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Prediction of anthropogenic debris and its association with geomorphology in US urban streams

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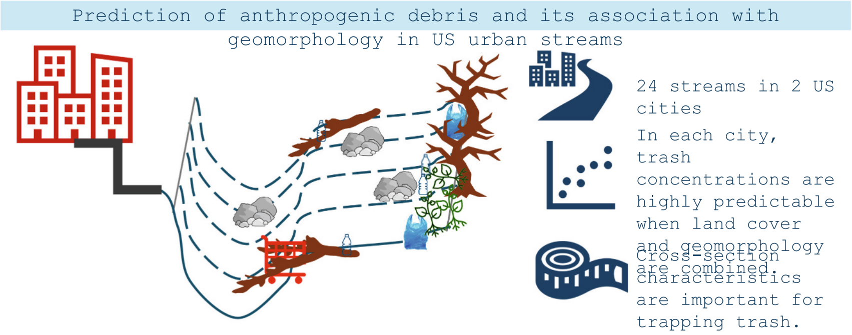
HIGHLIGHTS

- Strong predictability of debris concentrations by land cover and geomorphology.
- Stream cross-section characteristics are important controls on debris accumulation.
- Stream bank roughness and vegetation could play vital roles in debris accumulation.
- Land cover predictors highlight varying sources of debris to urban streams.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic debris in urban streams is a persistent environmental problem, yet previous studies have focused largely on how land use influences debris concentrations, while neglecting the potential role of fluvial geomorphology in mediating storage. To examine relationships between in-stream debris concentrations and different geomorphologic characteristics, catchment characteristics, and catchment and riparian land cover in US urban streams, we collected data on debris (>5 cm), large wood, cross-section and longitudinal profiles, and sediment sizes in 24 stream reaches in two metropolitan areas (Cleveland, Ohio; Charlotte, North Carolina). Debris concentrations ranged from 0.18 to 4.7 pieces/m bankfull width, with an average of 1.55 pieces/m. Plastic comprised 71.8 % of the collected debris, and in two reaches with repeated measurements, debris re-accumulated quickly following removal. In city-specific multiple linear regression models, debris concentrations across stream reaches was explained as well or better by geomorphologic variables than GIS variables, but when data from the two cities were combined, the opposite was true. Cross-section characteristics were among the strongest predictors of debris concentration in both cities. Our analysis suggests that roughness associated with stream banks plays an important role in debris storage, through trapping debris on riparian vegetation and by creating width constrictions that lead to low velocity zones and debris settling on the bed. Future work on

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interactions between bank and vegetative roughness and anthropogenic debris may reveal generalizable predictors of debris storage in urban streams.

1. Introduction

The accumulation of mismanaged waste, or anthropogenic debris, in and along rivers can adversely affect human health, freshwater ecosystems, and local economies (Cowger et al., 2019; Henry et al., 2006; Williams and Simmons, 1999). Mismanaged waste can reach streams and rivers via illegal dumping in or near the channel, or via wind, surface runoff, or pipes from upland and riparian areas (van Emmerik and Schwarz, 2020). Once in urban streams, waste may be transported downstream to another water body or retained within the stream channel or riparian zone (Hoellein et al., 2024). Ultimately, rivers are the main source of mismanaged waste to the marine environment (Lebreton et al., 2017). The movement and storage of mismanaged waste in streams and rivers is not yet fully understood. Urban streams are of particular interest in the study of mismanaged waste because they are close to the source of waste and are places where humans may come in contact with it.

Approximately 2 % of US solid waste is mismanaged and ends up in the environment (Law et al., 2020). We define anthropogenic debris as all human-manipulated materials not intentionally and legally placed within the channel. These materials include plastic, paper, glass, metal, ceramics, rubber, textiles, concrete, and bricks. This is a somewhat broader definition than may be used when discussing anthropogenic litter (Anon, 2021), and it avoids implying a mechanism by which the material is delivered to the stream. The coarse riparian urban debris (CRUD) of Grable and Harden (2006) focused on dense materials, such as displaced riprap, but other studies have shown that solid waste in the environment consists mostly of plastic (Hardesty et al., 2017; Hoellein et al., 2024). Among forms of anthropogenic debris, plastic pollution is considered as a critical problem, due to its slow decomposition rate (Hengstmann and Fischer, 2020) and a rapidly increasing global plastic production rate (Gourmelon, 2015). Microplastics in streams and rivers have recently gained a great deal of attention (e.g., Correa-Araneda et al., 2022; Frank et al., 2021; Napper et al., 2021; Stanton et al., 2020), but interest in the abundance, types, and dynamics of macroplastics in streams and rivers is also increasing (e.g., Al-Zawaidah et al., 2021; Liro et al., 2020, 2023; van Emmerik et al., 2018).

The relationship between hydrology and anthropogenic debris in urban streams and rivers is an area of active research. Limited sampling of floating macroplastics (>5 mm) in southern California suggests that they may exhibit clockwise hysteresis (i.e., first flush) within storms, and that concentrations may peak at moderate flows (Cowger et al., 2022). However, sampling of urban rivers in Germany and Florida, found no relationship between flow and macroplastic concentration (Wagner et al., 2019) or concentrations of plastics >500 μm (Haberstroh et al., 2021). In terms of retention of anthropogenic debris within the channel, accumulation rates have been found to be higher in the wet season than in the dry season (Bauer-Civiello et al., 2019; Moore et al., 2007), suggesting an important role for stormwater runoff delivering debris to streams. Finally, turnover times for debris in riparian zones are <1 year (McCormick and Hoellein, 2016), emphasizing the role of high flows and connectivity between streams and floodplains as influencing debris dynamics.

Multiple studies have shown that land cover and land use in the catchment and riparian areas may have a considerable impact on debris abundance in streams and rivers. An early study in the San Francisco Bay area showed that debris hotspots were located near schools, parks, and roads (Moore et al., 2007). Differences in anthropogenic debris storage in urban streams in Chicago parks were thought to be related to human activity in the riparian areas (McCormick and Hoellein, 2016). In Maryland, a general positive relationship between residential, institutional, and open areas near streams and anthropogenic debris was found to be modulated by season and material type (McCuen et al., 2014). In Iowa, garbage concentration in riparian areas was related to watershed scale road density, while the concentration of denser materials like metal was related to near-stream road density (Cowger et al., 2019), showing that difference in spatial scale is important in determining relationships between land use and types of debris materials. Similarly, microplastics concentrations in rivers and estuaries have been shown to be related to urban land use, impervious land cover and population density (Baldwin et al., 2016; Jin et al., 2022; Yonkos et al., 2014).

Spatial segregation of debris within and around channels has also been investigated. Within channels, wood jams and wooded islands have been identified as hotspots of debris storage (Hoellein et al., 2024; Liro et al., 2022). In urban streams in the San Francisco Bay area, around 9.5 pieces m^{-1} of debris were collected within 30.5 m reaches, but >10,000 pieces of debris were found at obstructed sites (Moore et al., 2007). Heavier anthropogenic debris, such as metal and glass, are more likely to be found more in benthic zones, while lighter materials, like plastic, were more likely in riparian zones and retained by wood jams (Hoellein et al., 2014, 2024; McCormick and Hoellein, 2016). In Sardinia, the presence of bridges is a significant explanatory variable for heavy materials (e.g., appliances) in intermittent rivers, but was less important for plastics (Palmas et al., 2022), likely reflecting differences in transport potential. While these studies point to the potential role of geomorphology in mediating the dynamics of anthropogenic debris in urban streams, only one study has examined any aspect of reach-scale channel morphology on debris storage in urban streams. In that study, sinuosity appeared alongside riparian land use in multiple regression models of anthropogenic debris in Maryland urban streams (McCuen et al., 2014).

