MACRO AND MICRO LITTER ACCUMULATION IN THE SAN MARCOS RIVER, SAN MARCOS, TEXAS, USA

by

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LIST OF ABBREVIATIONS

Abbreviation	Description
EAHCP	Edwards Aquifer Habitat Conservation Plan
KSMB	Keep San Marcos Beautiful

ABSTRACT

Litter accumulation in rivers is understudied in the United States and yet is a major problem that is becoming worse. Litter is the focus of recent management attention in urban river systems including the San Marcos River. The San Marcos River is primarily spring-fed by the Edwards Aquifer and provides habitat to seven federally-listed species, some of which are only found within the first few kilometers of the main stem. Thousands of tourists recreate on the San Marcos River during the late spring and summer, and these numbers increase every year. Additionally, San Marcos is in Flash Flood Alley, contributing to large amounts of runoff. Understanding the scope of litter pollution can assist with mitigation tactics that focus on source reduction of pollution.

This study investigates litter accumulation in the first eight kilometers of the main stem of the San Marcos River, with a specific focus on the history of the problem and community efforts to clean-up the river. Emphasis is placed on recreation and tourism sources, runoff-based culvert sources, and microplastic accumulation in bed substrates. My research uses existing litter collection data from the Edwards Aquifer Habitat Conservation Plan (EAHCP), Keep San Marcos Beautiful (KSMB), and primary litter and microplastic data I collected from the main stem of the San Marcos River twice a month for 5 months. Results show that the majority of litter found in all three survey locations are microplastics and plastic of various types. Velocity and substrate type of river stretches can be indicative of the amounts of litter found. Sources of litter can largely impact the types of items found. Lastly, current policy and deterrents are not

effective in reducing/stopping litter at the source.

I. INTRODUCTION

This study focuses on litter accumulation in the main stem of the San Marcos River, with a specific focus on the history of litter pollution in the area, community efforts to clean up the river, and a field survey of micro-litter. Emphasis is placed on recreation and tourism sources, tributary and runoff culvert outputs, and microplastic accumulation in bed substrates. Litter accumulation in rivers has not been widely measured in the United States and has not specifically been examined in the San Marcos River. Understanding the scope of the problem will assist with mitigation tactics that focus on source reduction of pollution and inform policy around water pollution.

Litter pollution in waterways is a persistent problem, and since the widespread production of plastics in the 1950s, the issue has increased extensively (Geyer et al. 2017). The long decomposition time for many of the materials that make up litter increases its persistence in the environment. Tens of thousands of tourists recreate on the San Marcos River during the late spring and summer, and the numbers are growing every year. More tourists, unfortunately, translate to higher volumes of litter entering the river. Urban runoff from precipitation events contributes to litter transport from the watershed. Additionally, the population of San Marcos and the greater central Texas region are rapidly growing. The associated development with these changes has led to increased impervious surfaces and potentially more litter entering waterways.

This study provides an overview of the variety of litter found in the river and their direct and indirect sources and includes a focus on microplastics. Due to the size of microplastic pellets, it is extremely difficult to implement cleanup efforts targeted at microplastic reduction. Microplastics are transported by flowing water, lodged into crevices, deposited among sediments, and consumed by organisms; rendering it virtually impossible to remove from the environment. Litter pollution has detrimental effects on aquatic ecosystems and may be an especially dangerous problem for the San Marcos River due to its high-quality condition that supports multiple endangered species.

This study aims to address the historic to the contemporary problem of litter pollution in the San Marcos River, categorize the most abundant types, and identify sources of litter. This research addresses categories and sizes of litter, i.e. microplastic or macroplastic, and combines data from multiple entities that perform clean-up efforts. The most abundant forms of litter are identified and described in terms of compositional material, size, and location in the river using latitude and longitude coordinates.

Specific research questions addressed in this study are: How much litter has been removed from the river since 2013? What are the most common types of litter? What are major sources of the litter and how is it entering the river – i.e. Where is the litter in relation to recreation activities, bridges, urban areas, and culverts? And finally, what are some mechanisms to help stop point and nonpoint source litter pollution from entering the river?

1.1 History of litter in waterways, beaches, and rivers

Anthropogenic litter is a growing problem around the world (Geyer et al. 2017). Litter is found in all environments, even in the most remote areas (UN Environment Programme 2017). Litter comes in a variety of sizes and materials and includes any solid human-made commodity not natural to the environment. These include but are not limited to plastic products, glass, paper, and metal objects. Some forms of litter are more harmful than others based on substance and chemical makeup, shape of the item, size, and how long it takes to biodegrade (Abdul-Rahman 2014).

Plastic is one of the most abundant types of litter pollution. Leo Baekeland created plastic in 1907, but its production increased exponentially during World War II to substitute for materials that became scarce, such as silk and ivory. Soon after, the mass production of plastic bottles and bags created various single-use items that have led society to the "throw-away" mentality known today where consumer items are seen as disposable (Davis 2014). Most packaged items produced since the 20th century are made from single-use plastics due to the extremely low cost of the material, but only around nine percent is recycled in the United States. The rest ends up in a landfill or the natural environment (Geyer et al. 2017). Every year, manufacturers produce over 300 million tons of plastic, and around 2 million tons are transported to oceans through rivers (Lebreton et al. 2017). As the population grows and product demands increase, more plastic will be produced for human use.

