Urban beaver ponds show limited impact on stream carbon quantity in contrast to stormwater ponds

Julian Sheppy[1,2], Elizabeth B. Sudduth[3], Sandra Clinton[4], Diego Riveros-Iregui[5], Sarah H. Ledford[1*]

[1]Department of Geosciences, Georgia State University, Atlanta, GA, USA, ORCID: 0000-0003-1802-1961
[2]Centre for Coastal Biogeochemistry, Southern Cross University, Lismore, NSW, Australia
[3]Department of Biological Sciences, Georgia Gwinnett College, Lawrenceville, GA, USA
[4]Department of Geography and Earth Sciences, University of North Carolina Charlotte, Charlotte, NC, USA
[5]Department of Geography, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

*Corresponding author: sledford@gsu.edu

Julian Sheppy ORCID 0009-0001-7610-125X
Elizabeth Sudduth ORCID 0000-0001-8274-8159
Sandra Clinton ORCID 0000-0002-8042-6671
Diego Riveros-Iregui ORCID 0000-0003-0919-2988
Sarah H. Ledford ORCID 0000-0003-1802-1961

Abstract

Urban beaver and stormwater ponds provide hydrologic retention in the landscape while collecting dissolved organic matter (DOM)-rich runoff that can promote primary productivity. Our objective was to determine how the quantity, source, and bioavailability of DOM changed across urban stormwater and beaver pond systems, then compare the two pond types to each other. We measured dissolved organic carbon (DOC) and specific ultraviolet absorbance at 254 nm ($SUVA_{254}$) from upstream, within, and downstream of seven ponds in Atlanta, GA, USA biweekly from March to December 2021. Additionally, we completed 28-day laboratory microcosm incubations of pond in- and out-flow during summer and autumn of 2021. We found higher concentrations of DOC in the pond and outflows of stormwater ponds, whereas beaver ponds did not cause any change. Effects of pond type (beaver vs. stormwater) were greater than other controls on concentration, including flow and season. In contrast, $SUVA_{254}$ showed a shift toward more aromatic carbon below both systems without a clear difference between pond types. Beaver and stormwater pond outflows had similar ranges of DOM bioavailability in summer, but during autumn bioavailability at both sites declined to near zero. Overall, we found that stormwater ponds and beaver ponds had similar impacts on aromaticity and bioavailability, however stormwater ponds increased the quantity of DOC while beaver ponds did not. This suggests that in addition to increasing hydrologic residence times in urbanized systems, urban beaver ponds may limit the export of bioavailable carbon and reduce microbial processing downstream.

Key words: Dissolved organic carbon, urban, beaver pond, stormwater pond, $SUVA_{254}$

Acknowledgements

We thank Claire Wadler and Alisha Gugielmi for their field work assistance along with numerous undergraduate lab assistants. Thanks to the Atlanta Department of Watershed Management and the Department of Parks and Recreation, Livable Buckhead, and the Gwinnett County Department of Community Services for site access.

1. Introduction

As the population of urban areas around the United States increases, urban sprawl is occurring at unprecedented rates, especially in the southeastern U.S. (Terando et al., 2014). Metropolitan centers in the Piedmont ecoregion, such as Atlanta, GA, are projected to expand 165% by 2060 (Terando et al., 2014). As a result, more undeveloped or agricultural land will be converted to impervious surfaces such as rooftops, concrete, and asphalt. This process hinders infiltration and increases surface runoff (Leopold, 1968). These changes are well known to have negative effects on the morphology, discharge, and ecological health of streams and rivers in urban environments. Along with changes in flow regimes (Bhaskar et al., 2016, 2020; Ledford et al., 2020; Leopold, 1968), replacing vegetated land with impervious surfaces and removing riparian vegetation reduces allochthonous inputs to streams and rivers (Chen et al., 2017; Hosen et al., 2014; Parr et al., 2015). This reduction has been described as a simplification or homogenization of the dissolved organic matter (DOM) pool (Bhattacharya & Osburn, 2020; Coble et al., 2019, 2022; Parr et al., 2015; Roebuck et al., 2020). Along with increases in other nutrients, urban waterbodies show increased autochthonous organic matter concentrations, enhanced eutrophication, and elevated greenhouse gas emissions compared to forested waterbodies (Goeckner et al., 2022; Kalev & Toor, 2020; McEnroe et al., 2013). Green stormwater infrastructure is one approach being used in urbanized areas to address high volumes of stormflow (e.g., Zuniga-Teran et al., 2020), but there are conflicting reports on the impacts of such practices on water quality, including carbon (Jefferson et al., 2017). Nonetheless, urban beaver ponds have been widely overlooked as a potential nature-based approach to restoring urban ecosystems by addressing water quality (Ledford et al., 2023) and quantity issues (Bailey et al., 2018), despite their positive impacts on carbon cycling (Wohl et al., 2012).

Cities are responsible for substantial changes to global biogeochemical cycles with major implications for water quality, stream temperatures, air pollution, and waste production (Pouyat et al., 2007). Urbanized streams in particular have caused alterations to the carbon cycle through changes in stream DOM quality (Hosen et al., 2014), leading to changes in stream metabolism as well as higher concentrations and fluxes of CO_2 and CH_4 to the atmosphere (Gu et al., 2022). Bacteria and macroinvertebrates consume organic matter in the water column and sediment of streams and rivers during respiration and release CO_2 into the water, which then diffuses to the atmosphere as water becomes supersaturated with CO_2 (Battin et al., 2008; Fischer & Pusch, 2001; Romeijn et al., 2019; Tank et al., 2010). A growing body of literature shows that this metabolic activity in freshwater is a significant contributor to the global carbon cycle (Goeckner et al., 2022; Romeijn et al., 2019; Williams et al., 2013). However, our understanding of the drivers of carbon quality and processing in urban streams remains limited (Gu et al., 2022).

Green stormwater infrastructure, specifically stormwater management ponds, collect nutrient-rich runoff from the surrounding urban landscape, becoming hotspots for increased primary production, algal blooms, and microbial respiration (Goeckner et al., 2022; Lusk & Toor, 2016). This microbially-derived material has a low aromaticity and molecular weight, making it comparatively bioavailable (Lennon & Pfaff, 2005; McKnight et al., 2001). Research has shown that as the concentration of biodegradable DOM increases, so does in-stream greenhouse gas production (Bodmer et al., 2016; Romeijn et al., 2019). Urban stormwater basins tend to exacerbate this issue because photosynthesis occurs readily in ponds and lakes due to their large surface area being exposed to direct sunlight. As a result, retention ponds can support increased microbial metabolism (Goeckner et al., 2022; Lusk & Toor, 2016).

Beaver dams and beaver dam analogs (BDAs) have been suggested as a more natural and less expensive way of providing similar benefits to urban areas as stormwater management ponds (Bailey et al., 2018). BDAs are human-made structures, typically either partially or fully spanning a stream width, meant to mimic the geomorphic and hydrologic impacts of beaver dams to restore stream reaches (Pollock et al., 2014). However, little research has been conducted to evaluate the effect of beaver activity on hydrologic retention or water quality in urban environments. Like stormwater ponds, beaver ponds have been shown to reduce stream velocity and increase water and nutrient retention (Majerova et al., 2015; Puttock et al., 2017; Westbrook et al., 2020). But unlike human-made basins, beaver dams often cause flooding that inundates nearby soil and reconnects a stream with its floodplain (Gorczyca et al., 2018; Green & Westbrook, 2009; Pollock et al., 2007; Westbrook et al., 2006), which has been shown to increase particulate organic carbon storage and increase downstream export of dissolved organic carbon (DOC; Błędzki et al., 2011; Cazzolla Gatti et al., 2018; Correll et al., 2000; Law et al., 2016; Naiman et al., 1994; Puttock et al., 2017). Beaver ponds increase lateral hydrologic connectivity (Westbrook et al., 2006) and inundate riparian soils, a source of allochthonous organic matter (Catalán et al., 2017). They also cause the deposition of fine sediment and organic matter, forming beaver wetlands (Wohl et al., 2012). In urban areas, the introduction of this less-bioavailable organic matter could diversify the DOM pool which may impact metabolic activity within beaver ponds and downstream in a way stormwater ponds do not (Lennon & Pfaff, 2005).

Given that beaver populations in developed areas are growing (Bailey et al., 2018; Ledford et al., 2023), urban environmental policies can and should incorporate them in multiple-benefit catchment management strategies that embrace natural flood management objectives (Puttock et al., 2021). Beaver dams and beaver dam analogs have the potential to counteract urban-driven hydrologic issues by altering flow regimes, and therefore could be used as natural flood management options (Puttock et al., 2021). However, we need a better understanding of the impact urban beaver ponds have on the carbon cycle to fully assess their potential impact across entire landscapes.

In this study, we look at how beaver and stormwater ponds impact the quantity (assessed through DOC concentration), quality (assessed through $SUVA_{254}$), and bioavailability (assessed through dark bottle incubations) of carbon in urban streams throughout Atlanta, GA. We hypothesize that (1) DOC concentrations increase in both beaver and stormwater ponds, and thus also in their outflows. We also hypothesize that, unlike stormwater ponds, beaver ponds are sites for the addition of allochthonous, more aromatic organic matter to urban fluvial systems, as has been seen in forested environments (Naiman et al., 1994) and thus (2) $SUVA_{254}$ increases within and below urban beaver ponds relative to stormwater ponds and (3) DOC in stormwater pond outflow is more bioavailable because it is dominated by organic matter from autochthonous sources while beaver pond outflow, with more allochthonous sources, shows less DOC bioavailability. Finally, we hypothesize that (4) seasonal and hydrological impacts on carbon quantity and source driven by changes in flow, leaf litter input, and light availability outweigh differences between site types.

2. Materials and Methods

2.1 Study Sites

Seven streams in the greater Atlanta, GA, area were sampled for this study, across Fulton, DeKalb, and Gwinnett counties (Figure 1). Three sites were classified as stormwater ponds and four sites were classified as beaver ponds, although one of those sites was fitted with beaver dam analogs and did not have current beaver activity. Two of the stormwater ponds were known to have beaver living in them, but beavers were not actively damming or building canals at either site. Surface watersheds contributing to each site ranged from 18 to 68 percent impervious surface cover from the 2019 National Landcover Dataset (NLCD) coverage (Table 1, Dewitz, 2021) and 0.2 to 10.8 km^2 in surface area (as determined by StreamStats; U.S. Geological Survey, 2019). Storm sewersheds could not be calculated as stormwater pipe locations are not available for the City of Atlanta. Each pond was sampled weekly or biweekly from March to December 2021 for DOC and $SUVA_{254}$ analysis (Table S1). In addition, samples were collected from each site except one stormwater site (Graves) for two laboratory incubations.