Geomorphic complexity, of which sinuosity is one measure, can be defined as the spatial variation in sediment bed composition, type and amount of vegetation, and channel geometry (Bartley and Rutherfurd, 2005; Wohl, 2016). Urban stream geomorphology is often described as degraded and simplified, as a result of stormwater inputs and other human manipulations (Russell et al., 2020; Vietz et al., 2016). Increasing geomorphic complexity is sometimes cited as a goal of urban stream restoration (Laub et al., 2012; Violin et al., 2011), partly because of its linkage with habitat diversity and biodiversity (e.g., Hasselquist et al., 2018). Complexity has been linked to attenuation of downstream fluxes of water, sediments, and particulate organic matter (e.g., Small et al., 2008; Westbrook et al., 2006; Wohl and Scott, 2017), but the potential association between geomorphic complexity and debris accumulation in urban streams is largely untested.

Our central hypothesis is that variables representing reach-scale channel morphology will be strongly related to anthropogenic debris storage in urban streams, because debris stored in the channel is subject to transport, deposition, and remobilization by fluvial flows (Al-Zawaidah et al., 2021; Liro et al., 2020) and fluvial geomorphology is intimately tied to flow hydraulics and sediment transport (Leopold et al., 1964). Specifically, we hypothesize that combining geomorphic variables with GIS-derived land cover and catchment variables strengthens predictability of anthropogenic debris concentration over GIS-derived variables alone. We hypothesize further that geomorphology is a stronger predictor of debris concentration than GIS-derived variables and that increased geomorphic complexity of stream reaches is associated with higher debris concentrations in urban streams. Ultimately, the goal of this study is to develop improved understanding of the controls on anthropogenic debris accumulation within US urban streams, so that we can manage and limit pollution not only on a small scale (e.g., urban streams) but also on a broader scale (e.g., inputs to marine systems).

2. Methods

2.1. Study areas

This study is situated in two US metropolitan areas: Cleveland, Ohio and Charlotte, North Carolina. Cleveland (41.49° N, 81.69° W) is the principal city in a metropolitan statistical area with a population of 2.1 million (U.S. Census Bureau, 2022a). Its climate is humid continental with an annual rainfall and a mean annual temperature of 1042 mm and 11.3 °C, respectively (NOAA, 2024). Cleveland streams are shaped by past glaciation (Bauer et al., 2004), with mostly gravel streambeds and some exposed bedrock. Sandy beds are found in some areas due to alluvial deposits and glacial outwash (Blauch and Jefferson, 2019). Charlotte (35.21° N, 80.95° W) is the largest city of North Carolina, with a population of 2.8 million in the metropolitan combined statistical area (U.S. Census Bureau, 2022b). Charlotte's climate is hot and humid with short winters (Robinson et al., 1996), an average annual rainfall of 1107 mm and annual average temperature of 16.3 °C (NOAA, 2024). The streams in Charlotte are underlain by metamorphic rocks, and due to a high degree of weathering in the region most of the soil is clay-rich B horizon (Ireland et al., 1939; Johnson et al., 2022; Rogers and Coleman, 2010; Trimble, 2008; Wortman et al., 2000).

Urban streams in both cities are affected by stormwater runoff that drives rapid responses to precipitation. In Charlotte, there is a strong relationship between impervious cover in the catchment and peak discharge per unit area (Bell et al., 2016), while the relationship is weaker in the Cleveland area (Blauch and Jefferson, 2019). Charlotte streams exhibit a flashier response to rainfall, with higher peaks and shorter duration responses, based on time above mean discharge (Bell et al., 2016; Blauch and Jefferson, 2019).

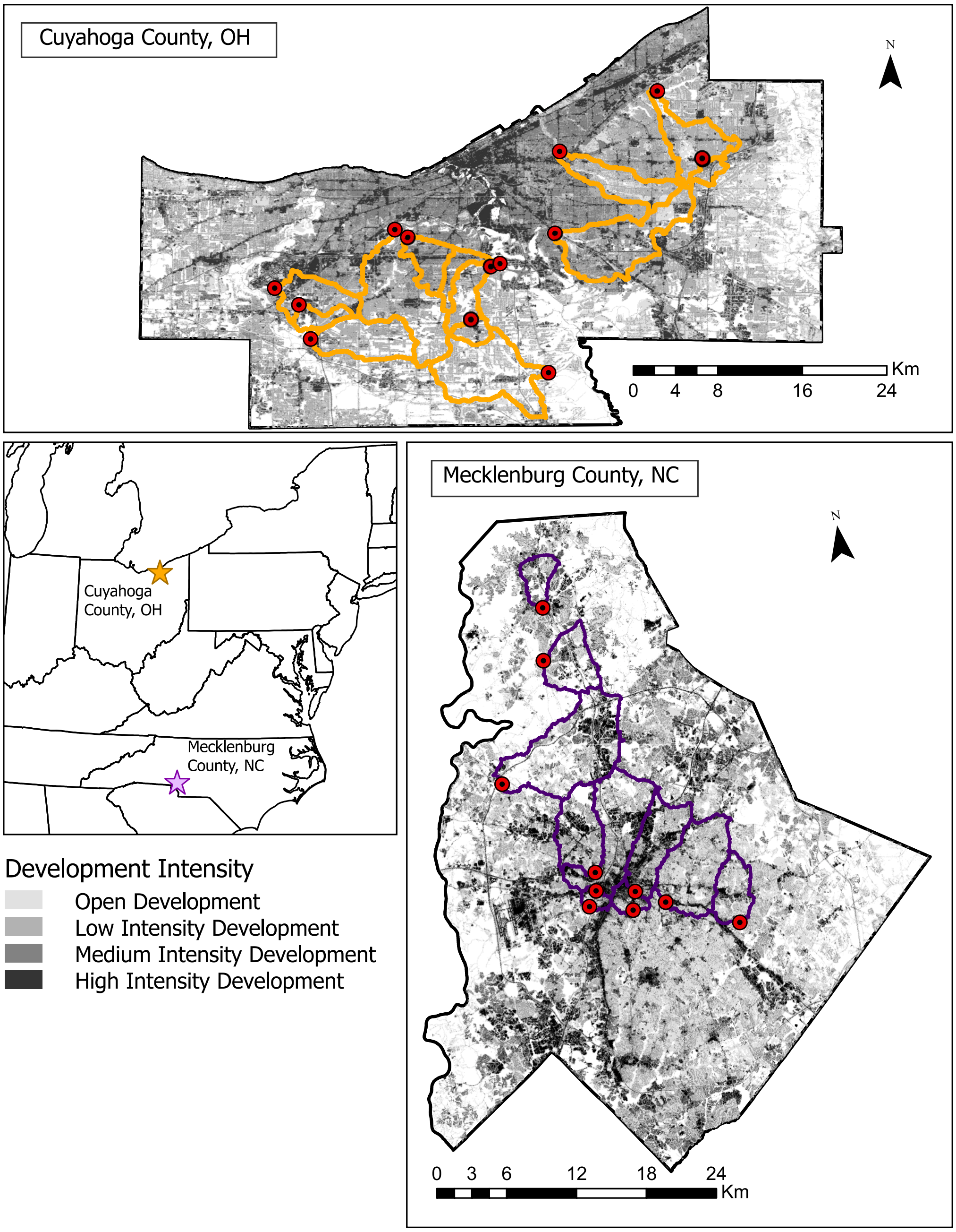

Fig. 1. Study area map showing selected stream reach locations and their drainage areas relative to the intensity of urban development in Cleveland (Cuyahoga County, OH) and Charlotte (Mecklenburg County, NC).