The most abundant form of plastic found in the environment comes in a tiny size—microplastics. Microplastics are less than 5 millimeters in diameter and vary by the source and product of the object (Dikareva and Simon 2019). Not all microplastics start micro, many break off from larger objects (i.e., water bottles) through photodegradation or in the case of rivers— exposure to flowing water. Microplastics are the most harmful form of plastic pollution since they are ingested by wildlife and can cause digestion complications and death. Microplastics and the chemicals they contain can bioaccumulate up the food chain to top predators, including humans (Baldwin et al. 2016). If litter pollution in rivers is so harmful, why is this not widely studied? Some of the most protected areas in the world experience litter pollution, especially high-use rivers such as the San Marcos River.

1.2 Geography of the San Marcos River

The San Marcos River is one of the oldest, continuously inhabited areas in North America, with evidence of human habitation dating back to over 12,000 years ago (The Meadows Center for Water and the Environment 2021). The San Marcos River is a relatively small river with a drainage area of 126.65 square kilometers. The river is primarily spring-fed by the karstic Edwards Aquifer and contains several large ephemeral headwater tributaries that drain the urban and rural areas of the City of San Marcos, and is subject to frequent flash flooding. Tributaries including Sink Creek, Sessom Creek, Purgatory Creek, and Willow Springs Creek accumulate litter and deposit it into the San Marcos River. There are also three dams in the upper river, including Spring Lake Dam, Rio Vista Dam, and Cape's Dam.

In 2020, San Marcos, Texas, had a population of over 67,000 (US Census Bureau 2021). Texas State University is centrally located within the city, with 38,000 students enrolled in 2020 (Texas State University 2021). The city manages nearly 730 hectares of parkland and 45 parks, 10 of which are adjacent to the river (City of San Marcos 2018).

This study focused on the first eight kilometers of the river, referred to as the Upper San Marcos River, that flows through the high-density urban core of the city. Within this urban setting, the river provides habitat to seven federally protected species, some are endemic to the first few kilometers of the river. These species include the Comal Springs Dryopid Beetle, Peck's Cave Amphipod, Comal Springs Riffle Beetle, Fountain Darter, San Marcos Salamander, Texas Blind Salamander, and Texas wild-rice (The Meadows Center for Water and the Environment 2021).

There are numerous stakeholders avidly protecting the San Marcos River through the Edwards Aquifer Habitat Conservation Plan (EAHCP), and many non-profits such as the San Marcos River Foundation, the Eyes of the San Marcos River, the Mermaid Society SMTX, and the city-led Keep San Marcos Beautiful group. The Edwards Aquifer Recovery Implementation Plan (EARIP) began the process to form the EAHCP in 2010 as part of a legislatively mandated effort for the Edwards Aquifer Authority to oversee the protection of 11 species in the Comal and San Marcos Springs (Edwards Aquifer Authority 2022). The EAHCP holds an incidental take permit (ITP) issued by the U.S. Fish and Wildlife Service. Active ITP partners include the City of San Marcos, the Edwards Aquifer Authority, the City of New Braunfels, the City of San Antonio (through San Antonio Water Systems), and Texas State University. In addition, there are numerous other contributing stakeholders including the Guadalupe Blanco River Authority, Texas Parks and Wildlife Department, the United States Fish and Wildlife Service, and various non-profits and aquifer water users (Edwards Aquifer Authority 2022). Recreation is a covered activity of the ITP, and to support this conservation measure the EAHCP actively removes litter regularly from the San Marcos River and watershed, though their efforts do not focus on micro-litter.

1.2.1 Historical to modern recreation activities of the San Marcos River

The San Marcos River flows close to 22.22 degrees Celsius year-round making it a recreational hotspot during the hot summer months when many students from the university, city residents, and tourists gather to find relief from the extreme Texas heat. The first park on the San Marcos River, Riverside Park formed in 1917, led by Dr. S.M. “Froggy” Sewell of Texas State University. It renamed to Sewell Park in 1946 (Texas State University 2020). The creation of Aquarena Springs and Wonder Cave in the 1960s brought more tourists to town (San Marcos Convention & Visitor Bureau 2022). River recreation has since increased. Today, over 300,000 people visit San Marcos parks every year and the number continues to grow (Julian et al. 2018), creating an increase in the litter that flows into the river. There are multiple water sports equipment rental facilities along the river, including Lions Club Tube Rental and Texas State University's Outdoor Center. There are 16 river access points from the headwaters to Stokes Park. The city recognizes litter as a problem, has programs in place to capture litter, and provides recommendations for improvement in their Parks, Recreation, and Open Space Master Plan.

The City of San Marcos has an ordinance that bans glass and styrofoam in parks, yet it is rarely enforced (City of San Marcos 2022). As a result, these littered materials accumulate in the river. With an already extensive litter problem and an increase in city population and tourist activity, the high-water quality and condition of the San Marcos River are threatened. Quantifying litter and continuing litter reduction mitigation actions are necessary for the best management practices of this river system.

