Using Nature Preserve Creek Cleanups to Quantify Anthropogenic Litter Accumulation in an Urban Watershed

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Abstract: Urban watersheds collect anthropogenic litter from populous areas and carry it through creeks and rivers to downstream ecosystems. Aquatic litter pollution has increasingly been addressed with the help of public engagement. Community science with amateur (citizen) scientist participation has focused on the assessment and remediation of plastic litter pollution through monitoring or cleanups. However, community science and more analytical research approaches have rarely been combined in upstream urban habitats where anthropogenic litter often originates. In freshwater streams, litter may be retained by natural and constructed obstructions, including beaver dams or restoration structures designed to mimic natural dams, but such retention has not yet been studied. Through community science cleanups, this study investigated the sources, material composition, functions, accumulation rates, and temporal and spatial distribution of litter in Mill Creek in the Blue Heron Nature Preserve, Atlanta, Georgia, USA. In 6 ~monthly cleanups, we removed, counted, and categorized 14,520 pieces of litter. Polystyrene was the most frequently collected material type (56.4%). Fragments that could not be functionally classified were the most abundant functional category (70.8%). Of the items that could be categorized by function, single-use plastics, such as food and beverage packaging, were most numerous. Presence of stream infrastructure, including beaver dam analogues (BDAs), increased the retention of total litter and most litter material types, but these effects often varied with time. BDAs affected litter capture patterns directly, as a barrier catching debris in the water column and floating on the water surface, and indirectly, by diverting flood waters over the banks and depositing litter into the floodplain. There were no consistent effects of rain-event magnitude, frequency, or total rain between cleanups on litter-accumulation rates. The dynamic temporal interactions of rain and litter are complex, but the functional types and spatial distribution of litter suggest that most litter was carried indirectly from consumers in the commercial, residential, and public roadway areas within the watershed. This study showed that community cleanup efforts can be coupled with quantitative and qualitative data collection. This multifaceted approach can help address anthropogenic litter problems, create opportunities for engagement and outreach, and contribute valuable information to ongoing community and scientific dialogs.

Key words: macrolitter, macroplastic pollution, freshwater debris, litter source identification, missing plastic problem, stormwater pollution, urban runoff, urban stream syndrome, citizen science

Every year, over 10 million tons of plastic debris enters the world's oceans (Almroth and Eggert 2019). Most marine debris is thought to originate on land (Jambeck et al. 2015, Lebreton et al. 2017, van Emmerik and Schwarz 2020) and then be transported to oceans by freshwater systems, such as rivers (McCormick and Hoellein 2016, Schmidt et al. 2017, Winton et al. 2020). However, there are still discrepancies between the rate at which rivers carry plastic toward the ocean and the observed quantity of marine plastic debris. This missing plastic problem (Schmidt et al. 2017, Owens and Kamil 2020) appears to be a function of our relative lack of understanding of freshwater litter residency time (Cable et al. 2017) and its accumulation rates (Jambeck et al. 2015, Winton et al. 2020). The discrepancies may be resolved by studying freshwater environments that dynamically accumulate plastic debris (Owens and Kamil 2020, Winton et al. 2020, Hoellein and Rochman 2021).

The presence of litter in freshwater environments has been correlated to the proximity of storm-water drain outlets, public roads (Willis et al. 2017), and urban populations (Rech et al. 2015, Lebreton et al. 2017). Urbanization removes natural vegetation barricades and creates an impervious landscape for precipitation. This inability to absorb rainfall generates high runoff volumes and power in

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local creeks and rivers during storm events, leading to degradation symptoms of a condition termed urban stream syndrome (Walsh et al. 2005, Booth et al. 2016). Anthropogenic litter and pollutants deposited on impervious surfaces are easily transported by runoff to streams and rivers within the watershed (Barbosa et al. 2012, Rech et al. 2015) via storm drains (Walsh et al. 2005, Blettler et al. 2018). The high variability between base flow and storm flow can compromise stream hydromorphic properties, subsequently increasing flood risk and erosion (Bernhardt and Palmer 2007, Barbosa et al. 2012).

Urban stream restoration has been approached in various ways to re-establish stream ecology and morphology altered by urbanization (Bernhardt and Palmer 2007). Methods of restoration, which can include replacing riparian vegetation and manipulating water trajectories to reconfigure stream morphology, may incidentally capture anthropogenic pollution (Charbonneau and Resh 1992). Emerging technologies, such as artisanal boom barriers and drainage nets, have also been implemented explicitly for freshwater litter capture (Blettler and Wantzen 2019). For example, the city of Atlanta, Georgia, USA, and its partners tested 2 different freshwater litter trap techniques in Atlanta's Proctor Creek in 2019 to 2020 (Wiener and White 2020). These techniques included floating boom and submerged aluminum traps, which collected a combined total of >450 kg of trash during the study period.

Beaver dam analogues (BDAs) offer a method of stream restoration by reducing flow rates of urban runoff and diverting flow into floodplains. They are artificially constructed, temporary structures that fulfill the functional role of natural beaver dams. They obstruct water flow and accelerate sediment accumulation while remaining semi-porous and allowing the movement of aquatic animals (Pollock et al. 2014). Reducing stream flow limits the water's power and turbulence, disperses a water body across a wider area, and potentially reduces the impact of runoff on erosion and flooding. BDAs prompt a stream's hydromorphology to re-adjust to a more natural state as a complex floodplain (Pollock et al. 2017). They also potentially function as barriers to floating debris and may act as sites of litter accrual; however, studies in this area are lacking (e.g., Ecke et al. 2017).

Freshwater litter assessments are typically sampling or accumulation based. In sampling studies, litter composition is observed in a representative area and extrapolated to a larger scale (Rech et al. 2015, Kiessling et al. 2019, Owens and Kamil 2020). In these studies, litter may be removed from the study area or left behind after data have been collected. This method offers efficiency in obtaining the data necessary for scientific study and allows large areas to be included through extrapolation of sample results (Owens and Kamil 2020). However, because litter is not removed from most of the study area, these studies do not contribute to remediation of litter prevalence. In contrast, accumulation studies incorporate cleanup methods that include removing all debris from the study region over repeated intervals. This method can reduce litter in the short term (Vincent and Hoellein 2017), and it offers an aspect of community service and public education that is difficult to attain via sampling (Rech et al. 2015, Owens and Kamil 2020). Additionally, with repeated cleanups in the same study area, net litter-accumulation rates can be established by observing the litter accumulated between cleanup events.