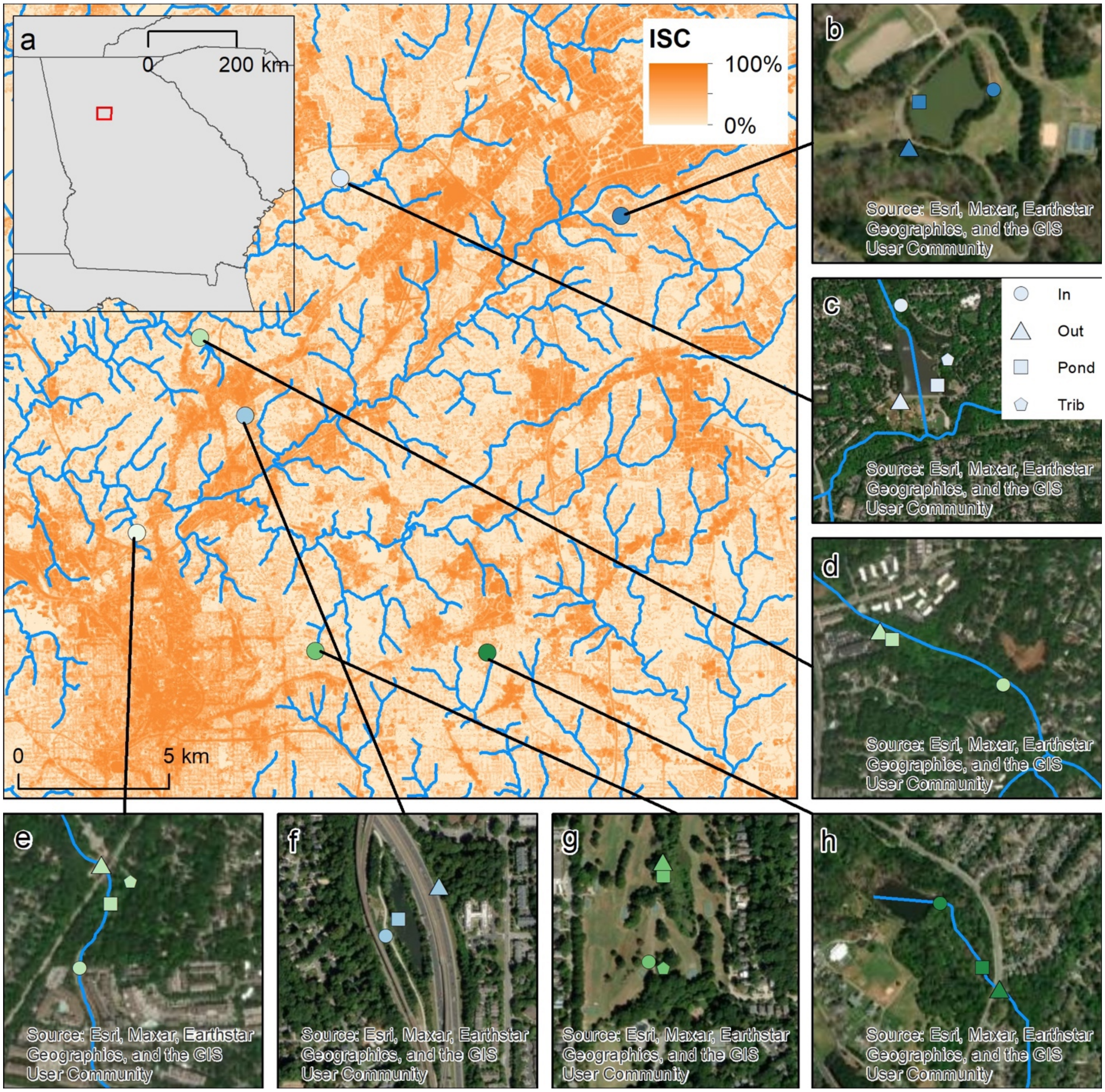

Figure 1. Site locations within the (a) Atlanta region for (b) Graves Park, (c) Murphy Candler Pond, (d) Blue Heron Naturel Preserve, (e) Tanyard Creek, (f) Path 400, (g) Candler Park, and (h) Shoal Creek. ISC = impervious surface cover. Scale varies for insets b-h.

Site Name	Latitude	Longitude	Type	Watershed area (km^2)	Average watershed ISC (%)
Murphy Candler	33.90930	-84.32554	Stormwater	6.3	32
Path 400	33.84062	-84.35964	Stormwater	1.4	56

Graves Park	33.89575	-84.22512	Stormwater	0.2	18
Tanyard Creek	33.80622	-84.40073	Beaver	10.8	68
Blue Heron	33.86458	-84.37847	Beaver/BDA	3.3	42
Candler Park	33.77022	-84.33713	Beaver	0.5	21
Shoal Creek	33.76676	-84.27549	Beaver	0.6	30

Table 1. Sites sampled for this study. Latitude and longitude are reported for the outlet of each pond. Pond type is the grouping of the pond for analyses. Watershed area was determined by StreamStats (U.S. Geological Survey, 2019) and is the contributing area to the outlet point of the pond. Average impervious surface cover (ISC) for each watershed is the from the 2019 NLCD (Dewitz, 2021).

2.2 Sample Collection

In situ water quality measurements (temperature, specific conductivity, dissolved oxygen, and pH) and grab samples were collected weekly (March 5 to August 27, 2021) then biweekly (September 10 to December 10, 2021) from the upstream ("In"), tributary ("Trib", if applicable), pond, and downstream ("Out") sections of all seven sites except one beaver pond where sampling started May 13, 2021 (Table S1). Water samples were collected from the surface of each location using a plastic half gallon container attached to a rope. A 125 mL acid-washed HDPE bottle was rinsed with sample water, then filled and stored on ice in a cooler until it reached the lab. Each sample was then passed through a 0.45 µm mixed cellulose ester (MCE) filter using a syringe and refrigerated in a 60 mL acid-washed HDPE bottle until analysis.

2.3 Sample Analysis

DOC concentrations were measured as non-purgeable organic carbon (NPOC) via high-temperature catalytic oxidation using a Shimadzu TOC Analyzer with an attached total nitrogen

(TN) module. RICCA Organic Carbon Standard and Ammonia Nitrogen Standard were used to produce standard curves for each run, and QC vials were analyzed after every 10-12 samples. A Genesys 10S UV/Visible spectrophotometer with a 10 mm quartz cuvette was used to measure the absorbance of each sample at 254 nm. $SUVA_{254}$ (Eq. 1) was then calculated with the absorbance and DOC concentration (Weishaar et al., 2003):

$$\text{Eq. 1 } SUVA_{254} = \left. \frac{absorbance\ at\ 254\ nm}{path\ length\ (m)} \right/ DOC\ (\frac{mg}{L})$$

No calibration is needed for absorbance measurements, but a blank was run after every three samples to monitor for drift in the equipment. Nitrate concentrations (used to estimate C:N and reported in the SI) were measured on a ThermoScientific Aquion Ion Chromatograph, calibrated using five independently created standards.

In addition to (bi)weekly sample collection and analysis, two bioassay incubations were conducted to compare the bioavailability of DOM in beaver ponds to that of stormwater ponds, one in summer and one in fall. Grab samples were collected from the upstream ("In"), tributary (if applicable and lumped with "In" for analysis), and downstream ("Out") section of six sites (all except Graves Park) using the same protocols described above between July 27 – August 26, 2021 (summer) and October 24 – November 10, 2021 (fall). Sample water was used to rinse and fill a 1 L acid-washed HDPE bottle for each location. Twenty mL of each sample was set aside for use as a microbial inoculum. The remaining sample volume was used to produce eighteen replicates of each sample. Each replicate contained 19 mL of sample water passed through a 0.2 µm MCE filter and 1 mL of unfiltered inoculum from the same sample location. Three replicates were immediately (t = 0 days) acidified with 0.2 mL (3 drops) of approximately 60% HCl, passed through a 0.2 µm MCE filter, and analyzed to determine an initial DOC concentration. The remaining fifteen replicates were incubated in acid-washed 40 mL amber bottles at room temperature without light. All vials were capped and stored on a shaker table throughout the incubation process to simulate streamflow (McDowell et al., 2006). Three of the replicates were acidified, re-filtered, and analyzed after 3, 5, 7, 14, and 28 days. DOC concentrations were measured on a Shimadzu TOC Analyzer via the same protocols described above. The decrease in DOC through time was fitted as a first-order rate decay following Parr et al. (2015):

Eq 2. $$[DOC]_t = [DOC]_0 e^{-kt}$$

Where $[DOC]_t$ is the concentration at time t, $[DOC]_0$ is the original concentration, k is the decay rate, and t is time. Bioavailable DOC (BDOC) was calculated as the percent loss in DOC from day 0 to 28.

2.4 Statistical Analysis

The UK Institute of Hydrology's method for graphical-analytical hydrograph separation (Wesselink & Gustard, 1992) was performed on depth data collected using HOBO water level data loggers to determine which samples were collected during baseflow. Rating curves could not be created for every site, so depth had to substitute for discharge (Brown et al., 2009). Quarter-hourly depth data was divided into non-overlapping bins of 5 measurements. The time of the minimum for each bin was recorded, then baseflow times were identified as minimum depths less than that of the neighboring bins. Linear interpolation was then used to compute depths between each successive baseflow measurement (Koskelo et al., 2012). If the maximum stream depth on a sample date exceeded the baseflow depth, we classified the samples collected that day as stormflow.

We used data from the USA National Phenology Network (https://www.usanpn.org) to determine which samples were collected when deciduous leaves were out and which samples were collected when deciduous leaves had died and fallen off trees (USA National Phenology Network, 2023). The cutoff-days determined from this dataset for 2021 were May 1 (leaf on) and October 20 (leaf off). Samples between these dates were assigned as leaf-on dates, whereas samples collected both before and after these dates were assigned as leaf-off.