1.3 River, lake, and ocean litter studies, microplastics, and the use of citizen science

River litter pollution studies are scarce, especially in the United States. Most studies focus on plastic and microplastic accumulation and avoid glass, metals, and other substances (Free et al. 2014; Wagner et al. 2014; Dikareva and Simon 2019; Lebreton et al. 2017; Martin 2018; Kiessling et al. 2019). This research fills gaps in literature surrounding litter accumulation and provides a comprehensive litter assessment of an urban waterway. Additionally, the lack of comparative litter studies in small to medium-sized rivers is another gap filled by my research. Holistically viewing litter accumulation, and not just one type such as plastics allows for a complete picture of the problem at hand, and therefore will better inform the public and appropriate recommendations for clean-up efforts.

Research focused on marine, river, and lake debris examines litter pollution in aquatic environments and explores potential impacts of the problem and successful mitigation techniques. Studies vary by geographic and economic context, with limitations based on the amount of litter and funding. Some studies found recreational and municipal litter, such as plastic bottles, food containers, and cigarettes to be the most abundant in waterways (Kiessling et al. 2019), but it varied based on location and land use around the survey area (Bruge et al. 2018; Cowger et al. 2019; Hoellein et al. 2015).

Seasonality of when litter was the most abundant varied from region to region (Hoellein et al. 2015; Lidia and Fischer 2003), but I expected to see the highest litter accumulation in the San Marcos River during the summer months. Many studies found that recreation was the main cause of litter pollution in waterways and along their respective banks and beaches (Bruge et al. 2018; Hoellein et al. 2015; Lidia and Fischer 2003). In some cases, litter was not directly linked to land use (impervious surfaces) of the surrounding area (Hoellein et al. 2015), but in others, it was directly linked (Baldwin et al. 2016). In the case of the San Marcos River, I hypothesized that urban areas and recreation activities would correlate with increased litter accumulation.

Microplastics have been a focus of ocean and some river studies in the last decade (Martin 2018; Dikareva and Simon 2019). In many cases, over 90% of samples taken found microplastics (Baldwin et al. 2016). Microplastic analysis is difficult to perform without lab equipment. Some microplastics cannot be seen without magnification, complicating studies, and their removal from the environment.

Citizen science is an inexpensive and effective way of collecting data with volunteers. This method is becoming more prominent in science, especially in the water resources field in the act of collecting litter data (Hoellein et al. 2015; Kiessling et al. 2019). Researchers found that data collected by citizen scientists were of the same quality as professional data collectors if given proper help and direction (Rech et al. 2015; van der Velde et at. 2017). The use of citizen scientists allows volunteers to understand the data collection process, the results, and be more involved in decision making (Kiessling et al. 2019).

In some instances, researchers required data gatherers to take photos of the litter found for future in-depth analysis (Kiessling et al. 2019). The analysis included grouping litter into categories and hypothesizing the source such as recreation, residents, or illegal dumping that helped researchers conclude what types of litter each group commonly produces (Kiessling et al. 2019).

This study can have impacts in the City of San Marcos and surrounding communities by understanding how much litter, including microplastics, are in the San Marcos River, and has the potential to inform best management practices including litter removal efforts, and stricter water quality laws and city code ordinances, and/or new regulations.

This study used a field-based spatial and temporal analysis to analyze riverine litter pollution. I implemented a quantitative litter count and a qualitative categorical approach in three representative sites in the main stem of the San Marcos River. It was important to view data both spatially and temporally to assess the full scale of the issue and track changes seasonally with recreation and location of litter over time. A lack of freshwater litter studies establishes a framework for the expansion of studies done on other rivers in the future.

1.4 Relevant environmental laws

In 1965, the Texas Legislature passed the Solid Waste Disposal Act to "safeguard the health, welfare, and physical property of the people and to protect the environment by controlling the management of solid waste" (Tex. Health and Safety Code § 361). The law outlines proper solid waste disposal techniques as well as source reduction and waste minimization. Waste minimization strategies involve individuals lowering their litter footprint by making smart decisions, including reusing items and recycling. Efforts to minimize waste may include consciously using an item more than once or diverting a recyclable item from the landfill, to avoid land disposal.

Section 12 of the Solid Waste Disposal Act outlines illegal dumping as "an offense if the person disposes or allows or permits the disposal of litter or other solid waste at a place that is not an approved solid waste site, including a place on or within 300 feet of a public highway, on a right-of-way, on other public or private property…" (Tex. Health and Safety Code § 365.012). The consequences are offense-based and can result in no action, a warning, a fine, a Class C misdemeanor, or in the worst cases, a felony or jail time. Section 35 of this act addresses the prohibition of glass near a river unless performing research or sampling (Tex. Health and Safety Code § 365.035).

The Texas Litter Abatement Act of 1989 allows landowners to dispose of waste on their property only if the waste originated there. Disposal of commercial and hazardous waste on properties are not permitted in this act (Texas Health and Safety

Code § 365.011 and §365.012).