Cleanup activities, however, have historically lacked structured scientific methodology (Cowger et al. 2019, van Emmerik and Schwarz 2020). These efforts, therefore, are typically missing quantification and categorization components, and there are few studies that demonstrate the combination of community cleanup with scientific analysis. However, this combined approach shows great promise for engaging the public while increasing data quantity and sampling effort in a research area that covers immense environmental and scientific problems (Hoellein et al. 2015, Barrows et al. 2018).

Litter quantification combined with composition analysis can be used to establish the distributions of various materials and functions of litter found in a given area. Litter can be quantified by count (Willis et al. 2017), mass (Vincent and Hoellein 2017), or density (Hoellein et al. 2014, Rech et al. 2015, Vincent and Hoellein 2017, Kiessling et al. 2019). Regardless of the quantification method, relative percentages are typically used to deduce the primary material and functional contributors, which can then be used to understand and mitigate the litter sources (Lebreton et al. 2017, Hoellein and Rochman 2021).

Litter source identification is important for informing litter management and mitigation strategies (Kiessling et al. 2019). For example, the presence of certain sanitary items can indicate issues with sewage overflow (Bruge et al. 2018). Litter sources can be identified by examining the spatial distribution of litter, which varies between sampling sites (Vincent et al. 2017) and can be assessed with counts or masses when comparing equivalent areas. Determining the sources of litter relies on an understanding of the surveyed area and nearby infrastructure. For example, shores that are closer to roads and easier to access experience higher visitor volumes and are correlated with increased litter levels (McCormick and Hoellein 2016, Willis et al. 2017, Kiessling et al. 2019). High litter concentrations near illegal dumping sites indicate illegal dumping as the likely source (Rech et al. 2015). Nearby manufacturing facilities can implicate industrial sources, such as if plastic preproduction pellets were found near a plastic manufacturer (Tramoy et al. 2019). Inversely, the absence of those facilities can eliminate their possibility as a source (Vincent and Hoellein 2017).

Litter can be classified by material, function, or purpose (McCormick and Hoellein 2016), and these classifications can also provide information on the likely (van Calcar and van Emmerik et al. 2019) or unlikely sources of the litter. For instance, food-related packaging may be evidence of onsite consumption and discard (Hoellein et al. 2014), and accumulation of single-use household waste is a reasonable indication that larger-scale sources, such as manufacturing or commercial fishing, are not the culprit (Owens and Kamil 2020). The level of weathering of a piece of litter can be used to infer its age and likelihood of travel via wind or rain (Vincent and Hoellein 2017).

This study aimed to characterize accumulation rates, composition, spatial and temporal distribution, and potential sources of litter in an urban creek. We sought to combine the ecological and community-service benefits of creek cleanups with standardized methods of quantitative riparian litter-collection studies (Owens and Kamil 2020) and identify options for litter management in the area. We also investigated the effects of BDA presence in an urban watershed, including effects on litter accumulation and stream morphology. Further, we expected litter was brought to the creek by runoff from the encompassing watershed area and, therefore, predicted a correlation between litter accumulation and precipitation events.

METHODS

To address our study objectives, we completed a creek cleanup accumulation study. We used citizen science methods to leverage stream-litter-cleanup efforts and collect data about litter during 6 data-collection events over a 6-mo period. We collected data on litter-accumulation rate, type, and distribution, and we used repeated measures multivariate analysis to compare these variables over time and before/after BDA installation. We also computed correlations for litter totals and accumulation rates with rainfall parameters to assess our expectation that precipitation events would be associated with litter accumulation.

Study design

Starting in April 2020, groups of 4 to 8 people completed 6 ~monthly litter cleanups (22 April, 13 May, 17 June, 22 July, 19 August, and 7 October) of Mill Creek in the Blue Heron Nature Preserve located in the Buckhead residential district of Atlanta, Georgia. Blue Heron Nature Preserve lies in the Nancy Creek watershed of the City of Atlanta (City of Atlanta Department of Watershed Management 2021). The total cleanup area consisted of 74 marked 10-m sections along the creek (Fig. 1A, B) that began at a marsh pond, about 70 m southeast of where Mill Creek merges with Nancy Creek, and ended upstream at the creek's entrance to the preserve. The point (lat 33.86591, long −84.38047) immediately downstream from the study site within Mill Creek receives runoff from 3.47 km^2, 79.9% of which was classified in 2011 as developed and 34.4% as impervious (USGS 2016a). Because of interruptions by unnavigable terrain and private property, the study area was not entirely contiguous, and ~200 m were excluded from the cleanups. Litter had not been removed from Mill Creek for at least 1 y prior to this study (K. McCauley, former Blue Heron Nature Preserve Director, Atlanta, Georgia, personal communication).

At the beginning of July 2020, between the June and July cleanups, 6 new BDAs were installed and 2 existing BDAs were fortified within the Mill Creek study site (see Fig. 1C for an example BDA). These BDAs were completed through a collaboration between the Blue Heron Nature Preserve and the City of Atlanta Department of Watershed Management. The ultimate goal of their project was to mitigate urban flooding from the preserve's surrounding Buckhead area (Blue Heron Nature Preserve n.d.). We used these BDA upgrades as an opportunity to assess the effects of BDAs on stream litter and stream morphology.

Collection

We combined community cleanup activities with the litter-categorization methodology suggested by Owens and Kamil (2020) to apply scientific methodology to our community service efforts (van Emmerik and Schwarz 2020). To maximize efficiency, volunteers split into 2 groups to clean up separate halves of the creek. Before beginning cleanups, volunteers were oriented on collection methods, study purpose, and how to field questions from park visitors. They were instructed to collect all anthropogenic litter in a given 10-m section and bring it to the group leader for categorization and counting. Exceptions were made for anything dangerously heavy, deeply buried, or too deep to be collected without volunteers submerging.

We quantified litter by counting the number of items/section collected by volunteer surveyors. For each section, all human-attributable waste was collected from the creek and 3 m on each side of the bank, yielding 60 m^2 of riparian zone/section. Because creek width varied, the surface area of the creek varied by section. Surveyors navigated the bank from a central walking path, where they could visually scan the entire 3-m section, and they were free to roam between bank and creek areas as appropriate for each section's terrain. To expedite the cleanup process, surveyors acting as collectors navigated upstream. They collected litter 1 section at a time and left it in piles for the cleanup leader to sort, categorize, and document. We did not clean, dry, or weigh the collected items. Only macrolitter items >0.5 cm (Moore et al. 2011, Bruge et al. 2018, van Emmerik and Schwarz 2020, Winton et al. 2020) were counted and categorized for this study, but surveyors were encouraged to remove all items to aid the cleanup effort. Litter collection was not time limited. Surveyors moved to the subsequent section when they could no longer find items to collect in their current section.

