EXPLORING POTENTIAL SOURCES OF SOLID WASTE IN A STORMWATER SYSTEM

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ABSTRACT

This study provides insight into how solid waste flows through a stormwater system, the common types of solid waste transported through such systems, and outlines a scalable, low-cost methodology that municipalities of all sizes can use. High quantities of mismanaged solid waste produced in urban areas leads to litter in the environment, potentially causing harm to wildlife and humans. Studies have been conducted on solid waste found in natural areas. However, few studies detail how urban settings contribute to this problem, and to what degree. A primary mode of solid waste transportation in urban areas is through stormwater systems. This study investigates the connection of upstream areas where water flows into a stormwater system and a retention lake downstream. The lake of focus for this study is in Tallahassee, Florida, in a popular park for recreation and wildlife. It functions as a filter for urban runoff before it enters natural waterways. Solid waste was collected first near the lake's littoral zone and then at 70 inlets in the upstream areas. The collected solid waste was analyzed by sorting it into twelve categories and obtaining the counts of each category. A descriptive analysis was used to determine similarities and differences between the sites and the lake. Tobacco Products and

Miscellaneous Plastics had high collection counts at all sites and Lake Elberta, likely due to their high mobility in water. The solid waste found around the littoral zone resembled that which was collected at upstream sites, indicating a relationship between them. Some sites upstream exhibited high counts of solid waste items that were also found at the lake in high counts.

INTRODUCTION

Municipal services often refer to discarded materials, such as bottles, cans, and paper products from commercial and residential activities, as solid waste. There have been many efforts to prevent solid waste from going to the oceans and to measure the amount of solid waste that enters those waterbodies (5 Gyres 2016; California Regional Water Quality Control Board 2010; Luebke 2018; Moore et al. 2007, 2016; NY/NJ Baykeeper 2016; Rech et al. 2014; Stickel et al. 2012). Solid waste cleanup events and studies often focus on oceans since there are many adverse effects on marine wildlife, such as animals ingesting or becoming entangled in the litter, causing subsequent reductions in wildlife populations (Giraudeau et al. 2018; NY/NJ Baykeeper 2016). However, the prevention of waste entering stormwater retention lakes is often overlooked.

Solid waste on city streets and neighborhood roads can ultimately travel to natural and human-made waterways (Cowger et al. 2019; Luebke 2018; U.S. EPA 2018). Stormwater lakes, a type of human-made waterway, function to collect urban runoff from stormwater systems that are in place to prevent surface water from accumulating and eventually flooding a region (U.S. EPA 2018). A properly functioning stormwater system transports rainwater from the city’s roads and streets to one of these lakes. However, during heavy rainfall events, solid waste present in these surfaces may be transported through the system and can end up at the stormwater lakes (U.S. EPA 2018).

Although recycling and composting programs have recently decreased the per capita solid waste generation rate, each person in the United States (U.S.) still generates an average of approximately 2 kg of solid waste each day (U.S. EPA 2017). A 2020 study estimated over 23 billion pieces of litter were on roadways in the U.S. (Keep America Beautiful 2021). The cost of this litter is yet to be published, but a similar study in 2009 estimated the cost to U.S. governments, businesses, educational institutions, and volunteer organizations to be $11.5 billion annually. However, this study had 50 billion pieces of litter collected (Keep America Beautiful 2009). When examining the expenses associated with solid waste in stormwater systems alone, it is difficult for a municipality to know how much they will spend annually on litter-related costs (Stickel et al. 2012). In midsize cities, such as Tallahassee, Florida, an estimated $370,000 will be spent annually on solid waste reduction in their stormwater systems (Stickel et al. 2012; U.S. Census Bureau 2019).

Solid waste is an issue for stormwater systems across the nation that can have local and global effects on the environment (Walsh 2000). Previous studies' solid waste collection focused on a single site and sources immediately adjacent to the site (Cowger et al. 2019; Keep America Beautiful 2009; Luebke 2018; US. EPA 2018). The novelty of this study is due to our analysis of solid waste that accumulates in a retention lake and potential sources upstream, using Lake Elberta, part of a stormwater system in Tallahassee, Florida, as a model. This study's objectives were (1) to determine whether there is a link between solid waste found around stormwater inlets and the solid waste found in Lake Elberta and (2) identify the potential sites contributing to the problem. We hypothesized that the composition of solid waste at the lake would resemble that of the upstream sites, and that some sites would have higher counts of solid waste, indicating they are possibly major contributors to the problem.