Another major legislative body that applies to the San Marcos River is the Texas Water Code, specifically sections 145, 147, and 148. Tex. Water Code § 7.145-7.147 addresses the discharge of pollutants, including litter, into waterways. An offense is committed when discharging pollution "into or adjacent to water in the state that causes or threatens to cause water pollution…". Section 148 states that an offense is committed when someone "fails to use pollution control or monitoring devices, systems, methods, or practices…" (Tex. Water Code § 7.148). This section holds the individual accountable for maintaining sustainable practices and not allowing pollution to make its way into the river.

Finally, the City of San Marcos has its own ordinances in place at the local level. Sec. 58.034 and 58.042 address the ban of styrofoam and glass in city parks. These laws and regulations together justify enforcement, but litter is still entering the river. Surrounding communities encouraged the City of San Marcos to propose a single-use container ban in 2021 (University Star 2021). This effort is ongoing.

The City of San Marcos does not have enough park rangers to identify and cite all violators. The number of park visitors heavily outweighs enforcement, but there are cost-effective options that can have positive long-term effects that do not involve the constant oversight of state and local officials. I outline these options in the mitigation and management implications section.

II. DATA AND METHODS

This research used existing litter data from the EAHCP, Keep San Marcos Beautiful, and primary litter and microplastic data I collected from the main stem of the San Marcos River twice a month from June to October 2021. There are a variety of organizations in San Marcos that help protect the river but do not consistently record data from litter cleanups. An attempt to obtain somewhat consistent data from other organizations was unsuccessful. This study focused on litter removal data from 2013 to 2020 for entities with accessible data. 2021 data were not included because the EAHCP had not released the annual report at the time this study concluded. The EAHCP was the most consistent source, with data records starting in 2013.

The EAHCP formulates yearly comprehensive reports that include the amount of litter taken out of the river and in adjacent parks by their conservation crew. The locations of litter pickups changed from year to year, but these reports provide an accurate representation of the spatial distribution of litter throughout the river and parks. The data included monthly litter removal estimates in cubic feet or yearly totals in some cases.

A major challenge for this analysis was that the litter data were not consistent. The EAHCP is missing data for certain months from some years. For example, 2018 reported record lows of litter collected every month. This is likely a gross underrepresentation of the actual amount collected. The City of San Marcos (Keep San Marcos Beautiful) and the EAHCP work closely together, so I assumed that the lack of data in the 2018 EAHCP was reported in the Keep San Marcos Beautiful data. I put the yearly average in place of months that did not report litter.

The Keep San Marcos Beautiful data provided by the City of San Marcos' Resource Recovery Department is problematic due to a small percentage of data collected directly from the river. This data is a record of the number of bags of litter and recycling volunteers picked up at multiple locations throughout the watershed during the year and from their spring and fall city-wide clean-up events. One way the data could be helpful is by looking at it broadly, in the sense that potentially most of the litter collected around the city could have eventually made its way into the San Marcos River from rainfall, wind, or other natural and unnatural transportation agents. The same is true for other organizations with litter data. Consistency is difficult to find due to the voluntary nature of litter collection and a lack of reporting done by volunteers.

2.1 Culvert, discharge, and precipitation data

Culvert point-discharge location data from the City of San Marcos illustrates the spatial distribution and proximity of culvert outputs to the river (Figure 1). Many culverts lead directly into the river, acting as a direct source of how litter enters the river, in addition to non-point source contributions from the landscape.