One 30-m segment of the creek (sections 0.1, 0.2, and 0.3) introduced complexities to the sampling process that required altered methods. These sections, where Mill Creek enters the Blue Heron Nature Preserve, lie near a concrete and metal architectural remnant that accumulates large quantities of natural debris and litter. Section 0.2 contained the structure, section 0.1 encompassed the pool preceding the

Figure 1. A.—The Mill Creek enters the Blue Heron Nature Preserve, Atlanta, Georgia, USA, at rectangle marker 0.0 and flows downstream to the end of the study site at rectangle marker 7.5. Cleanup plots are 10 m in length and lie between the connected white points. Dams are marked by numbered circles, indicating the nearest downstream marker. The non-beaver dam analogue (BDA) dam was located within section 0.2. New BDAs installed across Mill Creek in July were located within sections 2.2, 3.0, 4.5, 4.8, 5.2, and 5.5. The 2 preexisting BDAs that were reinforced in July were located within sections 1.7 and 2.8. The BDA in section 2.0 existed in April but was removed in July. B.—Map showing the location of the study site relative to the City of Atlanta, a city with a 2019 estimated population of 506,804 people (US Census Bureau 2019). Map was created using Google Earth. The inset white map of the contiguous US shows the approximate location of the Atlanta map as a black rectangle. C.—Picture of BDA in section 4.8 taken on 22 July 2020.

structure, and section 0.3 immediately followed the structure downstream. Because of practical constraints, floating litter from these sections was collected with 2-mm-pore-size dipnets and then sorted and categorized the following day. These first 3 sections of the creek yielded particularly large numbers of polystyrene fragments. To quantify the polystyrene, 2 participants counted piles of 10 fragments at a time, announcing each count of 10, while 1 researcher kept a tally.

Categorization

Items from each section were categorized by identity (e.g., tennis ball, water bottle), function (e.g., toy, smoking product), and material composition (e.g., polystyrene, metal) on a predesigned data sheet before being discarded (Appendix S1). Our data sheet was adapted from the sample outlined by the NOAA Marine Debris Shoreline Survey Field Guide (Opfer et al. 2012). We documented items with as much specificity as possible to provide flexibility when condensing data into broader material and functional groups for analysis (Owens and Kamil 2020). Item identity and material composition were evaluated visually. Our material category of polystyrene consisted exclusively of foamed polystyrene items. Hard polystyrene items were included in the "other plastics" category. All further references to polystyrene in this paper specifically refer to foamed polystyrene.

Density

We calculated litter density as the number of items/m^2 of surveyed surface area. The width of the creek varied, so we estimated the creek surface area for each section by multiplying creek width (April) at each marker by 10 m for each section (mean ± SD: 51.5 ± 21.3 m^2). We summed all sections to obtain total creek surface area (3961.38 m^2). The study area also included 3 m on both banks (60 m^2/plot), yielding a total surface area of 8581.38 m^2 of terrain cleaned during this study.

Accumulation rate

We assumed that after the initial cleanup, only newly accumulated litter would be encountered. Under this assumption, we calculated the area-specific litter-accumulation rate in terms of items m^{-2} d^{-1} by dividing the litter density by the number of days that had passed since the previous cleanup.

Time and BDA effects on litter count and category

To test for the effects of time and BDA presence on stream litter, we used JMP® software (version 16; SAS Institute, Cary, North Carolina) to perform repeated measures multivariate analysis of variance (rmMANOVA). Data used were raw counts of untransformed litter totals. We chose to use rmMANOVAs because our temporal replicates were not random samples of the study area but were taken repeatedly at the same sections. Because the number of BDAs increased between June and July samples, we performed separate rmMANOVAs for April-to-June and July-to-October litter datasets. Each analysis included all 74 plots sampled at 3 time points (time factor composed of April, May, and June samples or June, July, and October samples) with each section coded as either containing a BDA or not. The response variables were total litter count and each separate material category (plastic, polystyrene, metal, glass, paper, wood, ceramic, rubber, and textile). For all rmMANOVAs, we assessed the effects of BDA presence, time, and their interaction, BDA × time. We considered an α level of 0.05 for identifying statistical relationships, but we interpret our statistics conservatively because of the large number of tests and focus on the direction and magnitude of relationships.

Creek morphology

We collected creek morphology measurements during April, August, and November 2020 at each 10-m mark. A researcher assisted by volunteers used a tape measure to measure from water's edge to water's edge (creek width) and from creek bed to water surface (creek depth).

To assess the relationship between creek morphology and BDAs, we also used JMP software to perform an rmMANOVA. The August creek morphology measurements were strongly influenced by recent rains, so to test the effects of BDA upgrades on creek morphology, we excluded the August sample to allow comparison between before- and after-upgrade periods during baseflow conditions. Therefore, April and November creek width and depth were response variables and BDA presence/absence was the categorical predictor variable. As with the rmMANOVA to test BDA and time effects on litter, we assessed the effects of BDA presence, time, and their interaction, BDA × time.

Precipitation data

We expected rain events to deliver most of the litter to the creek and adjacent riparian zone. To address this prediction, we obtained the number and quantity of precipitation events from the United States Geological Survey (USGS) online database (USGS 2016b). USGS, via the City of Atlanta Department of Watershed Management, tracks a real-time (15-min resolution) stream gauge and water-quality monitor located ~380 m upstream of where our study creek merges into Nancy Creek.

To assess the predicted association between litter accumulation and precipitation events, we used correlation analysis. We used JMP software to compute simple Pearson correlation coefficients for monthly litter totals and accumulation rates with rainfall parameters. We excluded the 1st monthly (April) litter total and included only the last 5 monthly litter totals in correlation analysis because the litter accumulated for an unknown period of time before the 1st cleanup.