MATERIALS AND METHODS

Study Area

The City of Tallahassee has a municipal separate storm sewer system that allows stormwater to flow directly from storm drains into retention lakes (FL DEP 2020). One retention lake in Tallahassee's stormwater system is Lake Elberta. This lake is approximately 0.5 km south of the Florida State University (FSU) football stadium and campus. Its primary role is to serve as stormwater treatment and flood protection for those places. Lake Elberta Park has also become a popular recreation site in the community. It is currently ranked fourth in the total number of bird species observed among birdwatching hotspots in Leon County, according to the eBird online database (Cornell Lab of Ornithology 2020). This ranking is noteworthy for birdwatchers and people seeking an enjoyable outdoor environment (Chiesura 2004; Li 2020).

Lake Elberta is small, with a total area of approximately 9.5 ha and a depth of approximately 3 m (J. Yarbrough, personal communication, 2020). The lake's center has an elevation approximately 14 m above sea level, while the areas upstream have elevations up to 64 m. This elevation difference is essential when determining the flow of solid waste because stormwater systems rely on an elevation grade to move water. As a result, lower elevation areas receive stormwater and its contents from higher elevation areas.

Lake Elberta's intended function is to prevent solid waste from reaching Lake Munson, a highly degraded system downstream, and ultimately Wakulla Springs, one of Florida's largest springs (Kincaid and Werner 2008; McGlynn 2006). Since its construction, the amount of solid waste in Lake Elberta has been a concern, with many local groups regularly organizing cleanup events. Solid waste at Lake Elberta is typically seen in the water and on the lakeshore but not on the surrounding park grounds. Despite the numerous cleanup events, the amount of solid waste at the lake stays relatively constant.

The water that flows through Lake Elberta moves south into the Munson Slough, feeds into the Floridan aquifer, the primary source of drinking water for Tallahassee's residents, and ultimately flows out of several springs like Wakulla Springs (Kincaid and Werner 2008; McGlynn 2006; Scott et al. 2002). Many studies show how pollution in one body of water can introduce contaminants or solid waste particles to an entire watershed, several of which have focused on the region surrounding Tallahassee (Davis et al. 2010; McCormick and Hoellein 2016; Xu et al. 2015). Given the connectivity between Lake Elberta, Munson Slough, the Floridan aquifer, and Wakulla Springs, it is crucial to prevent the solid waste and associated pollutants from entering the stormwater system that could contaminate the aquifer.

The total study area was based on Lake Elberta's stormwater system (ESRI. 2019. ArcGIS Desktop: Release 10.8. Redlands, CA: Environmental Systems Research Institute). The Utility Network Analyst tool was used to determine the inlets and conduits connected to Lake Elberta (30.430411, -84.300237). Upstream traces were performed from two outfalls in the lake using ArcGIS. A total of 1,193 inlets that collect stormwater and solid waste were identified. A sample of 648 inlets were the focus for this study, excluding the inlets on the FSU campus due to Covid-19 restrictions (Fig. 1). In total, the stormwater infrastructure spans over three km^2 of Tallahassee.

This area includes the entirety of the FSU campus, many residential and commercial areas, and some government buildings.