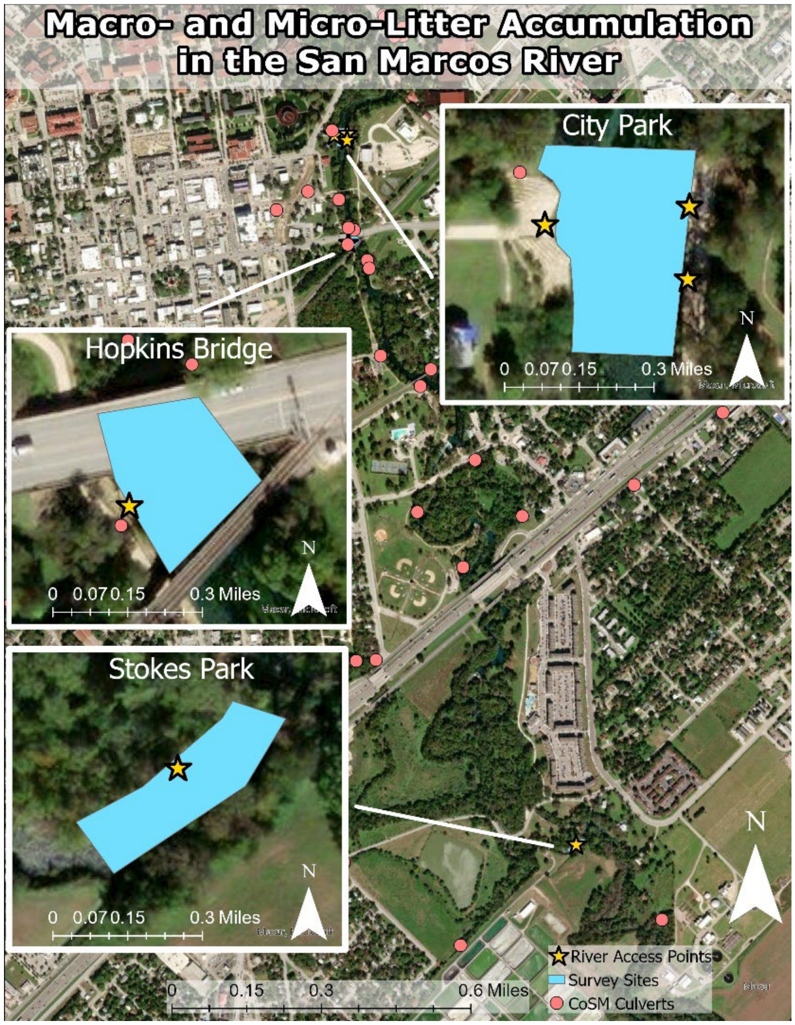

Figure 1. Map of Survey Sites, River Access Points, and Culvert Locations.

Precipitation data from NOAA outlines rainfall events during the collection period to indicate how this might impact the abundance and types of litter found (NOAA 2021). Lastly, a time series graph with daily discharge data from the USGS gage upstream of all survey locations, San Marcos River at San Marcos, Texas pairs with precipitation data in Figure 2.

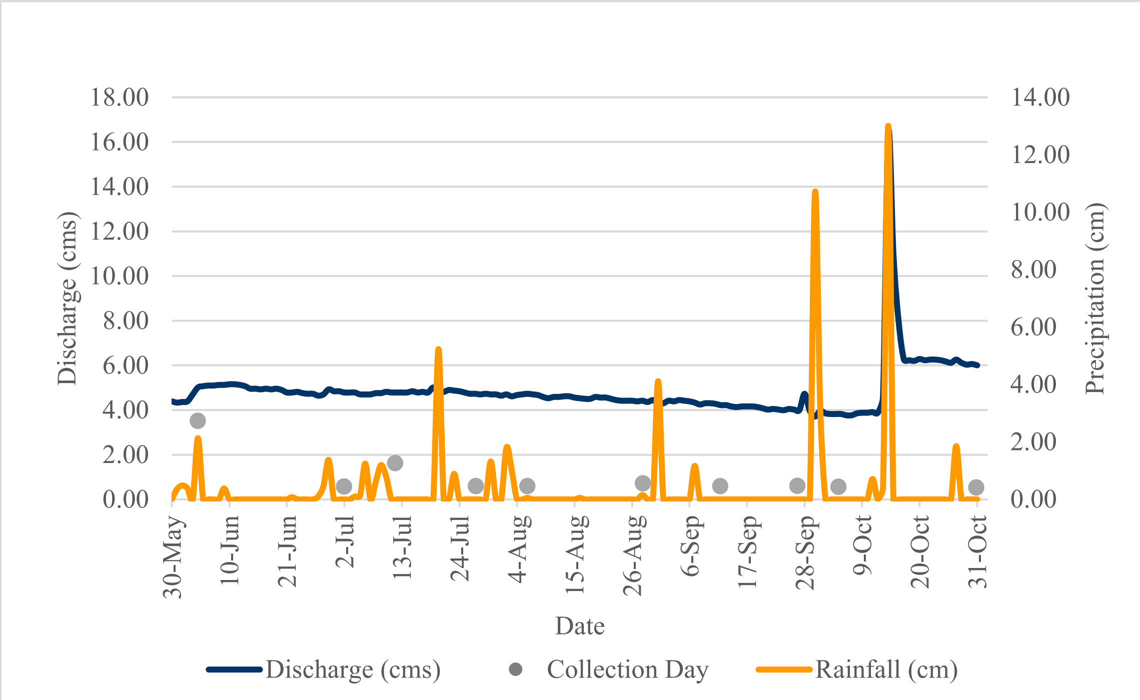

Figure 2. Discharge and Precipitation May 30, 2021-October 31, 2021.

This study focused on three sites in the main stem of the San Marcos River for the microplastic field data collection. The locations represent recreational hotspots and dense urban land use, including City Park (Figure 3), downstream of the Hopkins Street Bridge (Figure 4), and Stokes Park (Figure 5), a location downstream with less foot traffic and cars.

Figure 3. City Park Survey Site.

Figure 4. Hopkins Bridge Survey Site.

Figure 5. Stokes Park Survey Site.

2.2 Litter field survey

I surveyed litter from the surface of the riverbed substrate using a 1x1 meter square. This square comprised of PVC pipe weighted with pebbles (Figure 6) to allow the device to submerge in the river. I randomly placed it in ten spots in each of the three locations to survey litter as I made my way across the channel, avoiding vegetation and I repeated this process twice a month over the 5-month data collection period. Although the samples were random, I avoided Texas wild-rice to ensure no harm came to the species.

Figure 6. 1x1 m Survey Square for Primary Litter Collection.

I placed the square, removed, and bagged all litter including microplastics that were present within the area. Photos were taken for illustration. Most of the litter was shallow enough to collect from above the water surface. For City Park, the deepest site, I used goggles to see the bottom of the river. I counted all litter in the square and categorized it into 14 unique categories after analysis. I did not create categories beforehand due to the unknown items that would be found. This data collection method is not used in other litter studies and was chosen because of its minimal impact on the setting. The PVC surveying tool is an innovative approach to litter collection in rivers and does not harm sediment or species. The square was temporary during the survey period. I removed it immediately upon collecting the data.