2.2. Field methods and geomorphic variables

Twenty-four urban stream reaches were selected for this study, including 14 reaches in the Cleveland metropolitan area and 10 reaches in the Charlotte metropolitan area (Figs. 1, 2). Candidate reaches were identified in consultation with local individuals and organizations working on urban streams and based on our past research (Bell et al., 2016; Blauch and Jefferson, 2019), with consideration of landowner permission and proximity to USGS gages. After reconnaissance of 20–30 candidates in each city, the study reaches were selected to encompass a diversity of drainage areas, surrounding land uses, and morphologies.

All reaches were assessed in baseflow conditions. Field work in Charlotte occurred July 29–August 3, 2021, and no precipitation occurred during this time. On July 26, 2021, Charlotte recorded a 60 mm rainstorm, with a return period of <1 year for a 24-hour rainfall and USGS urban stream gages in Charlotte. Cleveland field work occurred between May 18 and July 21, 2021. During this period, a 48 mm rainfall on July 11–12, 2021 produced the largest flows at USGS urban stream gages in the Cleveland area. Three sites were assessed after this event, which had a return period of ~1.2 years at USGS gage 412453081395500, which has the longest record (11 years) of the gages near reaches assessed after the event.

Reach lengths ranged from 63.2 to 227 m, but 18 of 24 sites had 200 m reaches. Within the study reaches, we selected four to six transects representative of the range of channel units present (Bisson et al., 2017). If large wood was found in a reach, at least one transect included wood. For each transect, bankfull stage was identified based on breaks in slope, bar tops, vegetation lines, and other visual indicators (Wolman, 1955).

At each transect, we collected, counted, and identified the material of each piece of debris >5 cm in its long dimension within the bankfull channel width for 2 m upstream and downstream of the transect (4 m total width). All pieces of debris were < 2 m above the baseflow water

Fig. 2. Examples of study reaches in Cleveland (A) Chippewa Creek, (B) Euclid Creek at Highland Picnic Area, (C) West Creek at Tuxedo Park, and in Charlotte (D) Briar Creek, (E) Little Sugar Creek at Hospital, (F) Campbell Creek.

level and were at heights with evidence of downstream flow (e.g., flattened vegetation, racked wood, leaves, or debris). Over the entire reach, we counted all pieces of wood >1 m in length and > 0.1 m in diameter, and at least partially within the bankfull channel at the transect scale, presence or absence of wood was noted. At each transect, the cross section was surveyed using an autolevel at <2 m increments. For Cleveland reaches, the longitudinal profile along the thalweg and water surface was also surveyed for the whole reach. For Cleveland reaches, sediment size distributions of stream bed material were derived from pebble counts (Wolman, 1954) at each transect, measuring the b-axis of >100 particles of gravel size or larger and recording counts of sand-sized particles and exposed bedrock. Bed sediment size distributions are reported in Jefferson et al. (2023). Using cross-section, sediment, and long-profile data, we calculated 19 geomorphic complexity metrics, as defined in Polvi et al. (2014) and references therein (Table S2).

Two stream reaches on Euclid Creek in Cleveland were revisited 4 times after the initial assessment, in summer 2021. At each revisit, the total count of debris at the transects was recorded and debris was removed. Intervals between visits ranged from 6 to 46 days.

2.3. GIS analysis and variables

Catchment boundaries of drainage areas upstream of the study reaches were delineated using the USGS StreamStats tool, which uses 10 m DEMs developed from 1:24,000 digital line graph hypsography for Ohio and 30 ft. (9.144 m) digital elevation models (DEMs) developed from the 2004 National Elevation Dataset for North Carolina (U.S. Geological Survey, 2019). Thus, drainage areas do not account for any areas outside of the topographic catchment which are connected to the stream via the storm sewer network, nor do they account for any areas within the topographic catchment that might not drain into the stream.

Further analysis was completed in ArcGIS Pro version 3.0 or later. The National Hydrography Dataset (U.S. Geological Survey, 2023) stream network and the TIGER road network (U.S. Census Bureau, 2023) were clipped to the catchment boundaries to calculate stream density and street density, respectively. Land cover was calculated from the 2019 National Land Cover Database (NLCD) (Dewitz, 2021) for the catchment as a whole, for the area within 100 m of the stream network in the catchment, and for the area within 100 m of the stream network and within 1000 m upstream of the study reach. To calculate population and population density, 2020 census block population (U.S. Census Bureau, 2020) was represented as randomly located points within each block, and this point layer was then clipped to the catchment boundary.

2.4. Statistical analysis

Transect debris counts were normalized by bankfull width, and then averaged to form the response variable reach-scale debris concentration. All statistics were completed in R (version: 2022.07.1). For categorical variables, independent *t*-tests were performed to examine whether reach-scale debris concentration varied between cities, by restoration status, or by bedrock presence/absence. A t-test was also used to examine whether transect debris concentrations varied by presence/absence of wood. A *p*-value <0.05 was considered significant.

We used single and multiple linear regressions to find relationships between the response variable (reach scale debris concentration) and continuous explanatory variables (Table S1). For non-normal variables ($p < 0.05$ in the Shapiro-Wilks test), we first used Tukey transformations, log, and log+1 (Tables S3-S5) to generate a normal distribution using the “rcompanion” R package (Mangiafico, 2024). We excluded variables from further analysis if they did not follow a normal distribution even after transformations. All explanatory variables and response variables were then scaled by subtracting the mean and dividing by standard deviation. Finally, simple linear regression was performed using “lmtest” R Package (Zeileis and Hothorn, 2002) on each variable (Table S6) for Cleveland, Charlotte, and the two cities combined.

For multiple linear regression, we first grouped all continuous explanatory variables into six categories: cross section; longitudinal profile; sediments; catchment characteristics; catchment land cover, and riparian land cover (Table S1). Following reduction of multi-collinearity through stepwise elimination of variables with variance inflation factors (VIF) >10, we created the best model for each category using forwards and backwards stepwise selection based on Akaike Information criterion (AIC) using the “leaps” R package (Lumley and based on Fortran code by Alan Miller., 1997) for Cleveland, Charlotte and for both cities together. After creating the category models, we created a final model by combining the explanatory variables from each category model that had $p < 0.05$. As described above, stepwise VIF reduction followed by forward and backwards stepwise selection based on AIC was used to generate the final model for each city and both cities combined. Following the same procedure, final GIS-only models were also created.