RESULTS

Overview

Over the course of 6 cleanups, a total of 14,520 items of litter were collected and removed from an area of 8581.38 m^2 (Table 1). Between cleanups (20–49 d apart), there were 4 to 22 rain events (days of rain) totaling 5.13 to 27.00 cm. Total precipitation levels fluctuated throughout the study because of 5 large (>2.54 cm) rain events in total, 3 of which preceded the August cleanup. The density of litter found during all cleanups ranged from 0.19 to 1.66 items/m^2 with a mean density and standard deviation of 0.60 ± 0.54 items/m^2. The 1st cleanup accounted for ~½ the total number

Table 1. Summary statistics for 6 ~monthly cleanups of Mill Creek, Atlanta, Georgia, USA, in 2020.

Cleanup date	Days since last cleanup	Litter items collected	Total rain since last cleanup (cm)	Days of rain since last cleanup	Rain events >2.54 cm since last cleanup	Rain events >1.27 cm since last cleanup	Rain events >0.64 cm since last cleanup	Litter density (items/m^2)	Litter-accumulation rate (items m^{-2} d^{-1})
22 April	–	6683	–	–	–	–	–	1.66	–
13 May	20	2098	5.13	4	0	2	2	0.52	0.03
17 June	34	2187	13.69	19	0	3	7	0.54	0.02
22 July	34	753	9.72	16	1	2	5	0.19	0.01
19 August	28	1767	18.44	14	3	3	5	0.44	0.02
7 October	49	1032	27	22	2	7	11	0.26	0.01

of litter items collected. Subsequent accumulation rates ranged from 0.01 to 0.03 items m^{-2} d^{-1} with a mean of 0.01 ± 0.01 items m^{-2} d^{-1}.

Composition

Proportions of litter materials varied across study sections and sampling periods, but polystyrene and plastic constituted most litter across both space and time. Cumulatively, most of the litter collected across cleanups was made of (foamed) polystyrene (56.4%) and other plastics (36.3%), and the remaining items were primarily made of glass (2.8%) and metal (2.6%; Fig. 2A). Material composition was qualitatively similar among the 6 cleanups. Combined plastics (polystyrene and other plastics) were consistently the largest represented group in material composition, making up at least 86% of litter collected during each cleanup and representing 92.7% of total litter collected across all cleanups. Polystyrene was the largest material class of litter collected before BDA upgrades (April–June), but the relative proportion of other plastics surpassed that of polystyrene after BDA upgrades (July–August). Polystyrene then regained a slight lead over other plastics in October.

Although an overwhelming majority of the items collected were unidentifiable (polystyrene) fragments, identity and functional categories could be discerned for most other items. These items were predominantly single-use consumer products like food and beverage packaging, which included non-polystyrene plastic wrappers, bottles, and straws as well as polystyrene take-out food and beverage containers (Table S1, Fig. 2B).

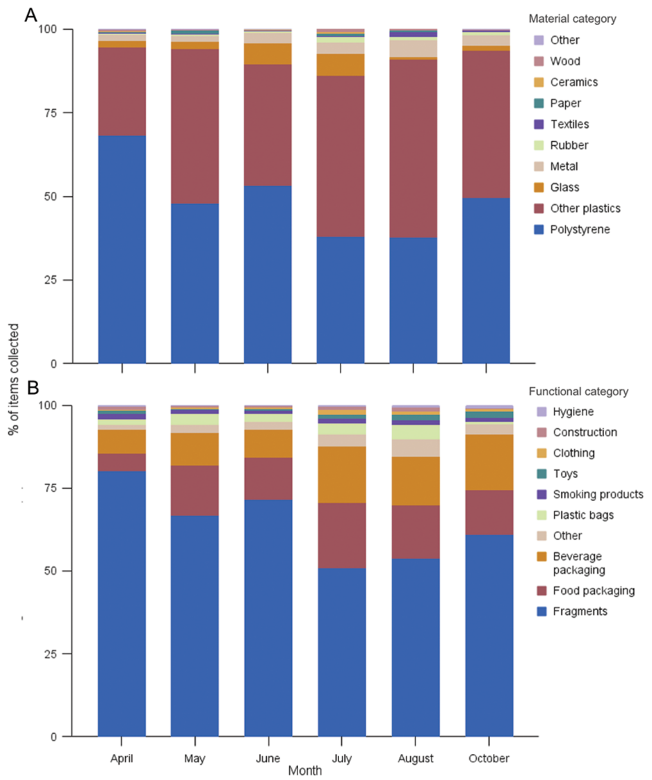

Figure 2. A.—Percentage of litter items by material collected each month from Mill Creek, Atlanta, Georgia, USA, in 2020. Mean and standard deviation for % of litter items categorized by material type across all cleanups are, from largest to smallest, as follows: polystyrene (49.04 ± 11.29), other plastics (42.37 ± 9.65), glass (3.23 ± 2.55), metal (3.03 ± 1.15), rubber (0.78 ± 0.51), textiles (0.54 ± 0.45), paper (0.39 ± 0.35), wood (0.29 ± 0.26), ceramics (0.23 ± 0.27), and other (0.10 ± 0.11). B.—Percentage of litter items by functional category collected each month from Mill Creek in 2020. Mean and standard deviation for % of items categorized by functional category across all cleanups are, from largest to smallest, as follows: fragments (63.97 ± 11.04), food packaging (13.73 ± 4.76), beverage packaging (12.30 ± 4.38), other (3.06 ± 1.30), plastic bags (2.69 ± 1.32), smoking products (1.28 ± 0.27), toys (1.11 ± 0.61), clothing (0.72 ± 0.40), construction (0.71 ± 0.38), and hygiene products (0.43 ± 0.24).

Spatial and temporal litter distribution

Total litter accumulation Litter accumulation varied both spatially and temporally throughout the study. Total litter accumulation was higher at sites with BDAs both before (April–June; mean = 300.6 items/section; Table 2) and after BDA upgrades (July–October; mean = 127.8 items/section) than those without BDAs (mean = 38.8 and 12.3 items/section before and after upgrades, respectively). Before BDA upgrades, most of the litter accumulated in the first 3 sections of the creek, where it was caught by the debris dam (Fig. 3). Following additional BDA upgrades, litter increased at most dam locations along the creek as litter accumulated in and above the intact dams. Most of the creek's litter was still caught at the dam at section 0.2, consistent with the findings of the April to June cleanups.