I collected a GPS point from the center of the square using Apple Maps®. I mapped these points to show the locations where the survey square was placed. I placed the square in similar locations in all survey sites for multiple reasons. Some areas in the river contained too high of a velocity to place the square or view litter on the substrate, i.e. Stokes Park. Some areas of Hopkins Bridge were too muddy to collect samples and the sediments made it difficult to see litter. During some visits to City Park, there were large numbers of recreators, preventing access to certain areas for data collection.

An underwater camera collected before and after photos as a reference for some sites. A flow meter captured depth and velocity measurements of the river channel. I averaged the depth and velocity after a cross-section measurement was taken every five feet in the river at each location. I only measured the entire width of the channel at City Park due to the difficulty of navigating Hopkins Bridge and the deep and rapid channel at Stokes Park. I captured the depth and velocity of only the portion of the channel where I collected data.

Microplastic quantification was more difficult to perform due to the size of plastic particles. Some microplastics were likely missed due to their lack of visibility among the substrates. Microplastics and micro-litter are not the same, so it is important to be able to differentiate between the two for the most accurate estimate. This is why I chose to include microplastics as a category. None of the analyses in this study required a lab environment.

2.2.1 Categorization of litter

Categorization of litter occurred after the sorting process. The uncertainty surrounding what items would be found was the main reason categories were not premade before the start of the collection period. I used descriptive statistics to illustrate litter from the survey sites and distinguish between multiple types of plastics. The 14 categories chosen included microplastic, macroplastic, straw, whole plastic items (bottles, cups), plastic film (whole), plastic film (piece), metal fragment, aluminum, can (whole), glass, paper, ceramic, rubber, and other. The ‘other’ category contained items that only appeared a few times or items comprised of multiple types of materials. Six categories included types of plastic due to the many variations of the material such as size, shape, and density. It is important to distinguish between them to properly classify litter. Items such as cloth and masks, comprised of multiple types of materials were grouped into the ‘other’ category.

2.3 Survey sites

The San Marcos River watershed is divided into two sections: the Upper and Lower San Marcos River. This study focused on the first eight kilometers of the Upper

San Marcos River from the headwaters to Stokes Park, a small city-owned park surrounding the river. Each spot is unique in surrounding land use, location within the city, and substrate type.

2.3.1 City Park

The City of San Marcos owns City Park. This location is a popular recreational spot. Lions Club Tube Rental operates here, and this location is where many recreators enter the river after renting a tube. The park hosts thousands of recreators per week during the summer months. A study from 2016 found over 24,000 recreators at San Marcos parks on a single July day (Davila 2016). Downtown San Marcos and Texas State University are proximal to City Park, allowing easy transport of litter from the city to enter the river as runoff and windblown debris. Some culverts lead directly into the river upstream of the park and one that outputs at this location.

The substrate at City Park is pebbles and gravel (Figure 7). The vegetation thickness, mainly Texas wild-rice, varies throughout the year. During peak recreational

Figure 7. City Park Substrate.

season, May through early September, there are patches of vegetation directly upstream and downstream of the park. The vegetation regrows during the offseason when fewer recreators are trampling the plants. The average depth of the river at City Park was 1.07 m. The average velocity was 0.66 meters per second. I chose City Park for the large number of recreators present, the proximity to the downtown area, and the type of substrate.

2.3.2 Hopkins Bridge

Hopkins Street is a busy, main street road in San Marcos that traverses the city parallel to I-35. This is one of the major roads that connects to downtown San Marcos and has a railroad track running perpendicular to it. I chose Hopkins Bridge because of the street traffic above, recreation, culvert outputs, and change in riverbed substrate. Tubers and recreators swim and float underneath the bridge. There are two culverts directly upstream and one downstream. There is an increase in Texas wild-rice directly downstream, in a matter of meters, and a change in riverbed substrate from gravel and pebbles to muddy silt (Figure 8). The average depth of the river at Hopkins Bridge was 0.63 m. The average velocity was 0.25 meters per second.

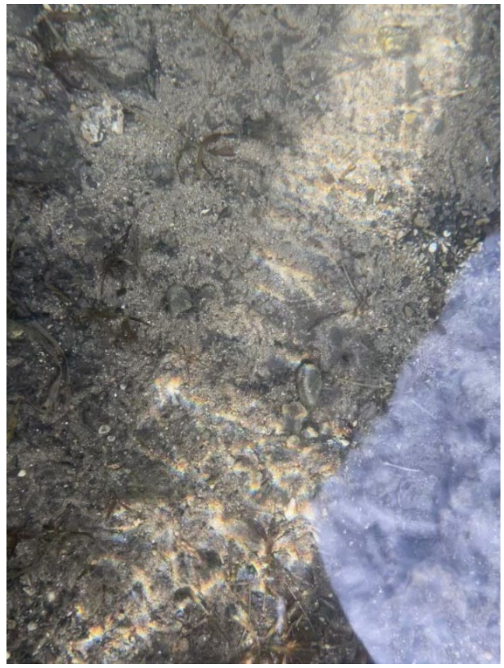

Figure 8. Hopkins Street Bridge Substrate.