3. Results

3.1. Dataset overview

Selected stream reaches in Cleveland were slightly wider (mean = 13.1 m) than Charlotte (mean = 8.5 m), even though drainage areas were slightly smaller in Cleveland (mean = 20.5 km^2) than Charlotte (mean = 34.7 km^2) (Table 1). The Cleveland watersheds had slightly less impervious surface cover (mean = 29.8 %) and high intensity developed land cover (mean = 7.7 %), than the Charlotte watersheds (mean = 35.3 % impervious, mean = 12.7 % high intensity development) (Tables S3 and S4).

Cleveland and Charlotte had similar debris concentrations in their urban streams (Table 1). In Cleveland, the debris concentration ranged from 0.18 to 2.37 pieces/m, with a mean of 1.24 pieces/m. In Charlotte, debris concentrations ranged from 0.3 to 4.7 pieces/m, with a mean of 2.09 pieces/m. For 73 transects in Cleveland, debris counts ranged from 1 to 87 per transect, while for the 50 Charlotte transects, debris counts ranged from 0 to 129 per transect (Table 1). Between Cleveland and Charlotte, the difference in mean debris concentrations was not significant ($p = 0.074$) (Fig. 3a).

Plastic is the dominant debris material in both cities (Fig. 4). We found 61.5 % and 64.4 % non-foamed plastic in Cleveland and Charlotte, respectively. Foamed plastic accounted for 7.9 % of debris in Cleveland and 9.6 % of debris Charlotte. Metal was the most abundant non-plastic debris material. Plastics (non-foamed and foamed) and metal encompassed 77 % and 85 % of the total debris in Cleveland and Charlotte respectively. Other material types encountered included glass, concrete, cloth, wood, and rubber. In total, our dataset includes 2190 pieces of debris collected from 123 transects.

Categorical variables describing reach geomorphology had no effect on mean debris concentrations. Reach-scale debris concentration was not significantly different between reaches where bedrock was present on the stream bed and those where it was absent ($p = 0.203$) (Fig. 3b). Similarly, restoration status made no difference (Fig. 3c), when *t*-tests were performed ($p = 0.530$). More Cleveland reaches ($n = 9$ of 14) had bedrock exposed on at least part of the streambed than did Charlotte reaches ($n = 0$ of 10). Conversely, we sampled more restored reaches in Charlotte ($n = 5$ of 10) than we did in Cleveland ($n = 4$ of 14). At the transect scale, wood presence/absence did not affect debris concentration ($p = 0.170$), although the 5 transects with the highest debris concentrations all had wood present (Fig. 3d).

3.2. Debris reaccumulation

Anthropogenic debris reaccumulated within the two revisited stream reaches after the initial assessment and debris removal. The Acacia reach had 71 pieces of debris across 5 transects during the initial visit, and 15–81 pieces on subsequent visits, while the Highland Picnic Area reach

Table 1
Debris concentration within Cleveland and Charlotte streams.

City	Stream	Debris concentration (pieces/m)	Bankfull width (m)	Imperviousness (%)	Drainage area (km^2)
Cleveland	Abram Creek at Airport	2.37	8.70	36.0	21.47
	Abram Creek at Sutfin Jam	0.77	13.89	28.2	5.44
	Baldwin Creek	1.34	8.87	20.1	22.87
	Big Creek	0.49	18.42	33.7	53.98
	Chippewa Creek	0.57	16.78	13.5	38.00
	Doan Brook Restored	0.70	11.48	21.3	19.14
	Euclid Creek Acacia	1.39	10.27	36.5	3.88
	Euclid Creek Highland Picnic Area	0.18	16.53	36.1	23.62
	Euclid Creek Log Jam	1.94	14.00	29.5	3.90
	Mill Creek Garfield Reservation	1.88	10.54	38.1	37.87
	Stickney at Brooklyn	2.31	11.72	44.4	11.44
	West Creek at Brooklyn	0.91	13.42	29.3	23.79
	West Creek at Pleasant Valley	2.35	9.00	25.7	5.01
	West Creek Tuxedo Park	0.22	20.25	24.5	16.61
Charlotte	Briar Creek	1.68	9.88	26.9	37.02
	Campbell Creek	4.70	8.00	30.4	15.50
	Irwin creek	2.96	13.32	38.7	66.20
	Little Sugar Creek at Elizabeth	2.09	7.57	50.1	25.50
	Little Sugar Creek at Hospital	1.84	6.59	51.9	31.10
	Long Creek	0.30	7.62	26.6	57.03
	McDowell Creek	1.77	5.38	30.5	9.06
	Stewart Creek at Government	3.85	14.20	38.0	62.74
	Stewart Creek at Seversville	1.25	6.60	36.4	24.09
	Torrence Creek	0.43	6.12	23.2	18.98

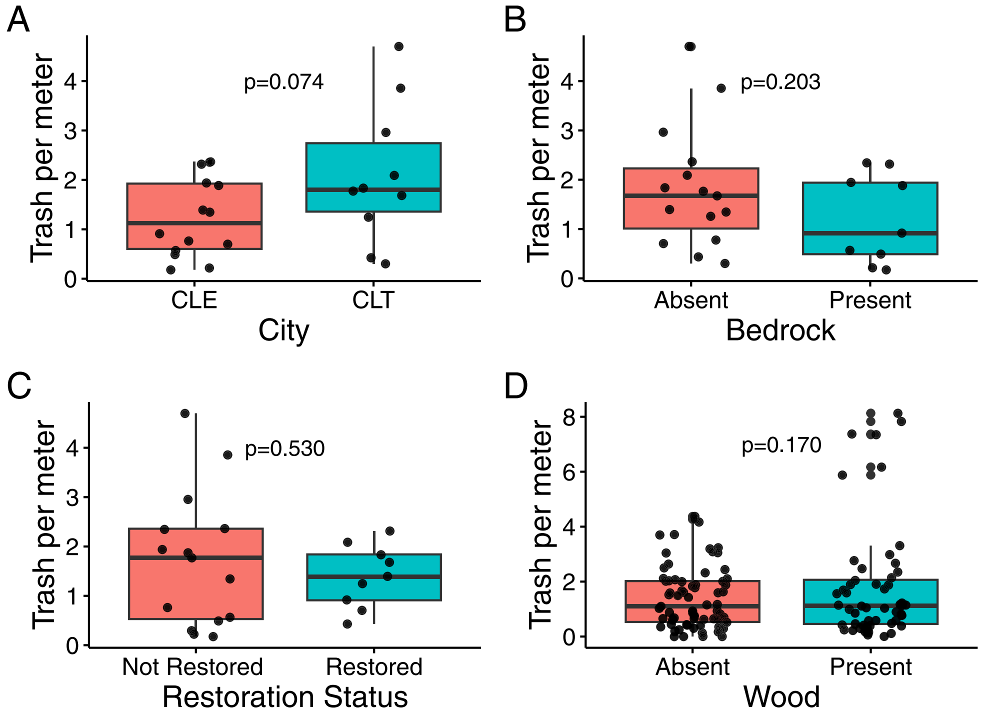

Fig. 3. Box and Whisker plots showing debris concentration between (a) cities, (b) bedrock present/absent, (c) restoration status, and (d) wood present/absent. t-tests were performed on the reach scale dataset between cities, restoration status, and bedrock presence/absence and on the transect scale dataset for wood presence/absence.

had 16 pieces of debris across 5 transects during the initial visit, and 9–23 pieces on subsequent visits. Debris accumulation rates, calculated as number of pieces observed divided by number of days between visits, decreased with the length of time between visits (Fig. 5). At Highland Picnic Area, the debris accumulation rate were very similar between the 46 period which contained the highest flow events and the 37 day period which had lower flows.