Data analysis was conducted in R, version 4.2.1 (R Core Team, 2022). Comparisons of DOC and $SUVA_{254}$ in baseflow samples were used to measure differences between sample locations at the same site (e.g., in, pond, and out at beaver sites) and across sites at the same sample location (e.g., in at beaver sites to in at stormwater sites) using a two-sided Wilcoxon rank-sum text because of unequal sample sizes. In addition, stormflow was compared to baseflow and leaf-on compared to leaf-off using the same test. Both flow and seasonal comparisons were done with pond and outflow sample locations grouped to remove any potential impacts of differences from upstream contributing areas on inflow concentrations and try to isolate the impact of the ponds themselves while keeping as large a sample size as possible. Lastly, individual sample locations within a site (e.g., in, trib, pond, and out across a beaver pond) and sample locations across sites (e.g., all inflows to individual stormwater ponds) were assessed with a pairwise comparison for the entire sampling period using a Dunn's all-pairs test in R with the PMCMRplus package. A Bonferroni p-value adjustment was used to minimize Type I errors in our comparisons. P-values < 0.05 were treated as significant differences for all statistical analyses.

3. Results

3.1 DOC and $SUVA_{254}$ Within and Between Sites

Inflow DOC concentrations during baseflow at stormwater sites are different from pond and outflow concentrations (p = 2.1e-9 for inflow to pond and p = 7.3e-9 for inflow to outflow), but beaver sites do not show a statistically significant difference across sampling locations (Figure 2a). The change in DOC across stormwater sites is driven by elevated concentrations within the stormwater ponds that then reached the outflow (Figure 2a). This change is observed across the whole sampling period (Figure 3a-c). The increase in DOC along the sampling gradient is observed at two of the three individual stormwater ponds and outlets (Murphy Candler and Path 400; Figure S1 and Table S1), matching the pattern seen when sites were combined. For beaver sites, only Shoal Creek shows a significant difference between the inflow and pond or outlet concentrations, due to a clear decline in DOC along the gradient (Figure S2 and Table S1), whereas the other three sites do not show such change.

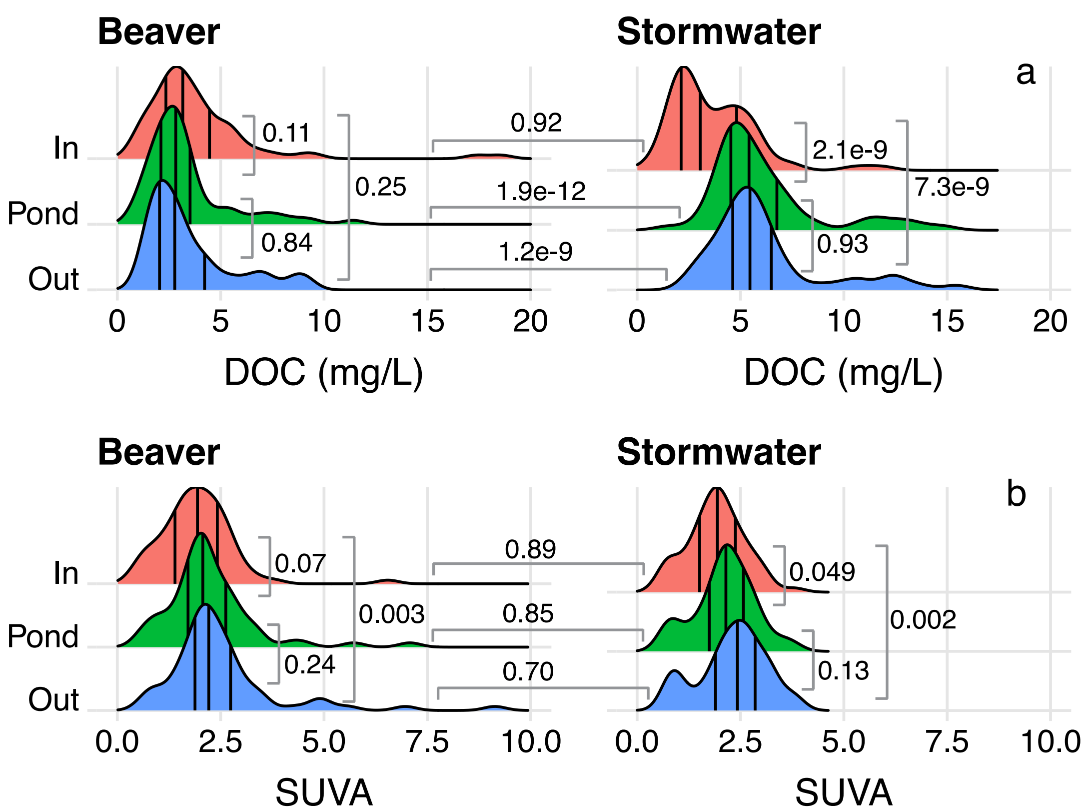

Figure 2. Density plots of DOC (a) and $SUVA_{254}$ (b) concentrations for inflows, ponds, and outflows of all beaver and stormwater ponds at baseflow conditions. Values shown correspond to p-values calculated using two-sided Wilcoxon rank-sum tests. Vertical black lines indicate quantile locations (25th, 50th, and 75th).

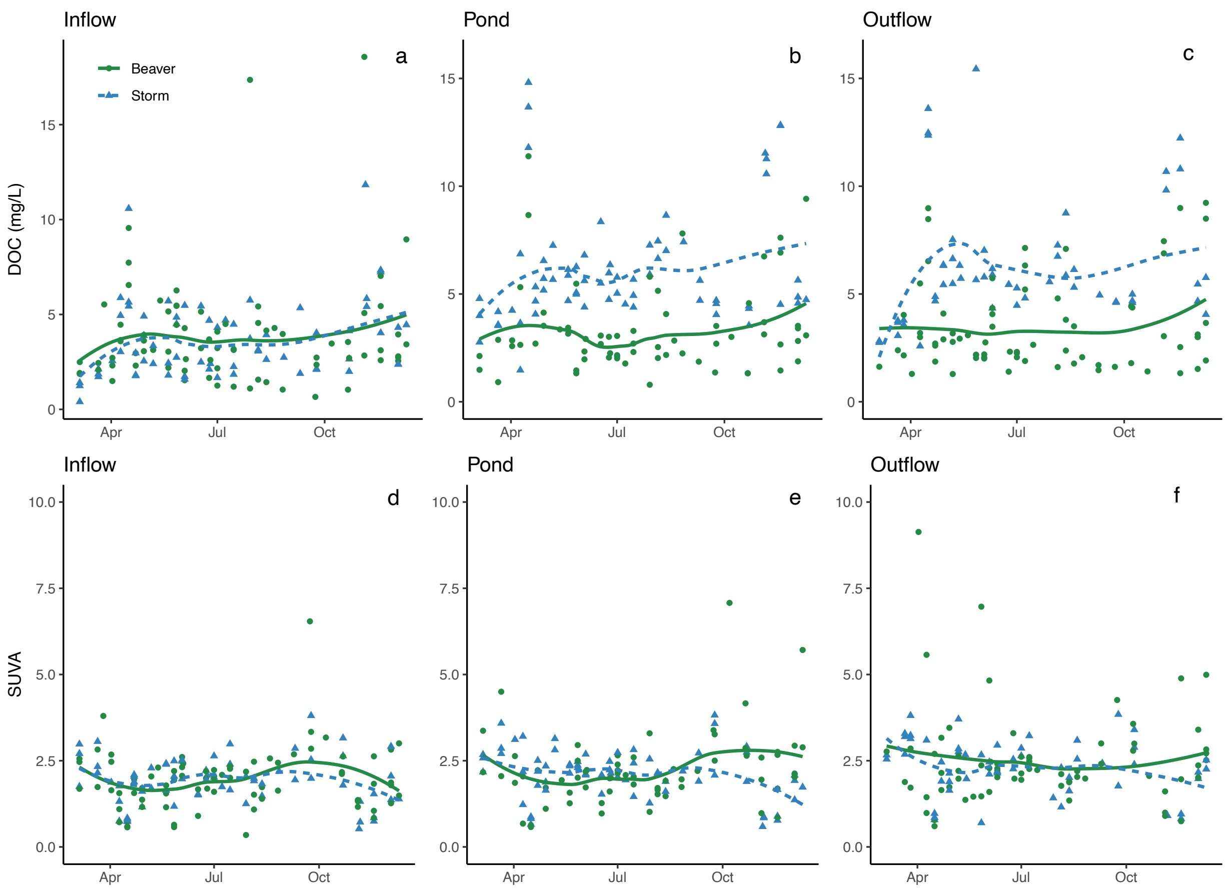

Figure 3. DOC and $SUVA_{254}$ concentrations for each baseflow sample through time at the inflow, pond, and outflow of urban beaver and stormwater ponds. The line is a loess smoothed line.

A similar pattern in DOC concentration increases is seen when evaluating the same sampling location across site types (e.g., beaver inflow compared to stormwater inflow). Among stormwater sites, inflow DOC concentrations are higher at Graves than the other two sites ($p = 0.0004$ compared to Murphy Candler and $p = 0.009$ compared to 400; Figure S3 and Table S1) but there were no significant differences in DOC among stormwater sites at the pond or outlet. Inflow DOC concentrations for beaver ponds are similar with the exception of Candler and Shoal ($p = 2.8e-4$) and Candler and Tanyard ($p = 0.049$; Figure S4 and Table S1). There are no statistical differences in inflow DOC concentrations between site types, indicating differences in impervious surface cover across the contributing watersheds does not seem to be driving these differences in inflow concentration. Furthermore, the full range of DOC concentrations observed is covered by the two sites with the most similar impervious surface covers. Candler (21% ISC) has the lowest inflow DOC while Graves (18% ISC) has the highest inflow DOC. Pond and outflow DOC concentrations differ between beaver and stormwater ponds ($p = 1.9e-12$ for pond and $p = 1.2e-9$ for outflow; Figure 2a). There are also no significant differences in pond DOC concentrations across the sampling locations in beaver sites, but Shoal had lower DOC at the outlet than Blue Heron ($p = 9.1e-4$) and Tanyard ($p = 0.005$). Overall, the patterns observed when comparing lumped DOC concentration patterns (Figure 2a) are seemingly driven by the patterns observed within and between individual sites (Figures S1-S4) and are not driven by individual outlier sites.