2.3.3 Stokes Park

Stokes Park is a small city-owned park that is more remote with less recreation than the other two locations. This location has shallower water in some areas with faster velocities. The riverbed substrate is similar to City Park and includes gravel, pebbles, and cobbles, as well as sand near the banks. The average depth of the river at Stokes Park was

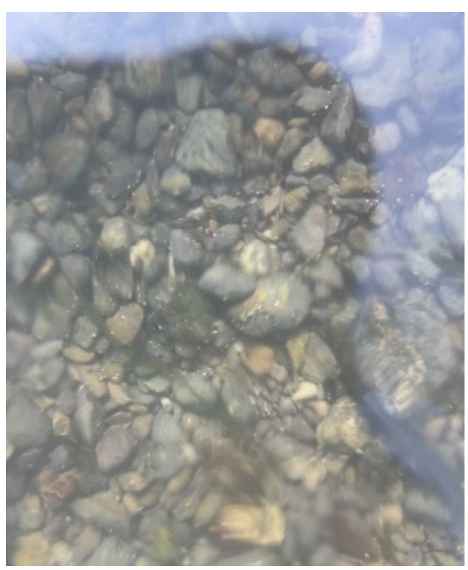

Figure 9. Stokes Park Substrate.

0.57 m. The average velocity was 1.28 meters per second. I chose Stokes Park because it is further away from downtown, has larger areas of surrounding green space, and has a differing substrate (Figure 9).

III. RESULTS

3.1 Sitewide totals

Results from all three survey sites differ in the most common items found. I collected a total of 653 pieces of litter. Microplastic represented 2.88% of samples, while plastic >5 mm represented 53.19%. Other plastic items such as straws, bottles, cups, and

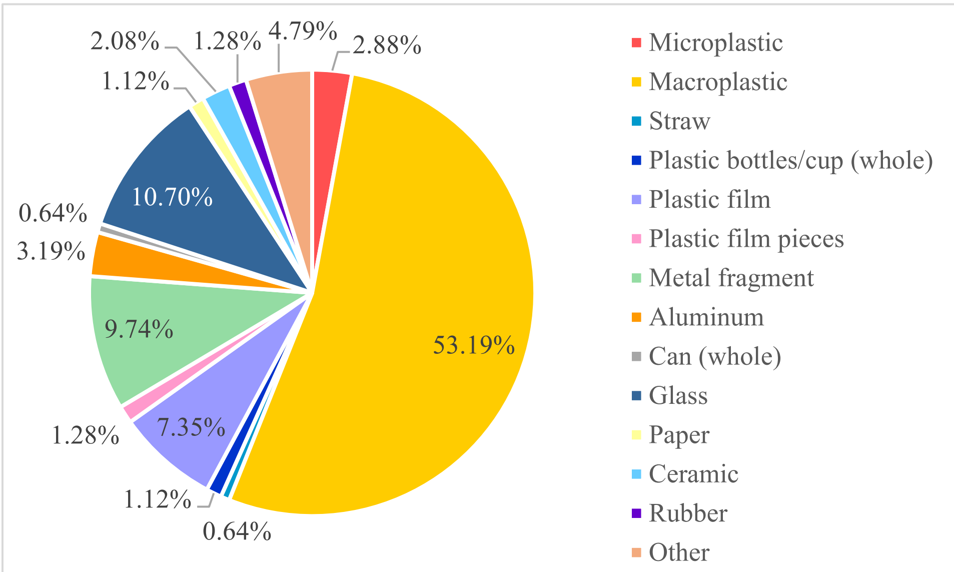

Figure 10. Composition of All Primary Litter Collected.

film pieces consisted of 0.64%, 1.12%, 7.35%, and 1.28% respectively. Metal fragments were 9.74% of the total and aluminum comprised 3.19% of samples. Whole cans represented 0.64% while glass pieces consisted of 10.70% of total litter found. Paper, ceramic, and rubber represented 1.12%, 2.08%, and 1.28%. The "Other" category represented 4.79% of samples. Macroplastics were the most common item collected (Figure 10). The percentage of different types of litter varied among sites (Figure 11). Plastic comprised of 66.46 percent of the total litter.