Relationships between litter accumulation, BDA presence, and time differed before and after BDA upgrades. Total litter count (April–June) was affected by time, BDA presence, and their interaction, time × BDA (rmMANOVA; Tables S2, S3). April had higher average total litter counts than May and June, and non-BDAs had greater proportional reductions than BDAs in total litter count after April (see monthly least squared means in Table S2). This time × BDA interaction resulted in BDA plots going from having ~4× more total litter than non-BDA plots in April to having >12× more in May and June. From July to October, there was also a strong positive effect of BDA presence on total litter count but no effects of time or the interaction between time and BDAs (rmMANOVA; Tables S2, S3). BDA plots ranged from having ~8× more litter in July to <2× more in August and 4.6× more litter in October.

Individual litter materials For individual material categories, BDA presence consistently increased accumulation

Table 2. Summary of the effects of beaver dam analogues (BDA) on total litter accumulation, accumulation of plastic and polystyrene litter, and creek morphology (creek width and depth) for Mill Creek, Atlanta, Georgia, USA, in 2020. Time periods for litter response variables are before (April–June) and after (July–October) BDA upgrades. Time periods for creek morphology variables are at the beginning of the study (April) and at the end (November). Means are adjusted means from repeated measures multivariate analysis of variance (rmMANOVA) for each time period, and ranges reflect the means from each individual month within the time period for litter variables and from plot-level measurements for morphology variables. Units of mean values for litter response variables are items/section. Units of mean values for creek morphology variables are in m. See Table S1 for full rmMANOVA results.

Time period	Response	Treatment	Mean (range)
April–June	Total litter	BDA	300.6 (246.0−356.7)
April–June	Total litter	No BDA	38.8 (18.2−79.1)
July–October	Total litter	BDA	42.6 (39.7−44.3)
July–October	Total litter	No BDA	12.3 (5.5−21.7)
April–June	Plastic	BDA	88.7 (71.0−116.0)
April–June	Plastic	No BDA	12.8 (8.2−19.8)
July–October	Plastic	BDA	22.1 (17.0−26.6)
July–October	Plastic	No BDA	6.0 (2.4−10.8)
April–June	Polystyrene	BDA	205.3 (161.0−232.3)
April–June	Polystyrene	No BDA	22.9 (7.0−54.4)
July–October	Polystyrene	BDA	22.1 (17.0−26.6)
July–October	Polystyrene	No BDA	5.1 (2.2−9.0)
April	Creek width	BDA	6.90 (2.9−11.1)
April	Creek width	No BDA	4.80 (1.1−12.0)
April	Creek depth	BDA	0.41 (0.36−0.46)
April	Creek depth	No BDA	0.33 (0.03−2.1)
November	Creek width	BDA	5.10 (2.9−8.3)
November	Creek width	No BDA	4.70 (1.4−12.1)
November	Creek depth	BDA	0.42 (2.0−6.2)
November	Creek depth	No BDA	0.43 (0.09−2.2)

of some, but not all, litter materials. Counts of 3 materials (plastic, metal, and rubber) were higher in BDA plots than non-BDA plots both before and after BDA upgrades (rmMANOVA; Tables 2, S2, S3). Wood litter counts were higher in BDA plots than non-BDA plots before upgrades but not after. In contrast, glass counts were not consistently different before upgrades but were up to 4× higher in BDA plots after. Paper and ceramic counts were not affected by BDA plots during either time period.

Similarly, time affected litter accumulation both before and after BDA upgrades for some materials but not others. Polystyrene and wood were affected by time before BDA upgrades, where they both showed highest counts in April and lowest in May, but they were not affected by time after. Plastic, metal, and textiles (highest counts in August) and glass (highest counts in July) all differed by time after upgrades but not before. Paper and rubber varied weakly over time during both time periods, but ceramic litter counts were not affected by time during either time period.

The interactive effect of BDAs and time also differed among materials before and after BDA upgrades (rmMANOVA; Table S3). For example, there was an interactive effect of BDA presence × time in both time periods for rubber, but there was no interactive effect in either time period for paper, ceramic, or textiles. The effect of BDAs on polystyrene and wood counts changed over time before upgrades but not after. In April, the polystyrene counts were ~4× greater in BDA plots than non-BDA plots, whereas in June BDA plots had ~31× higher counts than non-BDA plots. Wood, which had very low counts overall, had similar counts in BDA plots and non-BDA plots in May but ~10× greater counts in BDA plots in June. In contrast, the effect of BDAs changed over time for plastic, metal, and glass after, but not before, BDA updates. During July to October, plastic counts ranged from ~2.5 to 9× higher in BDAs than non-BDAs, and metal ranged from ~1.5 to 8× higher. Glass counts during July and August were up to 6× greater in BDA plots, but in October, glass counts were slightly greater in non-BDA plots.

Creek morphology

Creek morphology was not consistently affected by time or BDA upgrades. Some plots experienced erosion around

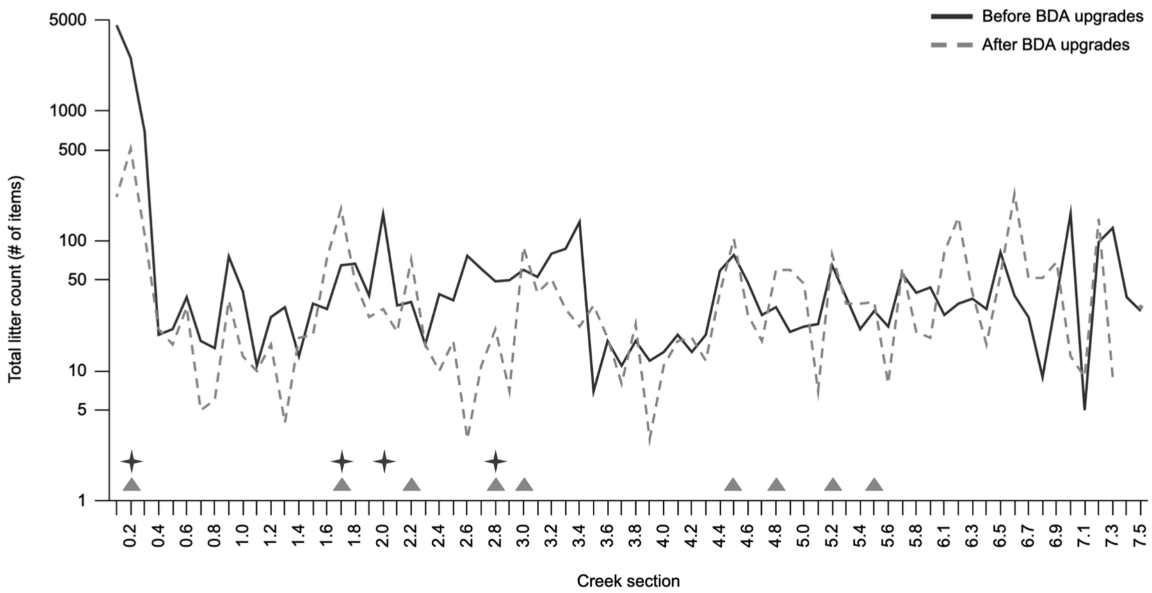

Figure 3. A comparison of the sum of litter collected in each section along Mill Creek, Atlanta, Georgia, USA, before beaver dam analogue (BDA) upgrades (April, May, and June) with that collected after BDA upgrades (July, August, and October). Locations of dams in April to June 2020 are indicated by 4-point stars, and location of dams in July to October 2020 are indicated by triangles. Note the *y*-axis is logarithmically scaled.