In contrast to DOC, both site types show a difference in $SUVA_{254}$ from inflow to outflow ($p = 0.003$ for beaver ponds and $p = 0.002$ for stormwater ponds; Figure 2b). These changes seem to be driven by $SUVA_{254}$ changes from inflow to pond ($p = 0.07$ for beaver and 0.049 for stormwater) rather than pond to outflow. However, despite the site summary statistics showing a small change in $SUVA_{254}$, the only individual site with a significant difference in $SUVA_{254}$ is the beaver-created Candler Pond ($p = 0.004$ for inflow to outflow; Figures S5 and S6 and Table S1).

There is no clear seasonal pattern driving the slight increases in $SUVA_{254}$ in the outflow of both pond types (Figure 3d-f), and the magnitude of difference is smaller than the changes in DOC. For sample locations within each pond site, there is no difference for stormwater inflow or outflow, although the Graves pond does have lower $SUVA_{254}$ than the Murphy Candler pond ($p = 0.019$; Figure S7). There are no differences in $SUVA_{254}$ among beaver inflow or pond locations, but Candler does have higher values than Tanyard in outflow samples ($p = 4e-4$; Figure S8).

3.2 Seasonal Incubations

Seasonal incubations of water collected from the inflow and outflow of beaver and stormwater ponds do not show clear spatial patterns in DOC uptake or BDOC, although there are seasonal differences (Figure 4). There is no pattern between inflow and outflow uptake rates of beaver or stormwater ponds in summer. Beaver pond inflow uptake ranges from 0.003 to 0.013 day^{-1}, while outflow ranges from 0 to 0.013 day^{-1} ($p = 0.9$). Stormwater ponds have a smaller range (0.001 to 0.005 day^{-1} inflow and 0.007 to 0.009 day^{-1} outflow) that still is not a significant change ($p = 0.2$). Similarly, there are no differences in inflow or outflow uptake between pond types ($p = 0.25$ for inflow and $p = 0.53$ for outflow). BDOC does not change from inflow to outflow of beaver ponds ($p = 0.71$), with an average of 19.9% ± 8.3% of inflow DOC and 15.6% ± 13.9% of outflow. Stormwater ponds have 2.3% ± 0.6% BDOC in inflow and 11.3% ± 1.8% in outflow, but it is not statistically different ($p = 0.14$), most likely due to a small number of samples. Inflow BDOC is higher in beaver ponds compared to stormwater ponds ($p = 0.03$), but there is no difference in outflow ($p = 0.8$). In autumn, there is no measured uptake at ten of the twelve sample locations, but there is a single location from each site type that does show removal at inflow and outflow, and rates are comparable to those measured in summer (Figure 4).

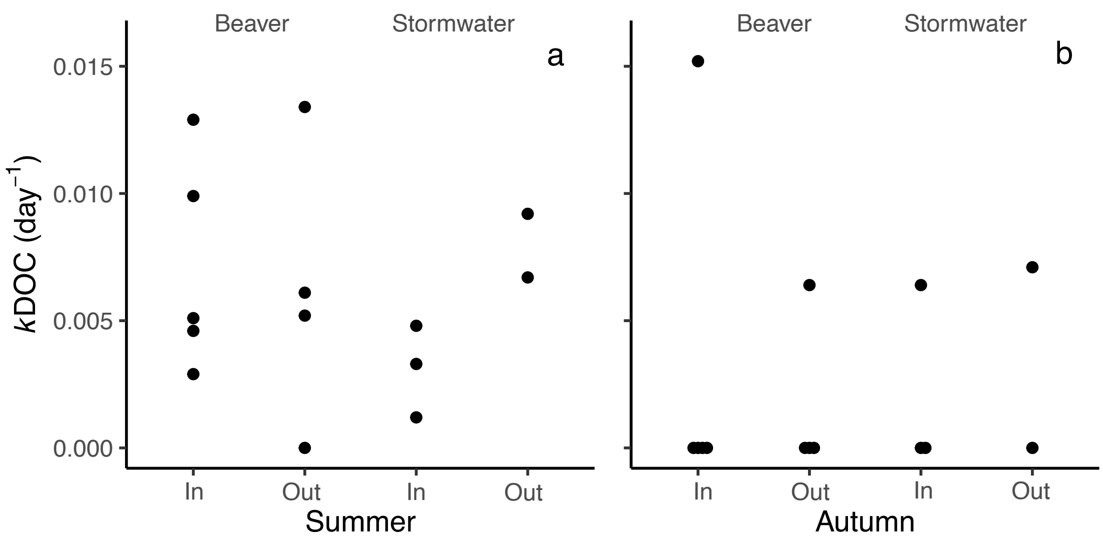

Figure 4. DOC decay rates for inflow and outflows of urban beaver and stormwater ponds in summer (a) and autumn (b). Tributaries are considered inflows. Rates identified as ‘zero’ did not show decay during the incubation period.

3.3 Temporal Factors

In addition to analysis of baseflow patterns across and between site types, we assess if antecedent moisture conditions, in this case defined as stormflow vs. baseflow, drive differences in DOC source and quantity. We compare pond and outflow samples to remove any potential upstream land use impacts on inflow concentrations. At each flow condition, stormwater sites have higher DOC concentrations in ponds and outflow than beaver sites (Figure 5a). Within-site differences at different flow conditions are less significant, with no difference in DOC in stormwater systems and a small increase in DOC in beaver ponds during storms. However, the lumped within-site differences in DOC concentration between baseflow and stormflow at beaver sites are not seen at individual sites, which do not show an impact of flow (Figure S9). Changes in organic matter source show a different pattern. Beaver and stormwater ponds do not differ in SUVA$_{254}$ at baseflow, but carbon is more aromatic in stormwater ponds compared to beaver during stormflow conditions (Figure 5b). Within pond type, there is no measured impact of flow condition on beaver site SUVA$_{254}$, but stormwater ponds do show higher SUVA$_{254}$ in stormflow. Individual site flow comparisons, however, only indicate one stormwater site where SUVA$_{254}$ is significantly higher during stormflow conditions (Graves; Figure S10). Overall, this contrast points to the potential for differences between beaver and stormwater sites in DOC quantity to outweigh differences driven by antecedent moisture conditions, while DOM source changes are driven by increases in aromaticity in stormwater ponds during stormflow conditions.

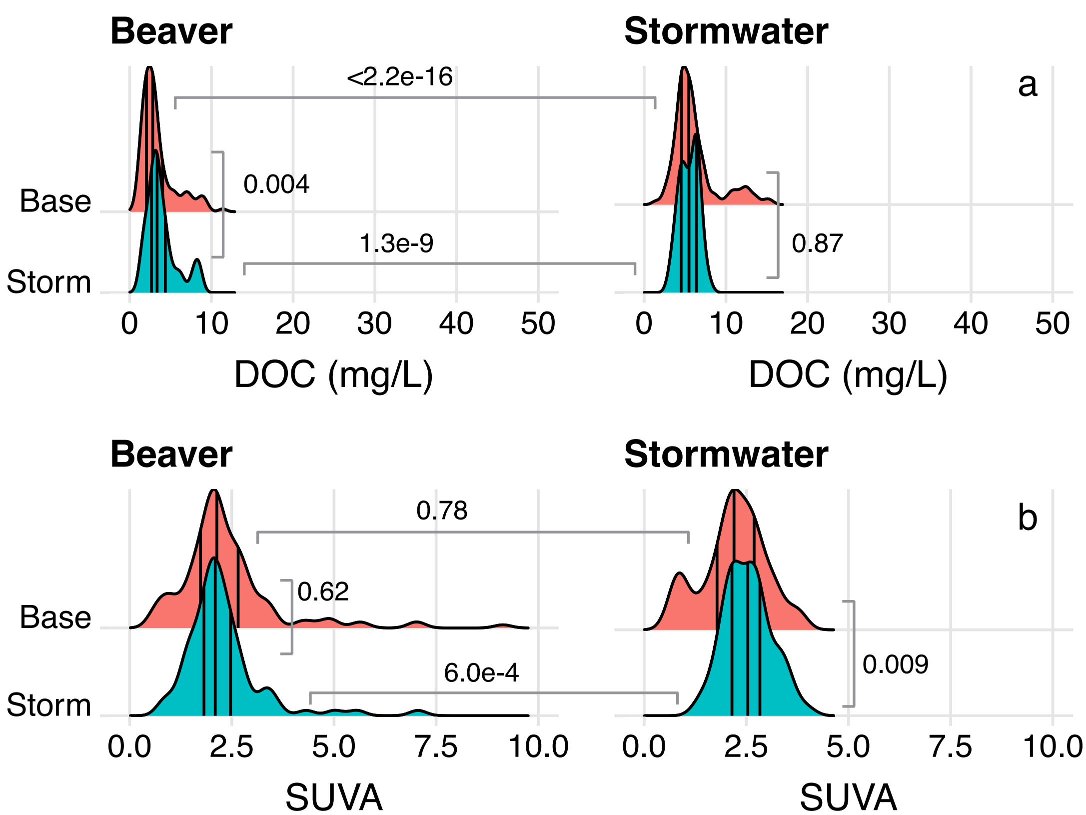

Figure 5. DOC (a) and $SUVA_{254}$ (b) density distributions for pond and out samples (combined) at baseflow compared to stormflow. Values shown correspond to p-values calculated using two-sided Wilcoxon rank-sum tests. Vertical black lines indicate quantile locations (25th, 50th, and 75th).

There are seasonal differences in DOC quantity, but not source, between the ponds and outflows of sites when grouped as leaf-on and leaf-off (Figure 6). Once again, ponds and outflows are grouped to remove any potential differences in input from upstream contributing areas and to attempt to isolate the impact of the ponds themselves. Beaver and stormwater ponds have significantly different DOC concentrations from each other within each seasonal time period (Figure 6a). Beaver systems have lower DOC than stormwater sites during both times. There are fewer significant or no differences at each site type between seasons. DOC is slightly higher in beaver ponds during leaf-off compared to on, but there is no difference in stormwater ponds. There are no differences in organic matter source across any comparison group (Figure 6b). The lack of seasonal differences is also seen at each individual site for both DOC quantity (Figure S11) and source (Figure S12), with the exception of one beaver pond which has more aromatic carbon during leaf-off than leaf-on.