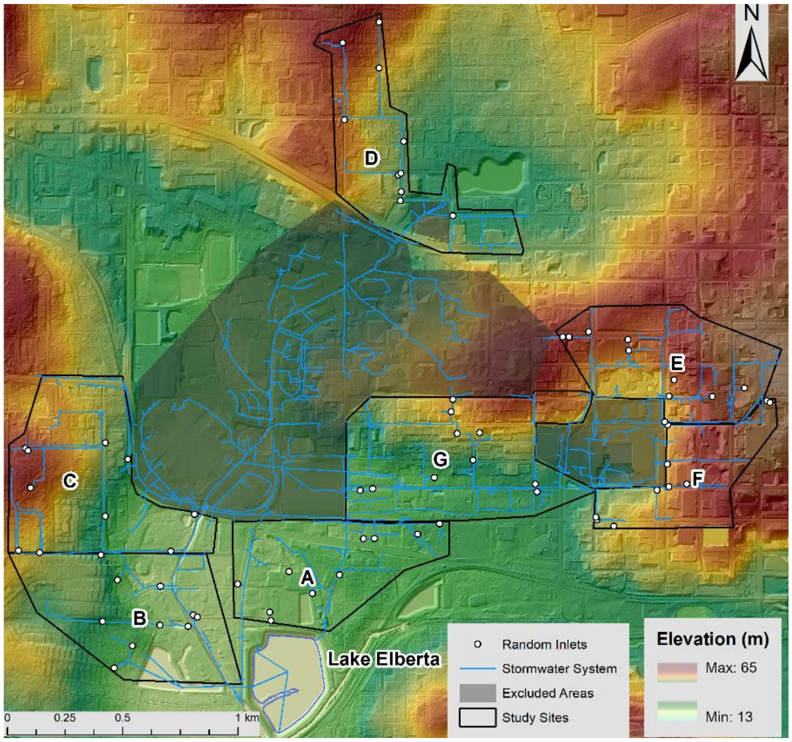

Figure 1. The stormwater system leading to Lake Elberta, with each of the study sites' randomly selected inlets (Dewberry and TLCGIS 2020).

Seven sites were selected as potential source(s) of solid waste at Lake Elberta based on the elevation difference with the lake and the conduits of the stormwater system that connects to the lake. Each site was assigned a unique letter (Fig. 1). Ten inlets at each site were randomly selected using ArcGIS, which equated to approximately 11% of the study area's available inlets.

Rain and Wind Data

The Tracking California Trash (TCT) project concluded that solid waste assessments on streets and sidewalks should not be conducted when more than 12.7 mm of rainfall occurred in 24 hours within two days of the evaluation. To ensure that our study followed this guideline, we obtained rainfall and wind speed data from FSU's weather station, less than 1 km north of Lake

Elberta. Daily measurements were considered since stormwater systems are primarily driven by precipitation. Data was obtained a week before the solid waste collection and during the solid waste sampling period (Fig. 2). The significant rain will cause an inaccurate depiction of the average level of solid waste present at these locations because the waste on roadways could enter the stormwater system after substantial rainfall (EOA 2016; U.S. EPA 2018).

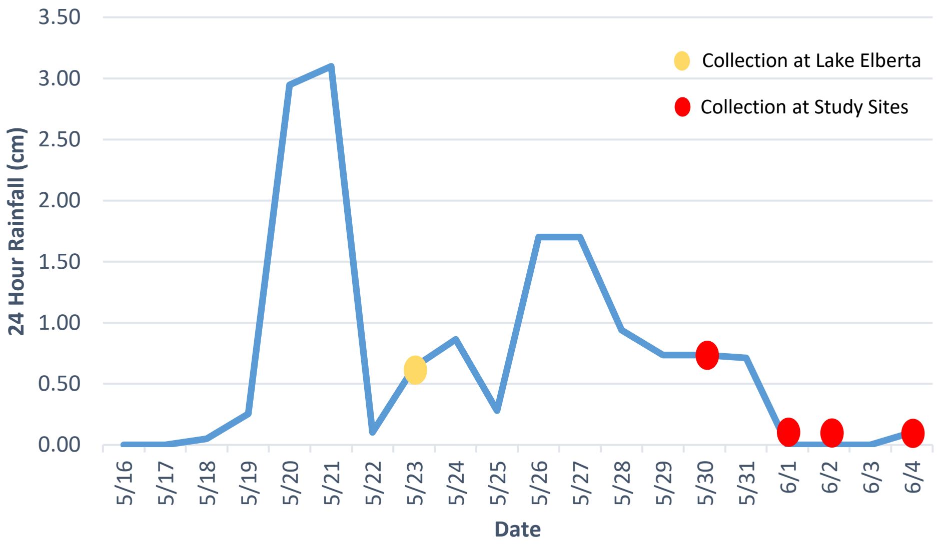

Figure 2. Tallahassee's precipitation from May 16 - June 4, 2020.

Lake Elberta Waste Collection and Characterization

The solid waste collection was done around Lake Elberta prior to collection at the study sites since collecting first at the sites could affect the amount of solid waste traveling to the lake. At approximately 400 meters, three equally-spaced points were selected to collect waste along the lakeshore. Solid waste was collected for two hours while moving in a clockwise direction. It was not possible to collect all of the solid waste present within this time frame; however, several 49 L bags of trash were collected.