3.3. *Linear regression models*

When linear regression is performed on the dataset from both cities combined, only 5 out of 35 variables examined showed significant ($p < 0.05$) associations with debris concentration (Table 2). All variables with significant relationships in the combined dataset were related to land cover. The strongest relationships were found with high intensity development at the riparian ($r^2 = 0.26, p = 0.010$) and catchment ($r^2 = 0.25, p = 0.013$) scales.

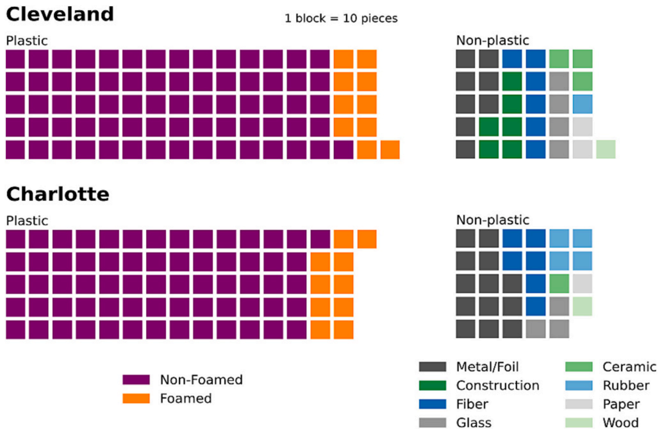

Fig. 4. Material types of debris collected in Cleveland and Charlotte streams.

When linear regression is performed for each city separately, significant relationships emerge between debris concentrations and predictor variables. When the dataset is limited to Cleveland, linear regression analysis showed significant relationships between debris concentration and 7 out of 52 variables, including 2 cross-section and 5 landcover variables (Table 2). Bankfull width was the strongest predictor of debris concentration in Cleveland ($r^2 = 0.59, p = 0.001$). Both cross-section variables had a negative relationship with debris concentration, while all of the land cover relationships were positively associated with debris concentration. None of the long profile, sediment, catchment characteristics, or land cover variables at the scale of the 100 m riparian buffer within 1 km of the outlet were significantly related to debris concentration.

In Charlotte, 5 out of 35 variables examined were significantly ($p < 0.05$) related to debris concentration (Table 2). Of those variables, the coefficient of variation (CV) of width showed the strongest correlation ($r^2 = 0.60, p = 0.008$) with debris concentration. All significant variables showed a positive association with debris concentration, except wet to bankfull width ratio which was negatively related. No significant correlation was identified between any catchment scale land cover variable and debris concentration.

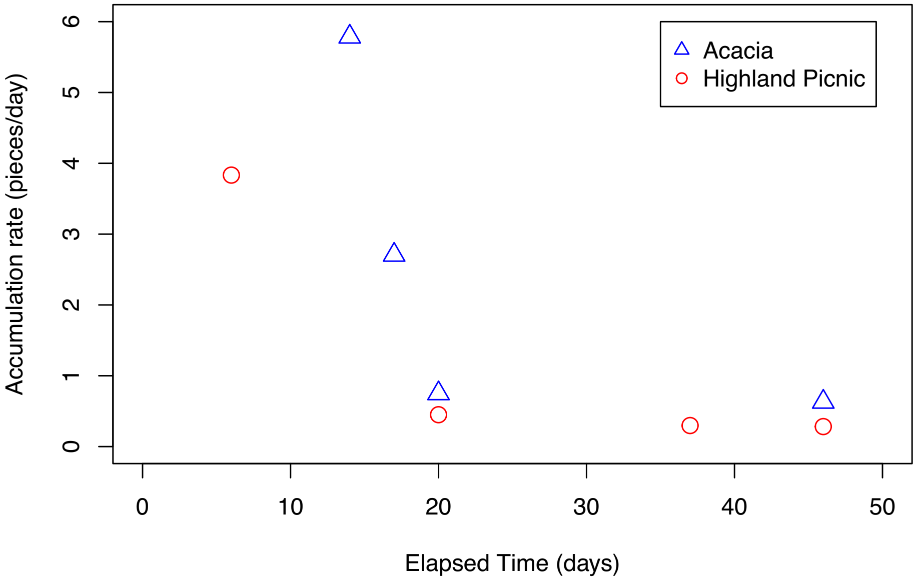

Fig. 5. Anthropogenic debris accumulation rate (pieces per day) versus elapsed days since debris removal for two stream reaches on Euclid Creek, in the Cleveland area. Data were collected May–September 2021.

Table 2
Summary of models from linear regression analysis.

City	Explanatory variable category	Explanatory variable	Coefficient (a_i)	R^2	p-value
Both Cities	Catchment land cover	NLCD_ISC	0.42	0.18	0.039*
		NLCD_dev_high	0.50	0.25	0.013*
		NLCD_dev_all	0.41	0.17	0.045*
	Riparian buffer land cover	X100m_DevHigh	0.51	0.26	0.010*
		X1kmbuff_ISC	0.45	0.20	0.028*
Cleveland	Cross-section	BF_width	−0.77	0.59	0.001*
		BFW_BFD_ratio	−0.67	0.45	0.008*
	Catchment land cover	NLCD_dev_high	0.65	0.42	0.012*
	Riparian buffer land cover	X100m_ISC	0.70	0.50	0.005*
		X100m_Devmed	0.69	0.47	0.007*
		X100m_Devhigh	0.67	0.45	0.009*
		X100m_Devlowhigh	0.67	0.46	0.008*
Charlotte	Cross-section	W_sd	0.68	0.46	0.032*
		W_cv	0.78	0.60	0.008*
		Wet_BFW_ratio	−0.65	0.42	0.043*
	Catchment characteristics	Pop_density	0.66	0.43	0.037*
	Riparian buffer land cover	X1kmbuff_Devlow	0.72	0.51	0.020*

Note: This table shows linear relationships with p-value <0.05. All regression models for each category variables are provided in supplementary information (Table S6).

3.4. Multiple regression models

When multiple regression analysis is performed on data from both cities, significant models ($p < 0.05$) predicting debris concentration were identified only in the categories of catchment scale and riparian land cover (Table 3). A two variable model related to land cover within the 100 m riparian buffer explaining 36 % of the variation in debris concentration produced the highest explanatory power (*adjusted* $r^2 = 0.30$, $p = 0.009$) of any of the category models. A two variable model based on catchment scale land cover variables explained 32 % of the variation (*adjusted* $r^2 = 0.26$, $p = 0.017$).