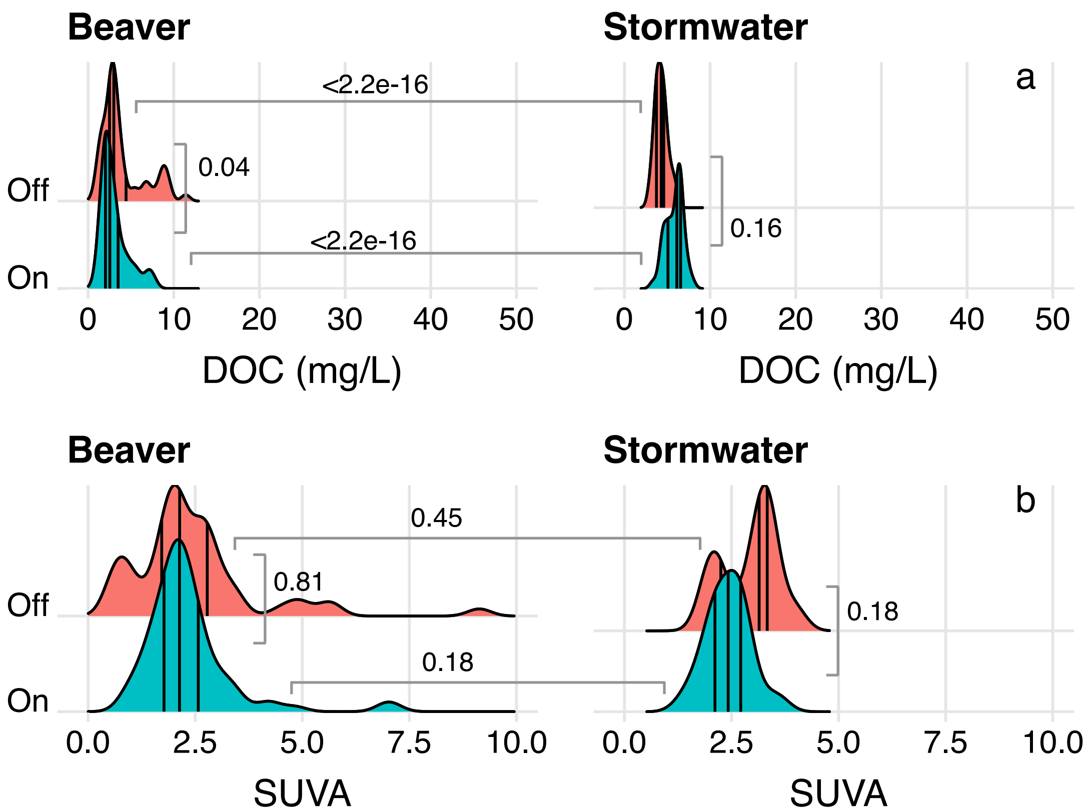

Figure 6. DOC and SUVA density distributions for pond, and out sites (combined) during baseflow periods when leaves were on and off. Values shown correspond to p-values calculated using two-sided Wilcoxon rank-sum tests where <2.2e-16 is the lower limit of p-value calculations in the wilcox.test() function.

4. Discussion

4.1 DOC concentrations increase within and below stormwater ponds but not beaver ponds

Our first hypothesis, that beaver and stormwater ponds will both have higher DOC concentrations in outflows, is rejected. During baseflow conditions, stormwater ponds and outlets have higher DOC concentrations than their inflows, a pattern that is not seen in beaver ponds (Figure 2a). DOC concentrations at baseflow in our urban stormwater ponds are on the higher end of what has been measured in other studies (median ranging from 4.7 to 5.9 mg/L, Table S1), but not out of range (Williams et al., 2016). The increase in DOC concentrations below urban stormwater ponds has been observed in other studies, driven by both high DOC runoff and autochthonous sources within ponds (Kalev et al., 2021; Kalev & Toor, 2020; Williams et al., 2013), although this control does not seem to be universal (Scarlett et al., 2018). When looking at individual ponds, two of the three stormwater ponds show a pattern of increased DOC concentrations in the outflow (Figure S1), and results from the outflows of all three ponds are statistically similar (Figure S3). The one pond that does not show an increase in DOC (Graves Pond) is the one pond that shows the potential for nitrogen limitation, with median baseflow C:N ratios that are much higher than any other sites (228 in the inflow, 93.2 in the pond, and 491 in the outflow; Table S1). Our study is an evaluation of the impact of stormwater ponds on concentrations only. When evaluating mass exports, most studies find ponds retain nutrients, including carbon, through hydrologic retention (i.e., reducing the volume of water) and not biogeochemical processing (Jefferson et al., 2017), but without discharge, we are unable to calculate mass flux.

We hypothesized that beaver ponds will have a similar effect on DOC to that of stormwater ponds, showing an increase in DOC from inflow to outflow, but this is not observed. Beaver ponds in non-urban areas more frequently show increases in DOC concentrations below ponded sections (e.g., Puttock et al., 2017). However, in non-urban beaver ponds, the increase in DOC is not driven by changes in in-pond processing, as has been seen in urban stormwater ponds, but is instead attributed to the shift from lentic to lotic conditions increasing sediment deposition (Błędzki et al., 2011; Puttock et al., 2017). Instead of our expected response, our overall beaver pond data suggest, on average, no change in DOC concentration from inflow to outflow (Figure 2a). However, at two of the three beaver sites (Shoal Creek and Candler Park) significant changes in DOC concentration are seen. DOC concentrations at the former decrease from the inflow to pond and outflow. In the latter, DOC concentrations are high in a small tributary and decrease in the pond and outflow. These contrasting effects of beaver ponds on DOC concentrations are quite different from the effects of stormwater ponds, which, on average, showed significant increases in DOC from inflow to outflow, suggesting that while the effects of stormwater ponds on DOC are consistent, the effects of beaver ponds are more site-specific.

4.2 Carbon becomes more aromatic below both pond types

Our second hypothesis is that urban beaver ponds will show more allochthonous DOM source in outflow than stormwater ponds, which is not observed. There are no differences in $SUVA_{254}$ between site types at the inflow, pond, or outflow (Figure 2b). Within sample locations of a site type, however, there are changes in aromaticity. Urban streams have less aromatic DOM than non-urbanized streams, as measured by $SUVA_{254}$, and our inflow ranges match those reported in other urban streams (Hosen et al., 2014), pointing to DOC from microbial sources in the inflows of our ponds. In addition, $SUVA_{254}$ is consistent across all individual inflows (Figure S7 and S8). This indicates that, despite having watersheds with 18-68% impervious surface cover, baseflow inflow aromaticity is not impacted by differences in contributing impervious surface cover. We observe a slight increase in aromaticity between the inflow and outflow of both beaver and stormwater ponds (Figure 2b). The increase in outflow $SUVA_{254}$ in our stormwater ponds differs from what has been reported in other systems. Schroer et al. (2018) found that terrestrial-source biomass accumulates in the sediment of stormwater detention ponds, not algal-derived biomass. The authors hypothesize that the lack of algal biomass accumulation means that DOC leaving ponds should be dominated by an autochthonous signal, especially in ponds where primary productivity is high. In addition, Romero González-Quijano et al. (2022) found that urban ponds and lakes have even higher proportions of autochthonous carbon than urban streams. Nonetheless, we observe a shift towards more allochthonous DOM leaving our stormwater ponds. Beaver ponds show the same pattern, following trends seen in non-urban sites where the re-saturation of soils by beaver activity causes a more allochthonous signature (Błędzki et al., 2011; Catalán et al., 2017; Naiman et al., 1994; Westbrook et al., 2006). The shift towards more aromatic carbon seen in both beaver and stormwater ponds (Figure 2b) indicates that it may not be the reconnection of floodplain soils which is driving this change. This increase in aromaticity is also in contrast to additional work in other urban beaver ponds that measure large diel dissolved oxygen swings (from anoxia to super-saturation) that suggest high pond primary productivity (Ledford et al., 2023), which is not reflected in the $SUVA_{254}$ signature in this study.

Instead, we hypothesize two potential drivers of the increase in aromaticity below both pond types. First, both ponds receive large volumes of runoff which could re-suspend pond sediment during storms. If pond sediment is dominated by terrestrial sources (Schroer et al., 2018), this could be the source of the more aromatic signal. This is supported by increases in $SUVA_{254}$ in stormwater ponds and outflows during wet conditions compared to baseflow (Figure 5b), although the same pattern is not seen in the beaver ponds. Another source could be beaver themselves resuspending sediment. Two of our stormwater ponds (Murphy Candler and Path 400) were inhabited by beaver, and some of their behaviors (e.g., swimming in shallow waters and building canals; Grudzinski et al., 2020) could result in re-suspension of pond sediment. There has been no research, as far as we can find, on the potential for beaver activity to resuspend sediment or impacts on water quality. It would be expected, however, that such activity would cause an increase in downstream suspended solid concentrations, which is not seen at most beaver sites (Larsen et al., 2021; Maret et al., 1987), and it is unclear if such activity could have a measurable impact, especially in large volume ponds. In addition, baseflow comparisons of $SUVA_{254}$ in the outflow of the two stormwater sites with beaver (Murphy Candler and Path 400) did not differ from the one stormwater pond without beaver (Graves), although Graves did have less aromatic pond carbon than Murphy Candler (Figure S7). Similarly, only one of the four beaver ponds showed an increase in $SUVA_{254}$ from inlet to outlet (Candler, Figure S6), also pointing to hydrologic sourcing of more aromatic DOM in outflows instead of biologically driven processes.

