z
Donner, S., and others. 2015. Recommendations of the expert panel to define removal rates for street and storm drain cleaning practices.
Durham City-County Environmental Affairs Board. 2015. Recommendations for sustaining a healthy urban forest in Durham, NC.
Johnson, P. L., and W. T. Swank. 1973. Studies of cation sorption to mineral surfaces in the preservation of organic matter in soils. Org. Geochem. 31: 711–725. doi:10.1016/S0146-6380(00)00046-2
Kaushal, S. S., and K. T. Belt. 2012. The urban watershed continuum: Evolving spatial and temporal dimensions. Urban Ecosyst. 15: 409–435. doi:10.1007/s11252-012-0226-7
Laudon, H., M. Berggren, A. Ågren, I. Buffam, K. Bishop, T. Grabs, M. Jansson, and S. Köhler. 2011. Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: The role of processes, connectivity, and scaling. Ecosystems 14: 880–893. doi:10.1002/1052-1138-2319
Lee, J. H., K. W. Bang, J. L. H. Ketchum, J. S. Choe, and M. J. Yu. 2002. First flush analysis of urban storm runoff. Sci. Total Environ. 293: 163–175. doi:10.1016/S0048-9697(02)00006-2
Lindsay, J. B. 2016. Whitebox GAT: A case study in geomorphometric analysis. Comput. Geosci. 95: 75–84. doi:10.1016/j.cageo.2016.07.003
Loperfido, J. V., G. B. Noe, S. T. Jarnagin, and D. M. Hogan. 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. J. Hydrol. 519: 2584–2595. doi:10.1016/j.jhydrol.2014.07.007
Lowry, J. H., M. E. Baker, and D. Ramsey. 2012. Determinants of urban tree canopy in residential neighborhoods: Household characteristics, urban form, and the geophysical landscape. Urban Ecosyst. 15: 247–266. doi:10.1007/s11252-011-0185-4
Martin, C. W., J. W. Hornbeck, G. E. Likens, and D. C. Buso. 2000. Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Can. J. Fish. Aquat. Sci. 57: 19–29. doi:10.1139/F00-106
McDowell, W. H., and G. E. Likens. 1988. Origin, composition and flux of dissolved organic-carbon in the Hubbard Brook Valley. Ecol. Monogr. 58: 177–195. doi:10.2307/2937024
McGlynn, B. L., and J. J. McDonnell. 2003. Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. Water Resour. Res. 39: 1090. doi:10.1029/2002WR001525
Miles, B. C. 2014. Small-scale residential stormwater management in urbanized watersheds: A geoinformatics-driven ecohydrology modeling approach. Univ. of North Carolina at Chapel Hill.
Miles, B., and L. E. Band. 2015. Green infrastructure stormwater management at the watershed scale: Urban variable source area and watershed capacitance. Hydrol. Process. 29: 2268–2274. doi:10.1002/hyp.10448
NC Rules Review Commission. 2011. Falls Nutrient Strategy. 46. Prairie, Y. T. 2008. Carbo-centric limnology: Looking back, looking forward. Can. J. Fish. Aquat. Sci. 548: 543–548. doi:10.1139/F08-011
Raymond, P. A., and J. E. Saiers. 2010. Event controlled DOC export from forested watersheds. Biogeochemistry 100: 197–209. doi:10.1007/s11307-010-9416-7
Sansalone, J. J., and S. G. Buchberger. 1997. Partitioning and first flush of metals in urban roadway storm
water. J. Environ. Eng. 123: 134–143. doi:10.1061/(ASCE)0733-9372(1997)123:2(134)

Schlesinger, W. H., and E. S. Bernhardt. 2013. Biogeochemistry: An analysis of global change, 3rd ed. Academic Press.

Schwarz, K., and others. 2015. Trees grow on money: Urban tree canopy cover and environmental justice. PLoS One 10: 1–17. doi:10.1371/journal.pone.0122051

Selbig, W. R. 2016. Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater. Sci. Total Environ. 571: 124–133. doi:10.1016/j.scitotenv.2016.07.003

Smith, R. M., and S. S. Kaushal. 2015. Carbon cycle of an urban watershed: Exports, sources, and metabolism. Biogeochemistry 126: 173–195. doi:10.1007/s10533-015-0151-y

Solomon, C. T., and others. 2015. Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: Current knowledge and future challenges. Ecosys- tems 18: 376–389. doi:10.1007/s10021-015-9848-y

Steele, M. K., and J. A. Aitkenhead-Peterson. 2012. Urban soils of Texas: Relating irrigation sodicity to water-extractable carbon and nutrients. Soil Sci. Soc. Am. J. 76: 972. doi:10.2136/sssaj2011.0274

Templer, P. H., J. W. Toll, L. R. Hutyra, and S. M. Raciti. 2015. Nitrogen and carbon export from urban areas through removal and export of litterfall. Environ. Pollut. 197: 256–261. doi:10.1016/j.envpol.2014.11.016

U.S. Geological Survey. 2016. The National Map: 3DEP products and services. 3D Elev. Proj.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of Earth’s ecosystems. Science 277: 494–499. doi:10.1126/science.277.5325.494

Volkmar, E. C., and R. A. Dahlgren. 2006. Biological oxygen demand dynamics in the Lower San Joaquin River, California. Environ. Sci. Technol. 40: 5653–5660. doi:10.1021/es0525399

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. I. Morgan. 2005. The urban stream syndrome: Current knowledge and the search for a cure. J. North Am. Benthol. Soc. 24: 706–723. doi:10.1899/04-028.1

Acknowledgments

We would like to thank E. Baruch, M. Zimmer, J. Mallard, C. Clifford, E. Isherwood, C. Chamberlain, J. Gardner, V. Green, L. McGill, and E. Van- derJeugdt for help with field work. Access to field sites was granted by M. Zimmer, J. Blaszczak, J. Coughlan, J. Harkness, T. Parolari, and E. Caves. H. Dutra with Durham’s Community Conservation Assistance Pro- gram provided information to aid estimation of downspout disconnec- tion. E.S. Bernhardt’s insights improved and clarified the presentation of the data, and M. Zimmer provided helpful comments on earlier versions of this manuscript. This work was funded in part by a National Science Foundation grant (#1258017) awarded to E.S. Bernhardt and D.L. Urban and is partially based on work supported by the National Science Foundation Graduate Research Fellowship (NSF GDE-1644868). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Submitted 16 June 2017
Revised 22 November 2017
Accepted 11 January 2018