For both cities combined, 39 % of the total variation in debris concentration was predicted through two variables, when all variables from the significant category models ($p < 0.05$) were used as candidates in the final model (Table 3). The final model included riparian medium intensity development and catchment scale developed open space (*adjusted* $r^2 = 0.33$, $p = 0.006$). The two final model variables had similar influence.

For each category of variables, multiple linear regression models for each city separately were able to explain a larger percentage of the variation in debris concentration than when the cities were combined (Table 3). For Cleveland, category models for cross-section variables, catchment scale land cover, and riparian land cover had significant relationships with debris concentration, explaining 61–63 % of the variation. Our analysis for Charlotte revealed that cross-section variables and riparian land cover variables produced significant ($p < 0.05$) relationships with debris concentration, explaining 51–84 % of the variation.

There were some common variables included in category models in both cities. Bankfull area appeared in the cross-section category models in both cities (Table 3). In Cleveland, two cross section variables were selected (*adjusted* $r^2 = 0.54$, $p = 0.005$), while in Charlotte four variables were selected (*adjusted* $r^2 = 0.7$, $p = 0.03$). Low intensity development in the 100-m riparian buffer within 1 km of the outlet also appeared in category models for both cities, and it was the only variable selected in Charlotte (*adjusted* $r^2 = 0.45$, $p = 0.02$) (Table 3). In Cleveland, riparian high intensity development was also selected (*adjusted* $r^2 = 0.57$, $p = 0.004$). In Cleveland, catchment scale landcover variables also produced a significant model (*adjusted* $r^2 = 0.51$, $p = 0.017$) (Table 3), but the category did not produce a statistically significant model in Charlotte ($p > 0.05$). Category models with catchment characteristics not derived from the NLCD were not significant in either city ($p > 0.05$). In Cleveland, models of the relationship between debris concentration and sediment and long profile variables were not significant ($p > 0.05$).

Final models for each city explained most of the variation in debris concentration across stream reaches. In Cleveland, when the final model was made using candidate variables ($p < 0.05$) from all of the category models, four variables explained 82 % of the variation in debris concentration (Table 3). Bankfull width to depth ratio, catchment scale impervious surface cover, riparian high intensity development, and low

Table 3
Multiple regression model results summary for all variables.

City	Explanatory variable category	Explanatory variables	Coefficient (a_i)	Multiple R^2	Adjusted R^2	p-value
Both cities	Cross-section	BF_area	−0.43	0.18	0.06	0.245
		W_cv	0.35			
		BFW_BFD_ratio	−0.32			
	Catchment characteristics	Street_density	0.42	0.19	0.12	0.105
		Stream_density	0.29			
	Catchment land cover	NLCD_dev_open	0.61	0.32	0.26	0.017*
		NLCD_dev_med	0.71			
	Riparian buffer land cover	X100m_DevOpen	0.48	0.36	0.30	0.009*
		X100m_DevMed	0.56			
	Final model	NLCD_dev_open	0.75	0.39	0.33	0.006*
		X100m_DevMed	−0.42			
Cleveland	Cross-section	BF_area	−0.42	0.61	0.54	0.005*
		BFW_BFD_ratio	−0.79			
	Long profile	LP_R2	−0.43	0.18	0.11	0.130
	Sediments	Sed_grad	−0.46	0.33	0.13	0.236
		Sed_kurt	−0.64			
		Sed_skew	0.54			
	Catchment characteristics	Area_km2	−0.37	0.14	0.07	0.188
	Catchment land cover	NLCD_dev_high	1.40	0.62	0.51	0.017*
		NLCD_ISC	−0.09			
		NLCD_water	−0.52			
	Riparian buffer land cover	X100m_DevHigh	0.73	0.63	0.57	0.004*
		X1kmbuff_DevLow	0.39			
	Final model	BFW_BFD_ratio	−0.36	0.82	0.74	0.002*
		NLCD_ISC	−0.35			
		X100m_DevHigh	0.87			
		X1kmbuff_DevLow	0.38			
Charlotte	Cross-section	BF_area	−0.64	0.84	0.70	0.034*
		BF_width	0.91			
		XS_CV_d	−0.34			
		Wet_BFW_ratio	−0.79			
	Catchment characteristic	Area_km2	0.35	0.55	0.42	0.061
		Pop_density	0.77			
	Catchment land cover	NLCD_dev_open	0.37	0.46	0.31	0.113
		NLCD_forest	−0.64			
	Riparian buffer land cover	X1kmbuff_DevLow	0.71	0.51	0.45	0.020*
	Final model	BF_area	−0.28	0.94	0.89	0.003*
		BF_width	0.31			
		Wet_BFW_ratio	−0.66			
		X1kmbuff_DevLow	0.49			

Note: In Cleveland, no significant model was identified from catchment characteristics, long profile, and sediments variable categories. In Charlotte, no significant model was identified from catchment characteristics and catchment landcover. In both cities combined, no significant model was identified from catchment characteristics. Significant *p*-values are shown with * sign.

intensity development in the 100-m riparian buffer within 1 km of the outlet can be used to predict debris in Cleveland urban streams (*adjusted* $r^2 = 0.74$, $p = 0.002$). All but the last of those variables also had significance in single regression models with debris concentration (Table 2). The final model for Charlotte explained 94 % of the total variation in debris concentration, using four variables (Table 3). Charlotte's urban stream debris concentration can be predicted by three cross-section variables, plus one riparian land cover variable (*adjusted* $r^2 = 0.89$, $p = 0.003$). When final multiple regression models are limited to only candidate variables derived by GIS and appearing in significant category models ($p < 0.05$), the riparian land cover category models are reproduced in both cities, explaining 51–63 % of the variation in debris concentrations.

We further explored the influence of bankfull width in the multiple regression models. Bankfull width had the strongest single linear regression coefficient in Cleveland, but was eliminated during the stepwise VIF reduction before multiple regression models were created. Conversely, bankfull width did not have a significant single linear regression relationship with debris concentration in Charlotte (Table 2) but it had the most influential coefficient in the cross-section model. If bankfull width is forcibly excluded, the cross-section category model for Charlotte identifies a single variable model with CV of width (*adjusted* $r^2 = 0.55$, $p = 0.008$) and the final model contains two variables: CV of width and a riparian land cover variable (*adjusted* $r^2 = 0.73$, $p = 0.004$).

4. Discussion

4.1. Debris accumulation and transport dynamics

Our analyses support our hypothesis that combining measures of land cover and geomorphology can effectively predict anthropogenic debris storage at the stream-reach scale. While the movement of debris through urban streams may be driven by stormflow events (e.g., Bauer-Civiello et al., 2019; Cowger et al., 2022; McCormick and Hoellein, 2016) explicit analysis of hydrologic dynamics is not required to predict the standing stock of debris within a reach. Indeed, in Charlotte, where there is a very strong relationship between peak discharge (m^3 s^{-1} km^{-2}) and impervious surface cover (Bell et al., 2016), there was no significant relationship (Table S6) between impervious surface cover and debris concentration.

At the sites that were revisited multiple times, debris reaccumulated quickly, to concentrations similar to or exceeding the concentrations measured during the initial assessment. This suggests that large stormflow events are not needed to drive debris storage in urban stream channels, and that small stormflows and baseflow may contribute significantly to debris accumulation. The observed decreasing accumulation rate with elapsed time further suggests that stormflows likely also remove stored debris from stream reaches, moving it farther downstream, to the floodplain, or to a receiving water body.