4.3 No difference in outflow DOM bioavailability between system types, but inflow differs

We hypothesize that an increase in autochthonous and less aromatic carbon in stormwater pond outflows will increase the bioavailability of the organic matter pool compared to beaver pond outflows, but there are not differences in uptake rates between the inflows and outflows of the two site types or between the outflows of each site type in summer or autumn (Figure 4). This could be in part due to the lack of differences in organic matter source between beaver and stormwater ponds (Figure 2b). Across all sites, rates of decay observed match those seen in other urban streams (Parr et al., 2015). Other studies show metabolic rates increase below urban stormwater ponds and correlate to chlorophyll-*a* concentrations, pointing once again to the importance of autochthonous sources for metabolism (McCabe et al., 2021) and increases in bioavailability of other nutrients (Lusk & Toor, 2016). However, our stormwater ponds show a slight increase in $SUVA_{254}$ from inflow to outflow (Figure 2b), which does not indicate that the ponds are hot-spots for in-pond microbial productivity that would result in increased bioavailability. Despite the similarity in OM bioavailability between pond types, the higher DOC concentrations in stormwater ponds, indicates/suggests that stormwater ponds are larger sources of greenhouse gas emissions than beaver ponds (Bodmer et al., 2016; Romeijn et al., 2019). High allochthonous inputs of leaves in the fall combined with high autochthonous in-pond production in winter could constitute two counteracting $SUVA_{254}$ signals that would cancel each other out, also explaining the lack of seasonal difference in $SUVA_{254}$ (Figure 6b). In fact, other studies show streams with higher $SUVA_{254}$ have lower bioavailability, although also noting that more urbanized streams have higher bioavailability (Coble et al., 2022). Conversely, incubations of urban stormflow show $SUVA_{254}$ increasing through time, thus decreasing in bioavailability (Fork et al., 2020). Overall, the two pond types seem to both be homogenizing carbon, so that BDOC in outflows is the same between pond types, despite statistically significant differences in BDOC of inflow. BDOC was higher in beaver inflows than stormwater inflows, suggesting landscape, such as impervious surface cover, and hydrologic drivers further up in the stormwater pond watersheds differ from those at the beaver sites. The lack of difference in either uptake or BDOC of outflows of both pond types is also interesting as the stormwater ponds and outflows both have higher C:N ratios than most of the beaver ponds (range of 33.0 - 491 for stormwater ponds and 3.0 - 38.4 for beaver ponds; Table S1), pointing to potential nitrogen limitation. However, this is not true for the inflow concentrations, where we see significant differences in BDOC but less difference in C:N (range of 2.0 - 148 for beaver ponds and 1.1 - 228 for stormwater ponds).

4.4. System type differences are larger than changes driven by flow or season

Our final hypothesis states that seasonal and hydrological differences in DOC quantity and source will be greater than differences observed between site types, which we also reject. Instead, we find site types to be more different from each other under a given condition. Bell et al. (2017) observed that DOC concentrations increase below stormwater ponds during high flow events, and most urban streams also show flushing behavior of DOC during storms (Fork et al., 2018; Hook & Yeakley, 2005; Kaushal & Belt, 2012; Pennino et al., 2016). We do not observe any difference in DOC concentration at stormwater ponds and outflows when comparing storm events to baseflow, whereas beaver ponds and outflows show flushing behavior (Figure 5a). The increase at the beaver sites matches what is seen in non-urban settings (Puttock et al., 2017). However, these differences between hydrologic conditions by site type are smaller than the differences between site types during a single hydrologic condition, where stormwater ponds and outflows always have higher DOC than beaver ponds and outflows (Figure 5a). During storm events, stormwater ponds and outflows show a more aromatic signature than both stormwater ponds and outflows at baseflow and beaver ponds and outflows during storm events (Figure 5b). There may be re-suspension of allochthonous sediment from these ponds during storms (Schroer et al., 2018) although it is unclear why this process would happen at stormwater sites but not beaver sites. Another hypothesized mechanism may relate to the difference in inflows; there may be more direct watershed delivery of particulate allochthonous inputs to stormwater ponds, which may have only upstream pipes with lower particulate organic matter retention and less labile carbon (Pennino et al., 2014), versus our beaver ponds which generally have more natural stream channel inflows that could have higher upstream particulate organic matter retention (Kaushal et al., 2014), even during storms. This difference in inflow quality and flushing is supported by the low BDOC and uptake rates of stormwater pond inflows in summer (Figure 4a), although there is not a measurable difference in aromaticity during baseflow between inflows at our beaver and stormwater sites (Figure 2b).

As with hydrologic conditions, we see minimal difference in DOC quantity or source comparing leaf-on to leaf-off periods, with beaver ponds and outflows showing a slightly significant response in DOC and stormwater ponds and outflows showing a change in $SUVA_{254}$ (Figure 6). Other studies show limited residence times in urban watersheds and decreased complexity of flowpaths that interact with soils decreases potential differences in DOC export between seasons (Seybold et al., 2019), which is reflected in our findings which show a slight decrease in DOC concentrations in beaver ponds and outflows when leaves are on, but no impact on stormwater ponds and outflows (Figure 6a). There are no seasonal impacts on $SUVA_{254}$ across any comparisons (Figure 6b). During each season, stormwater ponds and outflows have higher DOC than beaver ponds and outflows matching the overall pattern observed across the whole monitoring period (Figure 2a). Considering the high tree canopy coverage in Atlanta (estimated at 46.5% in 2018; City of Atlanta Department of Planning and Community Development & Giarrusso, 2018), however, and the impact of leaf litter on both DOC quantity and source in other urban systems (Duan et al., 2014), the lack of seasonal differences in concentration and source are surprising. In forested headwater catchments, seasonal changes in aromaticity are frequently attributed to changes in water table interactions with soils (Lambert et al., 2013) and associated mobilization of different pools of carbon (Hood et al., 2006) but there has been little research on the potential changes in urban systems. Romero González-Quijano et al. (2022) measured more labile DOM in summer, and Arango et al. (2017) measured higher quality DOM in spring, which matches our stormwater seasonality, but it is unclear why the pattern is not observed in beaver sites. This may be due to a balance between substantial allochthonous inputs from leaf litter and a simultaneous increase in autotrophic production in the ponds, especially possible considering the site location at the southern end of the temperate climate zone. However, our dataset is unable to piece apart if this is a driver or there are other processes at work.

5. Conclusions

With the increasing demand for urban stormwater management strategies, understanding the potential of beavers to act as nature-based solutions to water issues is warranted. In this study, we observe DOC and $SUVA_{254}$ changes upstream, within, and downstream of urban beaver and stormwater ponds in Atlanta, GA. We find that beaver ponds seem to have limited impact on carbon quantity in contrast to stormwater ponds which have higher concentrations, while both pond types show more aromatic DOC in the pond and outflow. We do not find differences in bioavailability of DOC leaving beaver ponds compared to stormwater ponds although both show changes across seasons. This indicates that beaver ponds may alleviate some of the downstream water quality issues driven by stormwater ponds while also working to retain water on the landscape. Leveraging this knowledge, beaver ponds may be able to be specifically managed to address urban water quality issues, and their potential benefit to water quality may be a tool that can be used when communicating about the benefits of beaver and navigating human-beaver conflict. Overall, beaver populations are clearly growing in cities across the United States; understanding their hydrologic and nutrient impacts on the landscape is key to allow for the creation of management strategies that allow for co-existence instead of eradication.

Statements and Declarations

Funding for this project came from NSF awards EAR-2024411, EAR-2024338, and EAR-2024421. DOC analysis was supported by NSF MRI-1826920. The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Conceptualization: Julian Sheppy and Sarah H. Ledford; Formal analysis: Julian Sheppy and Sarah H. Ledford; Methodology: Elizabeth Sudduth and Sandra Clinton; Investigation: Julian Sheppy; Data Curation: Julian Sheppy and Sarah H. Ledford; Writing- Original Draft: Julian Sheppy and Sarah H. Ledford; Writing- Editing and Reviewing: Julian Sheppy, Elizabeth Sudduth, Sandra Clinton, Diego Riveros-Iregui, and Sarah H. Ledford; Resources: Elizbeth Sudduth and Sarah H. Ledford; Visualization: Sarah H. Ledford; Supervision: Sarah H. Ledford; Funding Acquisition: Elizabeth Sudduth, Sandra Clinton, Diego Riveros-Iregui, and Sarah H. Ledford

Data Availability

The data used in this paper can be found at http://www.hydroshare.org/resource/e38dc2d79aa243a285437281d0a993ce.

References

Arango, C. P., Beaulieu, J. J., Fritz, K. M., Hill, B. H., Elonen, C. M., Pennino, M. J., Mayer, P. M., Kaushal, S. S., & Balz, A. D. (2017). Urban infrastructure influences dissolved organic matter quality and bacterial metabolism in an urban stream network. *Freshwater Biology*, *62*, 1917–1928. https://doi.org/10.1111/fwb.13035

Bailey, D. R., Dittbrenner, B. J., & Yocom, K. P. (2018). Reintegrating the North American beaver (Castor canadensis) in the urban landscape. *WIREs Water*. https://doi.org/10.1002/wat2.1323

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., Newbold, J. D., & Sabater, F. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience*, *1*(2), 95–100. https://doi.org/10.1038/ngeo101

Bell, C. D., McMillan, S. K., Clinton, S. M., & Jefferson, A. J. (2017). Characterizing the effects of stormwater mitigation on nutrient export and stream concentrations. *Environmental Management*, *59*, 604–618.

Bhaskar, A. S., Beesley, L., Burns, M. J., Fletcher, T. D., Hamel, P., Oldham, C. E., & Roy, A. H. (2016). Will it rise or will it fall? Managing the complex effects of urbanization on base flow. *Freshwater Science*, *35*(1), 293–310.

Bhaskar, A. S., Hopkins, K. G., Smith, B. K., Stephens, T. A., & Miller, A. J. (2020). Hydrologic signals and surprises in U.S. streamflow records during urbanization. *Water Resources Research*, *56*. https://doi.org/10.1029/2019WR027039

Bhattacharya, R., & Osburn, C. L. (2020). Spatial patterns in dissolved organic matter composition controlled by watershed characteristics in a coastal river network: The Neuse River Basin, USA. *Water Research*, *169*, 115248. https://doi.org/10.1016/j.watres.2019.115248

Błędzki, L. A., Bubier, J. L., Moulton, L. A., & Kyker-Snowman, T. D. (2011). Downstream effects of beaver ponds on the water quality of New England first- and second-order streams. *Ecohydrology*, *4*(5), 698–707. https://doi.org/10.1002/eco.163

Bodmer, P., Heinz, M., Pusch, M., Singer, G., & Premke, K. (2016). Carbon dynamics and their link to dissolved organic matter quality across contrasting stream ecosystems. *Science of The Total Environment*, *553*, 574–586. https://doi.org/10.1016/j.scitotenv.2016.02.095

Brown, L. R., Cuffney, T. F., Coles, J. F., Fitzpatrick, F., McMahon, G., Steuer, J., Bell, A. H., & May, J. T. (2009). Urban streams across the USA: lessons learned from studies in 9 metropolitan areas. *Journal of the North American Benthological Society*, *28*(4), 1051–1069.