Collected solid waste was classified into 12 categories based on previous cleanup events and the 2018 Draft of the Escaped Solid waste Assessment Protocol (ETAP) (U.S. EPA 2018).

These categories are—Paper, Glass, Metal, Medical and Drug Paraphernalia, Tobacco Products, Disposable Food Products, Plastic Bags, Plastic Food and Beverage Bottles, Other Plastic Food Packaging, Polymeric Foam, Miscellaneous Plastics, and Miscellaneous Non-plastics. Due to their extensive use, some materials were quite difficult to classify, such as plastics. Other studies designated multiple plastic categories, such as "Plastic Other" in the TCT project (5 Gyres 2016), which is why "Miscellaneous Plastic" was used for this study.

Counts of intact and degraded items for each category were tabulated. Like the ongoing study in Atlanta's Proctor Creek (J. Yu, personal communication, 2020), EPA-funded studies have recorded the mass or volume (U.S. EPA 2020a). These methods can skew analyses if the measurements are taken from items that could retain water and from larger or more dense items. A benefit of counting the items rather than obtaining the mass or volume of each group of objects is that it minimizes introducing biases in the data. Though items in categories more prone to degradation may skew counts, we proposed that a count was more appropriate for determining which categories are more of a concern due to a greater potential for error using mass or volume.

A challenge for the degraded items was that there could be high quantities of them. Therefore, volume (L) was used instead of count for degraded items in categories with large numbers at a particular site based on the ETAP (U.S. EPA 2018). The number of items was estimated by obtaining 0.5 L (when compressed by hand) scoops of solid waste inside a 1 L measuring cup. Scoops of each category of degraded solid waste were taken randomly three separate times, and an average number of items per 0.5 L was calculated. These averages were used to estimate the volumetric measurements' counts to allow a comparison among the number of items within and across sites.

Data quality was assured by limiting our collections and analysis to five people. To ensure an accurate count of both degraded and intact items, one person would monitor the person counting the solid waste. The monitor took notes of anything that may clarify the differences among the samples.

Waste Collection and Characterization at Study Sites

The inlets were located using a map of each site with its inlets displayed. The inlets were labeled with their associated site and assigned number, which was needed to record each site's attributes. The attribute data collection form was based on the ETAP's Field Summary sheet and the Visual Trash Assessments (VTA) conducted by several other solid waste studies (EOA 2016; Harris 2018; Luebke 2018; Moore et al. 2007; U.S. EPA 2018). Noting the solid waste receptacles and other preventative measures may give insight into which waste management strategies could work best at a given location (U.S. EPA 2018). The VTAs are a convenient qualitative method for assessing a large area relatively quickly. However, a challenge in this approach is the temporal and spatial variability of solid waste conditions in an area that will make it difficult to accurately reflect the level of solid waste (Conley et al. 2019).

Solid waste was collected from 70 randomly selected inlets in each study site using ArcGIS. The sampling area at each inlet was approximately 314 m^2. The area was based on a 10 m buffer from each inlet's center, which included its immediate area where solid waste is likely to be discarded by pedestrians or spilled out of solid waste receptacles and the entire width of most roads adjacent to the sampled inlets. Solid waste within the buffer would likely accumulate in the stormwater system (EOA 2016). Four pairs of inlets had combined sampling areas due to the points being too close. Solid waste was collected into a labeled bag and counted according to each category, as was done for the solid waste from Lake Elberta.

Data Analyses

The data was tested for normality using a Shapiro-Wilk test, which was found to be non-parametric. The sample size was not large enough for statistical analyses. Due to the inherent limits of the dataset, a descriptive statistics approach was used. Though descriptive statistics are not a robust analysis, it is the best use of the limited dataset and provides insight for the purpose of this baseline assessment. Descriptive statistics were used to determine a basic relationship between the study sites and the lake and identify sites contributing to the solid waste problem.

RESULTS

Rain and Wind Data

The average daily rainfall from May 16 to June 4 was 7.4 mm, and the total was 148.6 mm. The average daily wind speed was 6.82 km/h. As seen in Figure 2, our sampling days at the sites did not violate the TCT project’s rule which proposes a maximum rainfall of 12.7 mm in 24 hours within two days of sampling. Two days before collecting solid waste at Lake Elberta, rainfall exceeded the maximum of 12.7 mm. However, the rule is only applicable to streets and sidewalks, not bodies of water (EOA 2016).