While the data collected in this study cannot exclude wind as a transport mechanism (e.g., Mellink et al., 2024) for debris stored within urban streams, field observations strongly support fluvial transport of anthropogenic debris. Much of the debris made of plastic, paper, and fiber encountered in this study was highly flexible, and often wrapped around wood, roots, or vegetation in a flow-aligned manner. Such consistent flow-alignment is unlikely to occur solely by wind. Further, most of the non-plastic debris (28.2 % of total) is made of material generally considered too heavy for aeolian transport. Regardless of how anthropogenic debris is initially introduced into urban streams, we suggest that fluvial processes control its storage within the bankfull channel.

4.2. Prediction of debris concentration through land cover and geomorphology

The best linear regression models for each city support our hypothesis that the debris concentration would be better predicted by stream geomorphology than GIS derived land cover and catchment variables (Tables 2 and 3). In each city, the strongest single linear regressions are with geomorphic variables (Table 2): a negative relationship with width in Cleveland and a positive relationship with CV of width in Charlotte. For Cleveland, the cross-section variables model explains a similar amount of the variation in debris concentration (61 %) as the best model based on GIS-derived variables (63 %). For Charlotte, the cross-section variables model explains more variability (84 %) than the best GIS-derived model (55 %). Past studies have found positive associations between anthropogenic debris and urban development (Cowger et al., 2019; Poletti and Landberg, 2021), but our study found that geomorphology influences the accumulation of debris at the stream reach scale more than land cover in urban watersheds. Inclusion of geomorphic variables will advance prediction of the spatial distribution of debris in urban streams.

For each city, combining geomorphic and GIS-derived variables in the final model explains the highest amount of variation in debris concentration (82 % in Cleveland, 94 % in Charlotte) and generates the lowest *p*-value. This finding suggests that the inclusion of both geomorphic and GIS-derived variables is important in predicting debris concentration. GIS-derived variables, such as high intensity development and developed open space, may be helpful in predicting the magnitude of debris sources reaching urban streams, while geomorphic variables, such as bankfull width and CV of width, may be helpful in predicting the cause of debris retention at the reach scale.

While our dataset supports previously-identified associations between urban land cover and debris concentration in streams (Cowger et al., 2019; McCuen et al., 2014; Poletti and Landberg, 2021), no single or consistent set of measures of urban land cover (catchment or riparian) was identified across cities. Instead, a variety of measures of development intensity emerged in the models of debris concentration (Tables 2 and 3), including variables representing the catchment, riparian land cover along the entire stream network, and riparian land cover within 1 km of the measured reach. The multiple significant relationships probably reflect the lack of a single dominant land cover control, as well as the inter-dependencies between the land cover variables. This echoes findings by McCuen et al. (2014) who identified different significant combinations of riparian land use types by type of anthropogenic debris (e.g., bags vs. bottles) and season.

Land cover and use associated with the release of anthropogenic debris into streams may differ between the two cities. In Cleveland, high intensity developed land cover had the strongest relationships with debris concentration of the land cover variables, which aligns with previous studies that have found relationships between multiple pollutants and high intensity development in urbanized watersheds (Jin et al., 2022; Mohammadi et al., 2022). For Charlotte, single regression model results revealed a positive correlation of debris concentration with population density, and our data showed strong positive correlations between population density and all development types (including low, medium, high, and open development) in both cities (Figures S1 and S2). The association of population density with developed open areas ($r^2 = 0.72$) for Charlotte is likely the reason for positive association of debris concentration with developed open areas. With higher population density, the demand for recreational space such as park and open lands increases so that people can engage in outdoor activities (McConnell and Walls, 2005). Many of the sampled reaches in Charlotte were within parklands classified as open developed land, and the median amount of open developed land within 100 m of the stream network was 29 % for the Charlotte reaches. This suggests that open recreational areas close to urban streams may be sources of debris to the streams, which supports previously posited associations between intensity of recreational use and debris in Chicago urban streams flowing through parks (McCormick and Hoellein, 2016).

4.3. Effect of channel geomorphology on debris concentration

Our analyses show that geomorphology, though not necessarily geomorphic complexity, strongly influence debris concentration. We evaluated 4 cross-section and wood metrics of complexity in Charlotte and an expanded set of 19 geomorphology metrics in Cleveland, including cross-section, wood, long profile, and sediment metrics (Tables S1 and S2). In Charlotte, debris concentration can be significantly predicted by a few geomorphic complexity metrics related to cross-section characteristics, including CV of width, width standard deviation, and CV of depth (Table 3). However, none of the cross-section, long profile, or sediment complexity metrics showed any significance either in single or multiple regression models in Cleveland (Table 3 and Table S6). Overall, our regression modeling approach did not identify variables that fully support our hypothesis that more complex stream reaches are associated with higher debris concentrations. Geomorphic complexity is not defined by a single variable, and there are many metrics which have been used to quantify the geomorphic complexity of streams (Polvi et al., 2014; Wohl, 2016). Streams with high complexity according to one metric often have low complexity by another measure (Laub et al., 2012).

Our data show that cross-section properties strongly influence debris concentration, through their association with boundary roughness that creates potential for debris trapping. Following normalization into debris concentration (pieces per meter), bankfull width was still significantly associated with debris concentration in Cleveland (Table 2) and bankfull area appears in multiple regression models in Cleveland, Charlotte, and the combined dataset (Table 3). Multiple regression models show that smaller channels tend to have higher debris concentrations than larger ones. In smaller channels, debris is more likely to be retained, because more of the flow, and thus the transported debris, interacts with the banks. The negative relationship between bankfull width to depth ratio and debris concentration, identified in Cleveland, points to the role of bank roughness as more important than bed roughness for trapping debris. A recent analysis showing that higher bank roughness relative to bed roughness produces narrower and deeper equilibrium channels (Fan et al., 2023) supports the inference that bank roughness is implicated by our regression results. The absence of strong relationships between debris concentration and measures of sediment size distribution also points to bank roughness as more important than that of the bed.

In natural channels, roughness that traps debris could be from riparian vegetation below the bankfull elevation or branches that overhang the channel, as can be seen in Fig. 2D-F. Direct interception and entanglement of flexible materials (e.g., plastic bags) by vegetation was commonly observed in the field, and hydraulic effects of bank vegetation may also contribute to the greater debris accumulation in narrower and deeper channels. In-stream vegetation increases drag, reducing shear stress and flow relative to unvegetated areas (Liu and Shen, 2008; Nepf, 1999), promoting sediment accumulation on the bed (Biggs et al., 2021; Cotton et al., 2006). Even with low emergent vegetative densities, the effects on drag and shear are much larger than that produced by the bed (Nepf, 1999). Patch-scale vegetative patterns are important for flow resistance at the reach scale, being described as a blockage factor (Nepf, 2012). Channels narrowed by riparian vegetation have more tendency to trap sediments (Davies-Colley, 1997), which is consistent with our findings that narrower channels are trapping more debris pieces. In more highly engineered channels, we observed debris trapped in placed rock revetments, as has previously been noted at beaches (Aguilera et al., 2016; Lawen et al., 2024).