Catalán, N., Ortega, S. H., Gröntoft, H., Hilmarsson, T. G., Bertilsson, S., Wu, P., Levanoni, O., Bishop, K., & Bravo, A. G. (2017). Effects of beaver impoundments on dissolved organic matter quality and biodegradability in boreal riverine systems. *Hydrobiologia*, *793*, 135–148. https://doi.org/10.1007/s10750-016-2766-y

Cazzolla Gatti, R., Callaghan, T. V., Rozhkova-Timina, I., Dudko, A., Lim, A., Vorobyev, S. N., Kirpotin, S. N., & Pokrovsky, O. S. (2018). The role of Eurasian beaver (Castor fiber) in the storage, emission and deposition of carbon in lakes and rivers of the River Ob flood plain, western Siberia. *Science of The Total Environment*, *644*, 1371–1379. https://doi.org/10.1016/j.scitotenv.2018.07.042

Chen, H., Liao, Z., Gu, X., Xie, J., Li, H., & Zhang, J. (2017). Anthropogenic Influences of Paved Runoff and Sanitary Sewage on the Dissolved Organic Matter Quality of Wet Weather Overflows: An Excitation–Emission Matrix Parallel Factor Analysis Assessment.

Environmental Science & Technology, *51*(3), 1157–1167. https://doi.org/10.1021/acs.est.6b03727

City of Atlanta Department of Planning and Community Development, & Giarrusso, T. (2018). *2018 City of Atlanta Urban Tree Canopy Assessment and Change Analysis (2008-2018)*.

Coble, A. A., Koenig, L. E., Potter, J. D., Parham, L. M., & McDowell, W. H. (2019). Homogenization of dissolved organic matter within a river network occurs in the smallest headwaters. *Biogeochemistry*, *143*(1), 85–104. https://doi.org/10.1007/s10533-019-00551-y

Coble, A. A., Wymore, A. S., Potter, J. D., & McDowell, W. H. (2022). Land Use Overrides Stream Order and Season in Driving Dissolved Organic Matter Dynamics Throughout the Year in a River Network. *Environmental Science & Technology*, *56*(3), 2009–2020. https://doi.org/10.1021/acs.est.1c06305

Correll, D. L., Jordan, T. E., & Weller, D. E. (2000). Beaver pond biogeochemical effects in the Maryland Coastal Plain. *Biogeochemistry*, *49*, 217–239.

Dewitz, J. (2021). *National Land Cover Database (NLCD) 2019 Products [data set]* [Computer software]. U.S. Geological Survey. https://doi.org/10.5066/P9KZCM54

Duan, S., Delaney-Newcomb, K., Kaushal, S. S., Findlay, S. E. G., & Belt, K. T. (2014). Potential effects of leaf litter on water quality in urban watersheds. *Biogeochemistry*, *121*(1), 61–80. https://doi.org/10.1007/s10533-014-0016-9

Fischer, H., & Pusch, M. (2001). Comparison of bacterial production in sediments, epiphyton and the pelagic zone of a lowland river. *Freshwater Biology*, *46*(10), 1335–1348. https://doi.org/10.1046/j.1365-2427.2001.00753.x

Fork, M. L., Blaszczak, J. R., Delesantro, J. M., & Heffernan, J. B. (2018). Engineered headwaters can act as sources of dissolved organic matter and nitrogen to urban stream networks. *Limnology and Oceanography Letters*, *3*, 215–224. https://doi.org/10.1002/lol2.10066

Fork, M. L., Osburn, C. L., & Heffernan, J. B. (2020). Bioavailability and compositional changes of dissolved organic matter in urban headwaters. *Aquatic Sciences*, *82*(4). https://doi.org/10.1007/s00027-020-00739-7

Goeckner, A. H., Lusk, M. G., Reisinger, A. J., Hosen, J. D., & Smoak, J. M. (2022). Florida's urban stormwater ponds are net sources of carbon to the atmosphere despite increased carbon burial over time. *Communications Earth & Environment*, *3*(1), 1–8. https://doi.org/10.1038/s43247-022-00384-y

Gorczyca, E., Krzemień, K., Sobucki, M., & Jarzyna, K. (2018). Can beaver impact promote river renaturalization? The example of the Raba River, southern Poland. *Science of The Total Environment*, *615*, 1048–1060. https://doi.org/10.1016/j.scitotenv.2017.09.245

Green, K. C., & Westbrook, C. J. (2009). Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *Journal of Ecosystems and Management*, *10*(1). https://doi.org/10.22230/jem.2009v10n1a412

Grudzinski, B. P., Cummins, H., & Vang, T. K. (2020). Beaver canals and their environmental effects. *Progress in Physical Geography: Earth and Environment*, *44*(2), 189–211. https://doi.org/10.1177/0309133319873116

Gu, C., Waldron, S., & Bass, A. M. (2022). Anthropogenic land use and urbanization alter the dynamics and increase the export of dissolved carbon in an urbanized river system.

Science of The Total Environment, *846*, 157436. https://doi.org/10.1016/j.scitotenv.2022.157436

Hood, E., Gooseff, M. N., & Johnson, S. L. (2006). Changes in the character of stream water dissolved organic carbon during flushing in three small watersheds, Oregon. *Journal of Geophysical Research*, *11*, G01007. https://doi.org/10.1029/2005JG000082

Hook, A. M., & Yeakley, J. A. (2005). Stormflow Dynamics of Dissolved Organic Carbon and Total Dissolved Nitrogen in a Small Urban Watershed. *Biogeochemistry*, *75*(3), 409–431. https://doi.org/10.1007/s10533-005-1860-4

Hosen, J. D., McDonough, O. T., Febria, C. M., & Palmer, M. A. (2014). Dissolved Organic Matter Quality and Bioavailability Changes Across an Urbanization Gradient in Headwater Streams. *Environmental Science & Technology*, *48*(14), 7817–7824. https://doi.org/10.1021/es501422z

Jefferson, A. J., Bhaskar, A. S., Hopkins, K. G., Fanelli, R., Avellaneda, P. M., & McMillan, S. K. (2017). Stormwater management network effectiveness and implications for urban watershed function: A critical review. *Hydrological Processes*, *31*(23), 4056–4080. https://doi.org/10.1002/hyp.11347

Kalev, S., Duan, S., & Toor, G. S. (2021). Enriched dissolved organic carbon export from a residential stormwater pond. *Science of The Total Environment*, *751*, 141773. https://doi.org/10.1016/j.scitotenv.2020.141773

Kalev, S., & Toor, G. S. (2020). Concentrations and Loads of Dissolved and Particulate Organic Carbon in Urban Stormwater Runoff. *Water*, *12*(4), 1031. https://doi.org/10.3390/w12041031

Kaushal, S. S., & Belt, K. T. (2012). The urban watershed continuum: Evolving spatial and temporal dimensions. *Urban Ecosystems*, *15*, 409–435. https://doi.org/10.1007/s11252-012-0226-7

Kaushal, S. S., Delaney-Newcomb, K., Findlay, S. E. G., Newcomer, T. A., Duan, S., Pennino, M. J., Sivirichi, G. M., Sides-Raley, A. M., Walbridge, M. R., & Belt, K. T. (2014). Longitudinal patterns in carbon and nitrogen fluxes and stream metabolism along an urban watershed continuum. *Biogeochemistry*, *121*(1), 23–44. https://doi.org/10.1007/s10533-014-9979-9

Koskelo, A. I., Fisher, T. R., Utz, R. M., & Jordan, T. E. (2012). A new precipitation-based method of baseflow separation and event identification for small watersheds (<50km2). *Journal of Hydrology*, *450–451*, 267–278. https://doi.org/10.1016/j.jhydrol.2012.04.055

Lambert, T., Pierson-Wickmann, A.-C., Gruau, G., Jaffrezic, A., Petitjean, P., Thibault, J.-N., & Jeanneau, L. (2013). Hydrologically driven seasonal changes in the sources and production mechanisms of dissolved organic carbon in a small lowland catchment. *Water Resources Research*, *49*(9), 5792–5803. https://doi.org/10.1002/wrcr.20466

Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, *218*, 103623. https://doi.org/10.1016/j.earscirev.2021.103623

Law, A., McLean, F., & Willby, N. J. (2016). Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams. *Freshwater Biology*, *61*(4), 486–499. https://doi.org/10.1111/fwb.12721

Ledford, S. H., Miller, S., Pangle, L., & Sudduth, E. B. (2023). Hyporheic exchange in an urban beaver pond mediates high nutrient groundwater inflow and pond productivity. *Journal of Hydrology*, *622*, 129758. https://doi.org/10.1016/j.jhydrol.2023.129758

Ledford, S. H., Zimmer, M., & Payan, D. (2020). Anthropogenic and biophysical controls on low flow hydrology in the Southeastern United States. *Water Resources Research*, *56*, e2020WR027098. https://doi.org/10.1029/2020WR027098

Lennon, J. T., & Pfaff, L. E. (2005). Source and supply of terrestrial organic matter affects aquatic microbial metabolism. *Aquatic Microbial Ecology*, *39*(2), 107–119. https://doi.org/10.3354/ame039107

Leopold, L. B. (1968). *Hydrology for urban land planning—A guidebook on the hydrologic effects of urban land use* (USGS Numbered Series 554; Circular, p. 26). U.S. Geological Survey. http://pubs.er.usgs.gov/publication/cir554

Lusk, M. G., & Toor, G. S. (2016). Biodegradability and Molecular Composition of Dissolved Organic Nitrogen in Urban Stormwater Runoff and Outflow Water from a Stormwater Retention Pond. *Environmental Science & Technology*, *50*(7), 3391–3398. https://doi.org/10.1021/acs.est.5b05714

Majerova, M., Neilson, B. T., Schmadel, N. M., Wheaton, J. M., & Snow, C. J. (2015). Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. *Hydrology and Earth System Sciences*, *19*(8), 3541–3556. https://doi.org/10.5194/hess-19-3541-2015

Maret, T. J., Parker, M., & Fannin, T. E. (1987). The effect of beaver ponds on the nonpoint source water quality of a stream in southweatern Wyoming. *Water Resources*, *21*(3), 263–268.