the banks of the BDAs, some remained unaffected, and others experienced erosion underneath the BDAs. However, neither creek width nor depth were consistently affected by BDAs or the time × BDA interaction (rmMANOVA; Table S3). Creek depth, but not width, was affected by time because the creek was deeper in November than in April.

Precipitation

Litter accumulation did not correlate with precipitation. Monthly litter total, accumulation rate, and litter density were not affected by days since last cleanup, total rain since last cleanup, number of days with rain since last cleanup, or number of rain events exceeding 2.54, 1.27, or 0.64 cm ($p >$ 0.05 for all 24 bivariate Pearson correlation tests).

DISCUSSION

This study combines community creek cleanup approaches used by nature centers and local environmental groups with scientific quantification and classification to assess the sources and accumulation rates of anthropogenic litter in an urban stream. Our results show that the main types of anthropogenic litter that accumulate in the Blue Heron Nature Preserve's Mill Creek are single-use plastics and polystyrene fragments carried by runoff from the surrounding roads, residential properties, and businesses. BDAs installed as part of creek restoration efforts had variable and inconsistent effects on creek morphology, but caused increases in litter accumulation in floating debris types that often varied in magnitude over time.

Litter counts and accumulation rate

The amount of litter removed from the creek during cleanups may be driven by changes over time, the presence of BDAs and their effects on stream geomorphology, and unpredictable interactions with stormwater-runoff dynamics. The large initial litter counts in April (Table 1) were a result of litter accumulating prior to creek cleanups, which exemplifies the impact of repeat cleanups on litter prevalence. Total litter removed generally decreased from the initial peak, but accumulation rates fluctuated in the following months. Barriers to surface flow contributed to this variation in the form of natural and constructed obstacles. Between the June and July cleanups, a storm felled some trees, which caused an accumulation of trash in the creek immediately upstream of our study area. This prevented some litter from reaching the study area for the July cleanup. These trees were substantially flooded between the July and August cleanups, releasing the trapped litter, which may help explain the increased litter collected in August as compared with July. Although the time period preceding the October cleanup experienced the largest volume of rainfall, the span between the July and August cleanups had the greatest number of large rain events, and ~70% more litter was collected in August than in October. Complex dynamics between buildup of litter source material on land and transport opportunities in stormwater runoff appear to make litter accumulation in our study area non-linear and uncorrelated with respect to simple rainfall metrics such as total precipitation, number of days with rain, and number of rain events exceeding various thresholds.

Although we observed increases in riparian litter following large flooding events, the relationship between precipitation and total litter accumulation is not clear. Litter moves at faster rates in the streams than in the riparian zones (McCormick and Hoellein 2016) and, presumably, even faster when floating at the surface than when submerged. Litter accumulation behind obstructions during normal flow regimes could be exported from the site during high flows as flood waters lift floating debris over obstacles. However, litter does not accumulate at a constant rate in the environment, and litter input to the creek is not consistent, regardless of rain levels. Litter takes time to accumulate, so storms on consecutive days would not capture the same amount of litter as similar storms spaced weeks apart. Additionally, spatial variation of precipitation within the watershed could affect the type and amount of litter captured by runoff. As seen elsewhere (e.g., Bhandaram et al. 2011), total precipitation and rain events did not correlate with our measured litter-accumulation rates. In another study, floating-litter counts in the Rhône River did not correlate with rainfall totals, because complex short-term dynamics, such as remobilization of trapped litter and stormwater overflow, caused high variability in short-term litter pulses (Castro-Jiménez et al. 2019). Similarly, flow rates of rivers in Jakarta did not correlate with litter load, because litter input rates probably varied, and storm runoff can deplete litter sources between frequent rain events (van Emmerik et al. 2019).

Our study included a few limitations that could have affected our measures of accumulation rates. First, our calculated accumulation rate was an estimate of the creek's net accumulation, which does not include the litter that was exported from the creek between cleanups (Vincent and Hoellein 2017). Therefore, we expect that there was likely more litter moving through the preserve than directly observed by this study. Litter traps or remote imaging techniques in future studies could provide valuable data on these missing values. Second, several factors may have contributed to litter being missed during cleanups and a resulting undercount of litter items. A small number of items were left behind because of inaccessible location or dangerous conditions (e.g., deep water, animal carcasses). Throughout the summer, riparian vegetation grew substantially, making the banks more difficult to navigate and obscuring some litter from view, so items were easier to miss. During the August cleanup, 1 litter pile was missed and partially swept away by rain before it could be collected the following day. The combined total quantity of known lost or unretrieved litter in the study is very small relative to the totals collected (<0.1% of grand totals), so we are confident that it does not substantially bias the results.

Litter density

Our litter density results (0.19−1.66 items/m^2) were comparable to densities reported by similar studies. Evaluation of 5 streams in the Chicago metropolitan area yielded similar results, with mean riparian litter density of 0.293 item/m^2 and mean benthic litter density of 0.117 item/m^2 (McCormick and Hoellein 2016). A combination of large and small rivers in Germany also exhibited densities within our data range (mean density of 0.54 item/m^2; Kiessling et al. 2019). However, the average density along Indonesia's Tukad Badung River was close to the upper bound of our dataset (1.19 items/m^2; Owens and Kamil 2020), and the average density found near India's Karamana River was much higher than our data range (3.26 items/m^2; Owens and Kamil 2020).