In Charlotte, regression results suggest an association between debris accumulation and variation in channel shape. The positive relationships between debris concentration and both standard deviation and CV of bankfull width (Table 2) may occur because high variation in channel width could create debris accumulation hotspots, associated with flow obstacles and eddy pools. Constrictions in channel width may also cause backwater effects during high flows (e.g., Thompson et al., 1999; Tracy and Carter, 1955; Wohl and Legleiter, 2003), causing debris pieces to be retained within the wider channel areas, increasing overall concentrations at the reach scale. While the AIC selection process for multiple linear regression modeling favored a single variable (width) over the pair of variables (CV of width and standard deviation of width) with significant relationships with debris concentration (Table 3) when we excluded width from consideration in the multiple regression, CV of width replaced it, explaining 60 % of the variation in Charlotte debris concentrations with a single variable. Conversely, the wetted (low flow) to bankfull width ratio indicates a negative relationship with debris concentration. Smaller wetted to bankfull width ratios may reflect channels that have concentrated high velocity zones with lower velocity areas along the channel margins where sediment may be deposited as flows recede (Steiger et al., 2001). Debris deposition may follow similar patterns.

Sinuosity is the only geomorphic variable previously investigated in relation to anthropogenic debris in urban stream (McCuen et al., 2014), with more sinuous reaches predicted to store more debris than less sinuous reaches in multiple regression models than included riparian land use. As sinuosity increases, the channel length and velocity variation both increase (Leopold et al., 1964), increasing opportunities for light flexible materials to become entrapped by bank vegetation and for heavier materials to be deposited on the bed in slow-moving areas. This previous finding amplifies our inference that flow interaction with the stream banks is a first-order control on debris storage.

We expected to find a significant relationship between in-stream wood and debris concentration, but no significant relationship was identified for Cleveland, Charlotte, or both cities combined (Figures S1-S3). Wood count did not appear in multiple regression models in Cleveland or when both cities were combined, and it was excluded from consideration in Charlotte because it could not be transformed into a normal distribution. Our analysis also suggests that debris concentration is independent of presence or absence of wood at the transect scale in streams (Fig. 3), though we noted that the transects with the highest debris concentrations all had wood present. However, wood jams have been shown to act as a trapping mechanisms for macroplastic in stream reaches in Poland and the US (Hoellein et al., 2024; Liro et al., 2022). The lack of a significant result in the present study emphasizes that not all in-stream wood is equally effective in trapping debris, and that wood size, branching, roots, orientation, and elevation relative to flow are likely important (e.g., Stachew et al., 2021). Based on our observations in the field, wood jams and channel spanning logs at the low flow water surface height can be high plastic accumulation zones. Conversely, we observed that partially buried or flow-aligned logs do not tend to accumulate plastic, especially if they lack fine branches and root wads. These nuances are lost when wood count or presence/absence is treated as a predictor variable in statistical analysis.

4.4. Generalizability of anthropogenic debris prediction and opportunities for future research

Our multiple linear regression model performance was remarkable when created separately for each city, with final models that explained 82 % and 94 % of the variation in debris concentration in Cleveland and Charlotte respectively. When both cities are combined, the performance of final model (*adjusted* $r^2 = 0.33$, $p = 0.006$) was not as good as it was for each city separately, only explaining 39 % of variation in debris concentration (Table 3). There was little overlap in the variables identified as significant between the two cities, and no geomorphic variables appear in the final model for the combined dataset. Some relevant relationships may be non-linear or threshold-driven and may have been missed using a linear regression-based approach (e.g., Zuur et al., 2009).

Urbanized land in both cities is correlated with debris in streams, but a generalized relationship between debris concentration and land cover variables across cities could not be developed, possibly because the pattern of urbanization and land management differed between them (e.g., development along stream corridors). It is possible that there is more potential for generalizability within a geographic region, where patterns of urban development may be more similar. However, in two adjacent Maryland counties, multiple regression models for anthropogenic litter also generated different significant variables (and sometimes opposite signs) when based on land use within 305 m of stream reaches (McCuen et al., 2014). This underscores the limits of using land cover and land use as predictors of in-stream anthropogenic debris within US urbanized areas, and it suggests that metrics that relate to the transport and storage of debris within the channel might be useful for generalizability.

Despite the potential for generalized physical controls on anthropogenic debris storage in urban streams, this study did not unambiguously identify the variables to describe those controls. The different geomorphology variables shown to have significant relationships with debris (Tables 2 and 3) might be because we did not collect data in a sufficient number of cities to identify a generalized relationship. The urban streams in this study also differed by city in terms of the history of glaciation, frequency of bedrock outcropping, and dominant grain size (Section 2.1), which may obscure cross-city relationships that could be found within a narrower range of geomorphological variation. We performed our analysis at the reach scale, which condensed the variability of data collected for individual transects and may have reduced the signal of geomorphology on debris concentration. Approaches that consider the fine-scale geomorphic context of debris storage should be explored.

We infer that bank roughness could be a possible parameter which describes the trapping of debris along banks, and it is not directly captured in our dataset. Therefore, more detailed data collected to quantify bank roughness and vegetation across multiple cities or within flume experiments may be helpful in developing a generalizable relationship between anthropogenic debris trapping and fluvial geomorphology. For example, examining how debris transport and entrapment is influenced by the boundary layer and secondary currents at meanders under different roughness and flow conditions (e.g., Thorne and Furbish, 1995) would be useful for improving models of anthropogenic debris transport and storage. In the field, quantifying debris concentrations associated with different exposed root densities and architectures (e.g., Stachew et al., 2021; Wynn et al., 2004) would also advance understanding of debris storage.

5. Conclusion

Anthropogenic debris stored in urban stream channels was ubiquitous, primarily plastic, and reaccumulated quickly following removal. Multiple regression models of anthropogenic debris concentrations in US urban stream reaches showed that very strong city-specific relationships can be developed when geomorphology is considered in addition to GIS-derived land cover and catchment characteristics. Debris concentration can be predicted based on cross-section variables as well as, or better than, by GIS-derived variables in city-specific analysis. Geomorphologically-informed models of anthropogenic debris concentration could be used to identify areas for stream cleanup efforts or targeted interventions designed to keep debris from reaching urban stream reaches.

Bankfull width, bankfull area, and width CV were found to be strongly related to anthropogenic debris concentration in city-specific models. Conversely, geomorphic complexity of the longitudinal profile and sediments were not predictive of anthropogenic debris storage in Cleveland streams. While geomorphic variables predictive of debris concentration were not identical in Cleveland and Charlotte, analysis of our results suggest that flow interaction with rough banks and vegetation is an important control on storage of anthropogenic debris within urban stream channels.

CRediT authorship contribution statement

Nageen Farooq: Writing – original draft, Methodology, Formal analysis, Data curation. **Anne Jefferson:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Chris Greising:** Investigation, Data curation. **Kayla Kearns:** Investigation, Data curation. **Sophia Muratori:** Investigation, Data curation. **Kylie Snyder:** Investigation, Data curation.

Declaration of competing interest

Authors declare no competing financial interest as well as any personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179317.

Data availability

Link to the data used for this research is provided in the manuscript.

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