McCabe, K. M., Smith, E. M., Lang, S. Q., Osburn, C. L., & Benitez-Nelson, C. R. (2021). Particulate and Dissolved Organic Matter in Stormwater Runoff Influences Oxygen Demand in Urbanized Headwater Catchments. *Environmental Science & Technology*, *55*(2), 952–961. https://doi.org/10.1021/acs.est.0c04502

McDowell, W. H., Zsolnay, A., Aitkenhead-Peterson, J. A., Gregorich, E. G., Jones, D. L., Jödemann, D., Kalbitz, K., Marschner, B., & Schwesig, D. (2006). A comparison of methods to determine the biodegradable dissolved organic carbon from different terrestrial sources. *Soil Biology and Biochemistry*, *38*(7), 1933–1942. https://doi.org/10.1016/j.soilbio.2005.12.018

McEnroe, N. A., Williams, C. J., Xenopoulos, M. A., Porcal, P., & Frost, P. C. (2013). Distinct Optical Chemistry of Dissolved Organic Matter in Urban Pond Ecosystems. *PLOS ONE*, *8*(11), e80334. https://doi.org/10.1371/journal.pone.0080334

McKnight, D. M., Boyer, E. W., Westerhoff, P. K., Doran, P. T., Kulbe, T., & Andersen, D. T. (2001). Spectrofluorometric characterization of dissolved organic matter for indication of precursor organic material and aromaticity. *Limnology and Oceanography*, *46*(1), 38–48. https://doi.org/10.4319/lo.2001.46.1.0038

Naiman, R. J., Pinay, G., Johnston, C. A., & Pastor, J. (1994). Beaver Influences on the Long-Term Biogeochemical Characteristics of Boreal Forest Drainage Networks. *Ecology*, *75*(4), 905–921. https://doi.org/10.2307/1939415

Parr, T. B., Cronan, C. S., Ohno, T., Findlay, S. E. G., Smith, S. M. C., & Simon, K. S. (2015). Urbanization changes the composition and bioavailability of dissolved organic matter in headwater streams. *Limnology and Oceanography*, *60*(3), 885–900. https://doi.org/10.1002/lno.10060

Pennino, M. J., Kaushal, S. S., Beaulieu, J. J., Mayer, P. M., & Arango, C. P. (2014). Effects of urban stream burial on nitrogen uptake and ecosystem metabolism: Implications for watershed nitrogen and carbon fluxes. *Biogeochemistry*, *121*(1), 247–269. https://doi.org/10.1007/s10533-014-9958-1

Pennino, M. J., Kaushal, S. S., Mayer, P. M., Utz, R. M., & Cooper, C. A. (2016). Stream restoration and sewers impact sources and fluxes of water, carbon, and nutrients in urban watersheds. *Hydrology and Earth System Sciences*, *20*(8), 3419–3439. https://doi.org/10.5194/hess-20-3419-2016

Pollock, M. M., Beechie, T. J., & Jordan, C. E. (2007). Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. *Earth Surface Processes and Landforms*, *32*(8), 1174–1185. https://doi.org/10.1002/esp.1553

Pollock, M. M., Beechie, T. J., Wheaton, J. M., Jordan, C. E., Bouwes, N., Weber, N., & Volk, C. (2014). Using Beaver Dams to Restore Incised Stream Ecosystems. *BioScience*, *64*(4), 279–290. https://doi.org/10.1093/biosci/biu036

Pouyat, R. V., Pataki, D. E., Belt, K. T., Groffman, P. M., Hom, J., & Band, L. E. (2007). Effects of Urban Land-Use Change on Biogeochemical Cycles. In J. G. Canadell, D. E. Pataki, & L. F.

Pitelka (Eds.), *Terrestrial Ecosystems in a Changing World* (pp. 45–58). Springer. https://doi.org/10.1007/978-3-540-32730-1_5

Puttock, A., Graham, H. A., Ashe, J., Luscombe, D. J., & Brazier, R. E. (2021). Beaver dams attenuate flow: A multi-site study. *Hydrological Processes*, *35*(2), 1–18. https://doi.org/10.1002/hyp.14017

Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., & Brazier, R. E. (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. *Science of The Total Environment*, *576*, 430–443. https://doi.org/10.1016/j.scitotenv.2016.10.122

R Core Team. (2022). *R: A language and environment for statistical computing* (4.0.2) [Computer software]. R Foundation for Statistical Computing. www.R-project.org/

Roebuck, J. A. Jr., Seidel, M., Dittmar, T., & Jaffé, R. (2020). Controls of Land Use and the River Continuum Concept on Dissolved Organic Matter Composition in an Anthropogenically Disturbed Subtropical Watershed. *Environmental Science & Technology*, *54*(1), 195–206. https://doi.org/10.1021/acs.est.9b04605

Romeijn, P., Comer-Warner, S. A., Ullah, S., Hannah, D. M., & Krause, S. (2019). Streambed Organic Matter Controls on Carbon Dioxide and Methane Emissions from Streams. *Environmental Science & Technology*, *53*(5), 2364–2374. https://doi.org/10.1021/acs.est.8b04243

Romero González-Quijano, C., Herrero Ortega, S., Casper, P., Gessner, M. O., & Singer, G. A. (2022). Dissolved organic matter signatures in urban surface waters: Spatio-temporal patterns and drivers. *Biogeosciences*, *19*(11), 2841–2853. https://doi.org/10.5194/bg-19-2841-2022

Scarlett, R. D., McMillan, S. K., Bell, C. D., Clinton, S. M., Jefferson, A. J., & Rao, P. S. C. (2018). Influence of stormwater control measures on water quality at nested sites in a small suburban watershed. *Urban Water Journal*, *15*(9), 868–879. https://doi.org/10.1080/1573062X.2019.1579347

Schroer, W. F., Benitez-Nelson, C. R., Smith, E. M., & Ziolkowski, L. A. (2018). Drivers of Sediment Accumulation and Nutrient Burial in Coastal Stormwater Detention Ponds, South Carolina, USA. *Ecosystems*, *21*(6), 1118–1138. https://doi.org/10.1007/s10021-017-0207-z

Seybold, E., Gold, A. J., Inamdar, S. P., Adair, C., Bowden, W. B., Vaughan, M. C. H., Pradhanang, S. M., Addy, K., Shanley, J. B., Vermilyea, A., Levia, D. F., Wemple, B. C., & Schroth, A. W. (2019). Influence of land use and hydrologic variability on seasonal dissolved organic carbon and nitrate export: Insights from a multi-year regional analysis for the northeastern United States. *Biogeochemistry*, *146*, 31–49. https://doi.org/10.1007/s10533-019-00609-x

Tank, J. L., Rosi-Marshall, E. J., Griffiths, N. A., Entrekin, S. A., & Stephen, M. L. (2010). A review of allochthonous organic matter dynamics and metabolism in streams. *Journal of the North American Benthological Society*, *29*(1), 118–146. https://doi.org/10.1899/08-170.1

Terando, A. J., Costanza, J., Belyea, C., Dunn, R. R., McKerrow, A., & Collazo, J. A. (2014). The southern megalopolis: Using the past to predict the future of urban sprawl in the Southeast U.S. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0102261

U.S. Geological Survey. (2019). *The StreamStats program* [Computer software]. U.S. Geological Survey. https://streamstats.usgs.gov/ss/

USA National Phenology Network. (2023). *Plant and Animal Phenology Data. Data Type: Site Phenometrics. 1/1/2021-12/31/2021 for region: 34.284 -85.461 (UL); 32.536 -82.245 (LR).* [Computer software]. USA-NPN. http://doi.org/10.5066/F78S4N1V

Weishaar, J. L., Aiken, G. R., Bergamaschi, B. A., Fram, M. S., Fujii, R., & Mopper, K. (2003). Evaluation of Specific Ultraviolet Absorbance as an Indicator of the Chemical Composition and Reactivity of Dissolved Organic Carbon. *Environmental Science & Technology*, *37*(20), 4702–4708. https://doi.org/10.1021/es030360x

Wesselink, A. J., & Gustard, A. (1992). *Groundwater Storage in Chalk Aquifers- estimations from hydrographs*. U.K. Institute of Hydrology. https://nora.nerc.ac.uk/id/eprint/15334/1/N015334CR.pdf

Westbrook, C. J., Cooper, D. J., & Baker, B. W. (2006). Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. *Water Resources Research*, *42*(6). https://doi.org/10.1029/2005WR004560

Westbrook, C. J., Ronnquist, A., & Bedard-Haughn, A. (2020). Hydrological functioning of a beaver dam sequence and regional dam persistence during an extreme rainstorm. *Hydrological Processes*, *34*(18), 3726–3737. https://doi.org/10.1002/hyp.13828

Williams, C. J., Frost, P. C., Morales-Williams, A. M., Larson, J. H., Richardson, W. B., Chiandet, A. S., & Xenopoulos, M. A. (2016). Human activities cause distinct dissolved organic matter composition across freshwater ecosystems. *Global Change Biology*, *22*(2), 613–626. https://doi.org/10.1111/gcb.13094

Williams, C. J., Frost, P. C., & Xenopoulos, M. A. (2013). Beyond best management practices: Pelagic biogeochemical dynamics in urban stormwater ponds. *Ecological Applications*, *23*(6), 1384–1395.

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., & Bazan, R. (2012). Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications*, *3*(1), 1–8. https://doi.org/10.1038/ncomms2274

Zuniga-Teran, A. A., Gerlak, A. K., Mayer, B., Evans, T. P., & Lansey, K. E. (2020). Urban resilience and green infrastructure systems: Towards a multidimensional evaluation. *Current Opinion in Environmental Sustainability*, *44*, 42–47. https://doi.org/10.1016/j.cosust.2020.05.001