Solid Waste Data

Sites A ($\bar{x}$=40.06) and G ($\bar{x}$=41.50) had the highest average count of solid waste items per category, as well as the highest variation in each category (SD=37.47 and SD=51.86, respectively). Sites C ($\bar{x}$=26.92) and F ($\bar{x}$=14.50) had the lowest average count of solid waste items per category and the lowest variation in each category (SD=21.44 and SD=15.01, respectively). Across the collection sites (Fig. 1), there was variation in the number of items of solid waste collected per category. The glass category had a very high count at Site G (Fig. 3). Most of the solid waste collected at the lake and the study sites was degraded (Fig. 4).

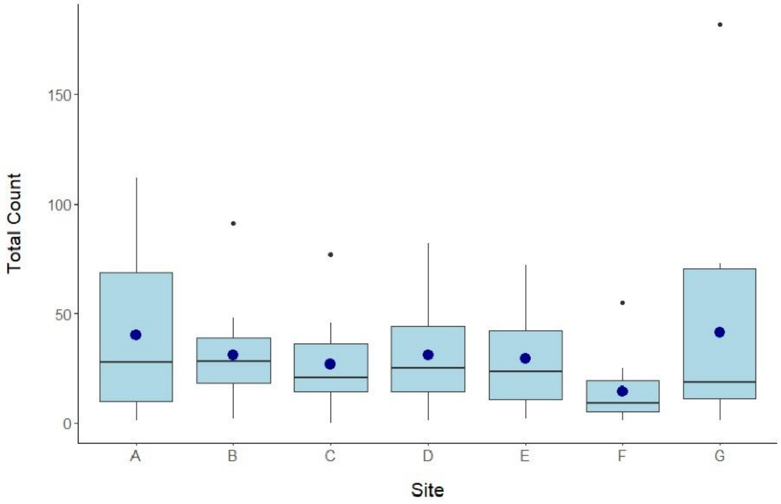

Figure 3. The spread of the total counts across all sites.

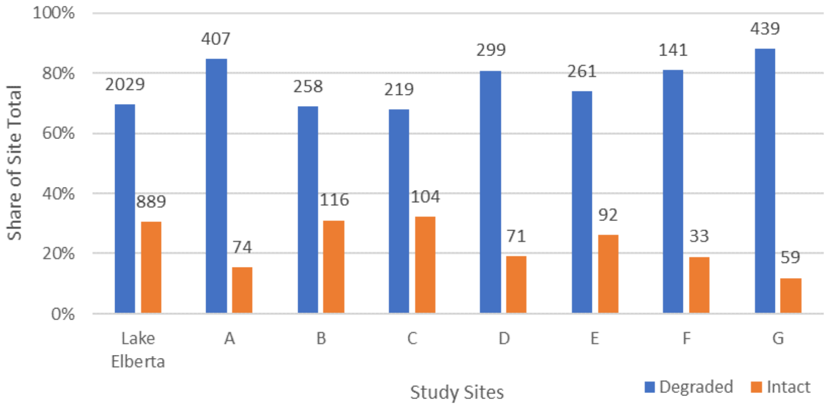

Figure 4. The condition of collected solid waste. Values on the tops of the bars are counts.

Miscellaneous Plastics (x̅=70.15) and Tobacco Products (x̅=62.71) were the most abundant on average across all sites. The categories with the highest variations of counts were Miscellaneous Plastics (SD=28.81) and Glass (SD=59.10). Medical/Drug Paraphernalia (x̅=1.57) and Plastic Bags (x̅=2.57) had the fewest items across all sites, as well as the lowest variation (SD=1.13 and SD=0.98, respectively) (Fig. 5). Each category's proportion was calculated and then compared across all sites and Lake Elberta (Table 1).