Differences in stream litter density could be related to differences in river size, hydrology, the size of the surrounding population, and methodological approaches. The Owens and Kamil (2020) study in Indonesia and India investigated litter accumulation along water bodies of larger magnitude than our very small urban creek. Larger rivers often experience higher litter densities (Kiessling et al. 2019) and higher flow rates and volumes to carry and deposit litter. Larger rivers also typically drain a larger watershed and are more accessible and attractive to visitors who are liable to pollute the area (Kiessling et al. 2019). However, these elevated litter densities do not appear to directly correlate to population density of the study regions, given the highest litter densities were found in the Indian state of Kerala, which is less populous (860 persons/km^2 in 2011; Census of India 2011) than both Indonesia's Denpasar municipality (7022 persons/km^2 in 2016; Rahayu et al. 2018) and the city of Atlanta (1218 persons/km^2 in 2010; USCB 2020). Another consideration is that litter collection in larger rivers often only includes floating debris or riparian litter accrual and overlooks benthic litter accumulation, which may lead to underreporting of the site's true litter content, making direct comparison with litter accumulation studies in smaller streams difficult.

Distribution of litter

Based on our dataset and observations, we deduce that runoff is a key factor driving the distribution of litter and that BDAs and other physical barriers drive its accumulation. We observed the highest densities of litter concentrated at the dams and located in the creek. Most other items were found deposited in the root systems hanging from the banks or on land after flooding. This pattern indicates that most items were swept to the preserve by runoff. Had the litter entered the preserve by other means, we would have expected to see different dispersal patterns. For example, we would expect direct littering by preserve visitors to be scattered in the riparian zone and pedestrian walkways rather than accumulated at the dams and bank walls. If illegal dumping was a source, we would expect to find large concentrated piles at the dump site.

The longitudinal distribution of litter aligns with observations of potential litter trapping sites. Before the BDA upgrades, most of the litter was collected at the structure located in section 0.2 (Fig. 3). From April to June, BDAs had a substantial positive effect on total litter count and on many individual material categories (Tables 2, S2, S3). For the July, August, and October cleanups, the largest accumulation of litter was still at the 0.2 structure. Other accumulation mostly occurred around the new and refurbished BDAs (Table 2, Fig. 3). However, there were also peaks in the marsh pond region (sites 7.5–6.0) that did not contain BDAs. The marsh pond is immediately adjacent to the busy Roswell Road, downstream from the rest of Mill Creek, and has low banks that become inundated with water during rain events. Most of the litter in this region was collected from the floodplain, where the litter is deposited by floodwaters.

Composition

Consistent with similar composition studies, most of the litter collected at Mill Creek was plastic (Williams and Simmons 1999, Rech et al. 2015, Willis et al. 2017, Kiessling et al. 2019, Owens and Kamil 2020; Fig. 2A), and most items collected were polystyrene and other plastic fragments (Fig. 2B). The deterioration into fragments is an indication of exposure to elements, particularly the impact of transporting rains and creek currents (Hoellein et al. 2014). Our data show that the proportion of both polystyrene litter and fragments decreased over the course of our study, and we observed anecdotally that polystyrene fragment size increased over that same period. During our first 2 cleanups, we collected large quantities of very small fragments below our 5-mm-macrolitter threshold (which we did not count). Later in the study, this material was not nearly as abundant, and polystyrene fragments tended to be larger, cleaner, and more durable. These observations suggest that polystyrene becomes increasingly fragile and fragmented over time and that smaller fragments have been circulating as litter for longer periods of time than larger, less-weathered fragments. We conclude that polystyrene entered the creek in larger pieces that broke down into smaller fragments. Perhaps the observed decrease in relative composition of polystyrene and fragments would not have existed had we assessed the mass of these fragments instead of item count (i.e., as fragments broke apart, the count increased but mass did not).

The functional categorization of the litter indicates that, other than fragments, the litter was primarily single-use consumer and household items. This result is similar to findings in rivers of both Indonesia and India (Owens and Kamil 2020), Great Lake beaches in the US (Vincent et al. 2017), and a beach in Brazil (Araújo and Costa 2007). Further, the litter found in Mill Creek was dominated by single-use packaging and smoking-related materials, including a large number of snack wrappers, plastic bottles, and cigarillo tips, which was similar to findings in German rivers (Kiessling et al. 2019).

For most of our cleanups, we had >1 person responsible for identifying and categorizing items, which left room for mismatch in how a single item might be categorized. Additionally, some of the categories are not mutually exclusive or could be interpreted differently depending on the classifier. For example, a plastic sandwich bag may have been included in the plastic bag category, the other-food-related category, or considered a filmed plastic. We expect that the potential lack of uniformity may have skewed our counts in those categories by a negligible amount. In future studies, we suggest establishing clear categorization definitions and direction prior to study to alleviate this inconsistency. Also, we could have categorized with a higher degree of specificity, such as splitting plastic bags into grocery, garbage, and sandwich bags, to further improve standardization (Owens and Kamil 2020).

Another limitation to our results is that our collection methods bias for floating debris. Floating plastics are visually obvious and are more likely to be caught in dams and washed onto banks than are denser materials, like metal, glass, and ceramics, which can submerge in the creek and are often buried out of view by sediment on the creek bed (McCormick and Hoellein 2016). Additionally, items like glass and ceramic fragments are easily camouflaged by creek-bed sediments. However, they are chemically inert and pose less of an environmental concern than plastics (Vincent and Hoellein 2017). Glass and ceramic fragments are also less mobile than plastics and, therefore, are less likely to move downstream to contribute to marine litter, but they are more likely to become a relatively permanent addition to the creek substrate.

Litter sources

Litter input sources to Mill Creek are constrained by the surrounding land types and uses. Blue Heron Nature Preserve is surrounded by residential neighborhoods, and much of Mill Creek flows parallel to private property. Within the watershed, there are multiple shopping centers, including Buckhead Station and Phillips Plaza, and a section of a major freeway, Georgia State Route 400. Mill Creek is not close to any manufacturing facilities, larger scale industrial complexes, or illegal dumping sites, which eliminates these as potential litter sources.

We can infer the sources of much of the collected litter by examining the litter itself. The nature of a large proportion of the items we collected, single-use food and beverage packaging and smoking paraphernalia, is the kind of litter we would expect to find on streets and in poorly secured garbage receptacles of Atlanta. Some of the items could be directly connected to businesses or addresses in the area, such as logoed fast-food containers, objects from nearby plant nurseries, and mail with delivery addresses. Many of the household items we found were children's toys, sports equipment, and gardening equipment. These items could have been picked up by floodwaters from the steep neighboring backyards and transported by wind and water to the creek. From the lack of deterioration of the non-fragmented items, we surmise that they had either been recently discarded or were not intended to be trash. A much smaller proportion of the items were clearly dated, such as degraded beer cans with pull tabs, which we found emerging from the eroding creek-bank walls. The distribution of litter across the study site also supports the watershed's culpability, rather than direct littering by park visitors. We conclude that the primary sources of litter in Mill Creek were streets and backyards within the watershed and that this litter was likely carried to the preserve by storm runoff.