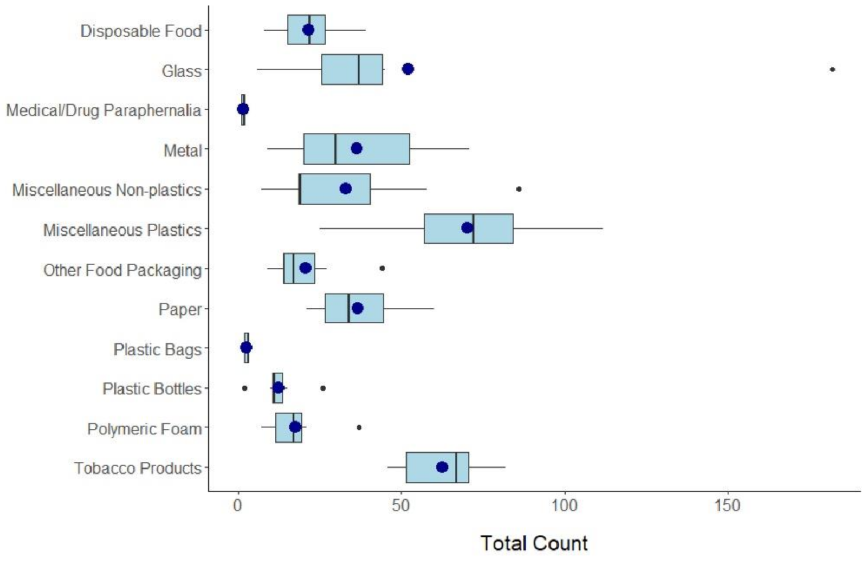

Figure 5. The spread of the total counts across all categories.

Table 1. Composition of solid waste at Lake Elberta and upstream sites. Bold values are within one standard deviation of the lake's composition within that category.

	Lake Elberta	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Paper	*0.72%*	11.44%	9.10%	10.53%	16.22%	7.08%	12.07%	5.62%
Glass	*0.03%*	**7.28%**	**4.28%**	13.31%	12.16%	**10.48%**	**3.45%**	36.55%
Metal	*1.23%*	14.77%	6.42%	10.53%	**4.32%**	8.50%	**5.17%**	14.26%
Medical/Drug Paraphernalia	*0.41%*	**0.21%**	**0.54%**	**0.00%**	**0.54%**	**0.57%**	**0.57%**	**0.60%**
Tobacco products	*16.49%*	**14.15%**	**12.85%**	**14.24%**	**22.16%**	**18.98%**	31.61%	**14.66%**
Disposable Food Products	*15.60%*	2.29%	8.03%	7.12%	10.54%	6.23%	10.92%	1.61%
Plastic Bags	*1.13%*	**0.62%**	**0.80%**	**0.93%**	0.27%	1.13%	1.72%	0.20%
Plastic Bottles	*6.61%*	2.29%	**6.96%**	4.64%	2.70%	3.12%	1.15%	2.41%
Other Food Packaging	*15.76%*	4.16%	11.78%	5.26%	7.30%	4.25%	5.17%	2.61%
Polymeric Foam	*19.84%*	1.46%	9.90%	4.02%	5.68%	2.83%	9.77%	3.61%
Miscellaneous Plastics	*21.38%*	**23.38%**	**24.26%**	**23.84%**	11.89%	**20.40%**	14.37%	14.06%
Miscellaneous Non-plastics	*0.79%*	17.96%	**5.08%**	**5.57%**	**6.22%**	16.43%	**4.02%**	**3.82%**

DISCUSSION

Upstream Sites and Retention Lake Solid Waste Comparisons

The highest number of items per category was counted at Sites A and G. These sites also had the highest standard deviation between categories (Fig. 3). This result is mainly due to the many miscellaneous plastics (Site A: 112) and broken glass (Site G: 182) collected items. The degraded items vastly outnumbered the intact items at all sites—similar to Lake Elberta (Fig. 4). This finding countered other studies where intact items upstream were degraded as they traveled through the stormwater system, leading to disproportionately larger percentages of degraded solid waste at the lake (McCormick and Hoellein 2016).Another difference between the sites and the lake were the counts for glass, metal, and paper. These were quite difficult to compare at the sites and Lake Elberta since they are less likely to flow great distances in water (5 Gyres 2016; McCormick and Hoellein 2016). Higher proportions of these categories were collected at the sites than at the lake (Table 1). This result indicates that glass, metal, and paper were not easily transported through the stormwater system.

Plastic bags and Medical/Drug Paraphernalia had a small count throughout the study area (Fig. 5), indicating they are relatively uncommon items. Plastic Bags are plentiful in the U.S. (U.S. EPA 2019), so collecting only a few was quite interesting. This count could be due to their tendency to sink in the stormwater system and at the lake (Cowger et al. 2019). Tobacco Products and Miscellaneous Plastics were the highest counted waste category across the entire study area (Fig. 5). Other related studies had similar findings (5 Gyres 2016; Harris 2018; Keep America Beautiful 2009; Moore et al. 2007, 2016; U.S. EPA 2020a). Rech et al. (2014) stated that cigarette butts, in particular, are semi-buoyant, and they travel in waterways for a longer time before sinking. Disposable Food Products, Other Food Packaging, and Polymeric Foam had low counts at the sites upstream, yet they were found in relatively high proportions at Lake Elberta (Fig. 5, Table 1). These categories are materials that flow easily in water which explains their high proportion at the lake (Clean Water Action California 2011; Luebke 2018; McCormick and Hoellein 2016; Moore et al. 2016).

The evidence presented in this study shows that solid waste found around stormwater inlets and Lake Elberta have similar characteristics. In addition, similar counts and proportions were identified for some categories across the study area. Therefore, it was inferred that the pollution from the study sites directly contributes to the problem observed downstream.

Potential Major Contributors

Many sites had similar categorical composition to Lake Elberta. We predicted that the sites with the highest counts and concentrations of solid waste contribute the most to the overall solid waste problem seen at Lake Elberta (Fig. 3, Fig. 4). When the composition of solid waste across the sites was compared to that of Lake Elberta, Site B had the most categories within one standard deviation of Lake Elberta’s category counts (Table 1). This result is likely because of Site B’s proximity to the lake (Fig. 1). Sites with a high count of Disposable Food Products, Other Food Packaging, and Polymeric are likely to be significant contributors since these items are very mobile in waterways. Site B had exceedingly high counts in two of those three categories (Table 2). Because the rain and wind leading up to our data collection did not cross the threshold described by TCT, rainfall and wind did not skew the data for any particular site.

Table 2. Counts of solid waste in highly mobile categories at Lake Elberta and upstream sites. Bold values are within one standard deviation of the average count across the sites within that category.

	A	**B**	**C**	**D**	**E**	**F**	**G**
Disposable Food Products	11	30	23	39	22	19	8
Other Food Packaging	20	**44**	17	27	15	9	13
Polymeric Foam	7	**37**	13	21	10	17	18

Limitations

Field sampling occurred during the period when the U.S.'s solid waste production is highest due to most residents being on summer vacation (Keep America Beautiful 2009). However, activity in Tallahassee was likely significantly decreased because its two major universities were on summer break and the Covid-19 pandemic restrictions. These factors likely influenced the amount of solid waste collected at the sites. Due to the pandemic and a budget of less than $2,000, volunteers and material resources were limited. As a result, we were only able to visit each site once and could not collect solid waste over an extended period. Consequently, these limitations prevented us from performing a thorough statistical analysis.

CONCLUSIONS AND RECOMMENDATIONS

We have designed a methodology that can help identify the source(s) of solid waste that enters stormwater systems by categorizing and comparing solid waste collected at upstream and downstream sites. It can be used in municipalities of all sizes because it is scalable, economical, and does not inherently require a large team. With this study, we have contributed to the body of knowledge about solid waste flow in Tallahassee's stormwater system by providing baseline data and additional insight into the movement of solid waste through other similar systems.

The results suggest that reducing the amount of solid waste entering the stormwater system by installing separating devices may be a worthwhile investment for the city and county's stormwater management (California Regional Water Quality Control Board 2010; EOA 2016; Luebke 2018; U.S. EPA 2020a; b; Vice et al. 2013). Additionally, more education about the importance of recycling and a more robust recycling program could reduce significant inputs of litter (Sidique et al. 2010). Future studies would benefit from counting specific items of interest that may link to a particular area, collecting solid waste from different zones in the retention lake's water column, collecting solid waste from more inlets in each study site, and sampling over a longer time frame. These adjustments to the study would allow for a better testing of the hypotheses and a more rigorous study to better identify specific sites of concern. More solid waste and recycling receptacles could be placed in those identified sites of concern to help reduce litter, ultimately benefiting the stormwater system and retention lake.

DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the submitted article.

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