Erosion of creek banks is a minor source of litter. The creek banks visibly eroded throughout the summer, particularly after the upgrades of the BDAs and the flash floods in August. Erosion was visible at certain BDAs as widening or deepening of the creek between the April and November morphology measurements. However, we found that these effects were not consistent across all BDAs ($p =$ 0.67 and 0.35 for effect of BDAs on creek width and depth, respectively; Table S3), which suggests that local stream sedimentary and structural physiographies (e.g., exposed rocks, tree roots, etc.) are critical to controlling whether erosion occurs in the stream bed, as bank erosion, both, or neither. The bank erosion revealed historic buried litter, primarily older glass bottles and beer cans with pull tabs. Mill Creek was dammed to form a lake for many decades before the dam was broken in 2003 (K. McCauley, former Blue Heron Nature Preserve Director, Atlanta, Georgia, personal communication). Sedimentary layers were visible in some parts of the creek bank, and these layers included litter that had been buried in the lake bottom and that was eroding into the creek during our study. Over the course of the study, we estimate that ~100 pieces of litter were collected from those strata, so the erosion did not produce a large proportion of the total litter collected (<0.8%). This very small contribution of eroded litter in our study supports the idea that stormwater flows bring in new litter to the preserve and uncover historic litter. It is also likely that stormwater brings in litter that is buried by sediment during hurricanes and other high-flow events, but further research is necessary to quantify this mechanism.

Implications of COVID-19

This study occurred in 2020, concurrent with the COVID-19 pandemic. The pandemic affected a wide range of factors that could contribute to patterns in litter amount, distribution, and category, such as vehicle traffic, consumer purchasing patterns, park visitors, and the types of litter encountered. The Georgia Department of Transportation collects traffic-volume data at the corner of Roswell Road and Lakemoore Drive, where the marsh pond is located. Traffic volume from the last full week of April exhibited a >50% decrease from 2018 to 2020 (204,447 cars in 2018 vs 97,408 cars in 2020; Georgia Department of Transportation n.d.). Similarly, with the temporary closure of many businesses and shelter-in-place recommendations, we expect that foot traffic outside the park likely decreased. We suspect that these reductions in human traffic would have led to a decrease in street litter and, subsequently, a decrease in litter entering the preserve during this time. For that reason, we believe that the data collected during this study were likely an underrepresentation of pre-pandemic litter levels and typical accumulation rates. However, the pandemic likely introduced increases in specific litter items, such as take-away paraphernalia and protective gear such as masks and gloves. Gloves (46 collected) were uniformly distributed throughout the survey period, but 3 out of 4 total masks were collected after 15 August, when local governments were permitted to enact mask mandates in Georgia (State of Georgia 2020). We also observed an increase in visitors to Blue Heron Nature Preserve following improvements to accessibility, including new bridges and boardwalks, as well as an apparent increase in outdoor recreation resulting from pandemic-related lifestyle changes.

Community service

Community service was an important aspect of this study. Although we recognize that cleanups are not a long-term solution to the litter problem (Owens and Kamil 2020), cleanup efforts can effectively reduce litter in the short term (Vincent and Hoellein 2017) to enhance the wellbeing of our local wildlife and create a safer space for visitors. Community science efforts can promote public awareness of litter issues (Rech et al. 2015, Owens and Kamil 2020), and they recruit additional human resources that can expand the scale of a study (Vincent et al. 2017, Kiessling et al. 2019). Additionally, volunteer and researcher interactions with Blue Heron Nature Preserve visitors during cleanups created another layer of outreach and established support for our efforts within the community.

Impacts on wildlife

Cleanup efforts can have unintended ecological consequences, including to wildlife. While dipnetting floating polystyrene fragments upstream of the debris dam at 0.2, we collected a large quantity of floating woody debris as well as Southern Two-lined Salamander (*Eurycea cirrigera*) larvae (51) and adults (2) and Green Frog (*Lithobates clamitans*) tadpoles (2) and adult (1). To reduce mortality of amphibian bycatch, we encourage researchers and cleanup crews to poke holes in litter collection bags so amphibians have access to oxygen and to store bags in cool, shaded locations for as short a time as possible before being sorted. Animals can be safely kept in water in non-airtight containers during the sorting process and returned immediately to their collection site.

Removal of litter could also result in the unintentional removal of materials used by fauna. Floating polystyrene is not widely known to provide refuges and habitat heterogeneity for amphibians, but their use of terrestrial and submerged plastic trash as cover objects has been reported previously (Neill 1948). However, we expect that removing the trash has a net benefit to amphibian assemblages because microplastics are rapidly consumed by amphibian larvae in a dose-dependent manner (Hu et al. 2016), and these environmental pollutants are toxic and mutagenic (da Costa Araújo et al. 2020).

Future directions

Our litter accumulation study met the twin goals of combining the community benefits of creek cleanup with quantification and scientific evaluation and shedding light on the missing plastics problem (Schmidt et al. 2017, Owens and Kamil 2020). We observed Mill Creek to be a transporter of litter to its higher order stream, Nancy Creek, a temporary stop for litter that is remobilized during heavy floods, and a sink for litter accumulation. Repeated cleanups, as employed in this study, are useful both as a short-term litter-mitigation measure and as a method to assess litter-accumulation rates. With repeated cleanups, the litter is also more likely to be collected earlier in its life cycle. Preweathered plastics can be collected in larger pieces before they degrade to more problematic microplastics. We encourage future researchers and environmental groups to adopt similar methodology so they can improve their local environment and create useful and standardized data on stream litter to inform their stakeholders and scientific debates.

Regular cleanups have reduced Mill Creek's litter in the short term, but we need intervention from the City of Atlanta Department of Watershed Management to capture litter before it reaches our creeks and rivers. The city should consider implementing litter-trap technologies in Nancy Creek similar to those installed in Atlanta's Proctor Creek (Wiener and White 2020). Future challenges involve cutting litter off at its source by reducing the production and use of single-use plastic and improving street litter management (Blettler and Wantzen 2019).

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