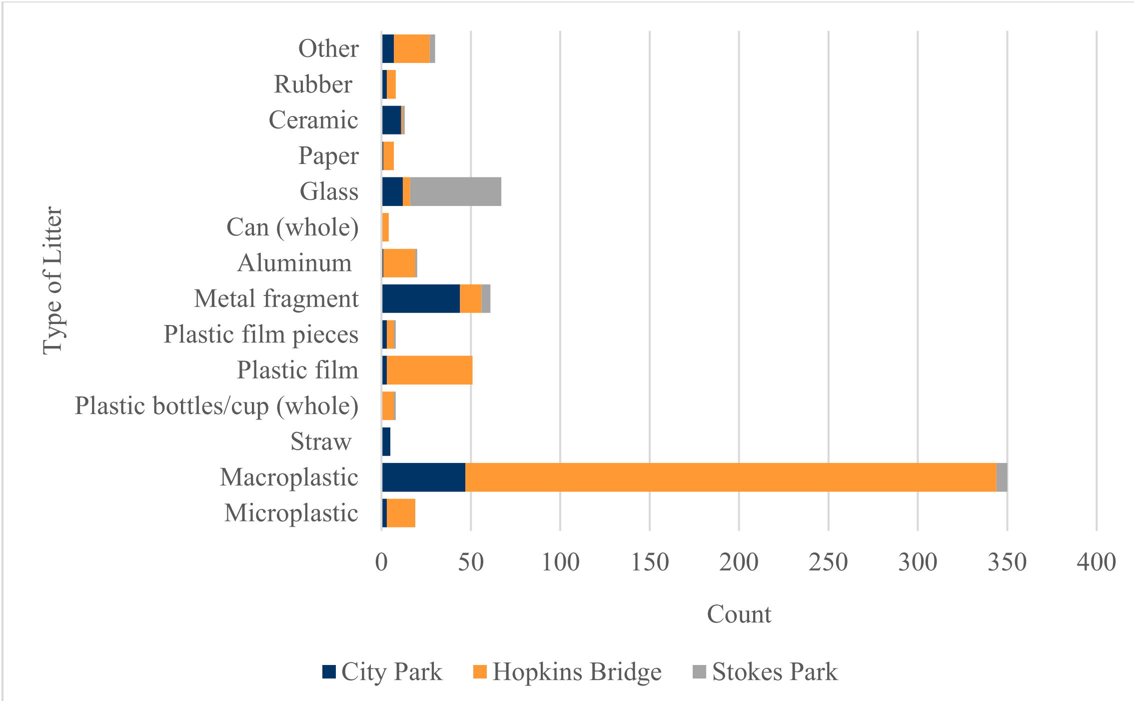

Figure 11. Types and Counts of Litter Found at Each Survey Site.

3.2 City Park

City Park had 2 microplastic pieces, 45 macroplastic pieces, 3 intact plastic films, 3 plastic film pieces, 35 metal fragments, 1 aluminum can, 12 pieces of glass, 1 small piece of paper, 7 pieces of ceramic, 3 pieces of rubber, and 5 miscellaneous items included in "other" (Figure 12). The "other" category included a piece of rope, a piece of duct tape, a lighter, two masks, and a bullet casing. Although a total of 47 pieces of plastic were found, only two were <5 mm, the standard for microplastic. Plastic pieces >5 mm represent 34.09% of samples found at City Park, followed by metal fragments at

33.33%. Plastic consisted of 40.15 percent of the total litter collected.

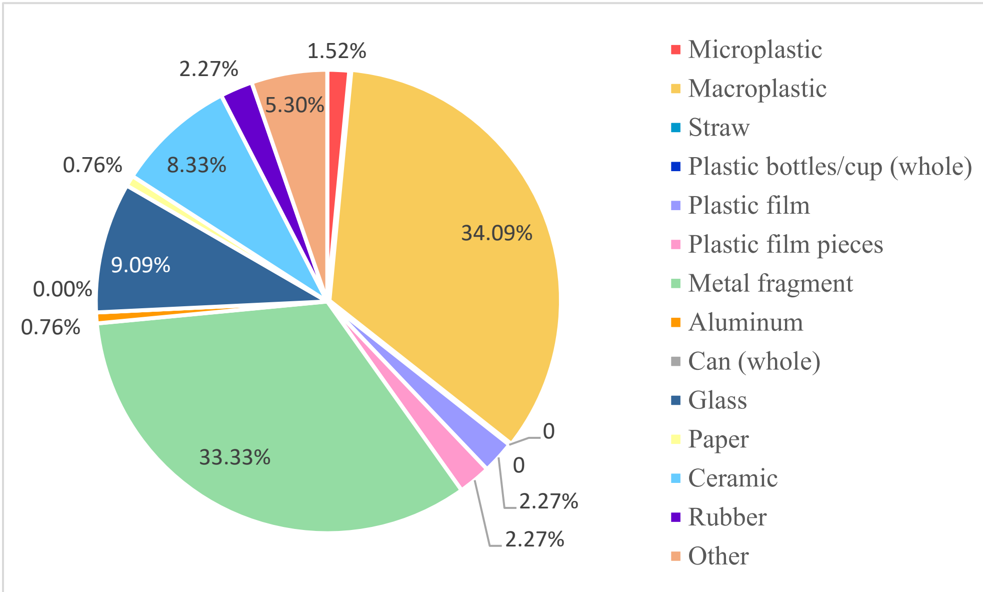

Figure 12. Composition of All Litter Found at City Park.

3.3 Hopkins Bridge

Hopkins Bridge contained 16 microplastics, 282 macroplastic pieces, 4 plastic straws, 3 whole plastic bottles, 3 whole plastic cups, 43 intact plastic films, 4 pieces of plastic film, 12 metal fragments, 18 pieces of aluminum, 4 whole cans, 4 pieces of glass, 6 pieces of paper, 1 piece of ceramic, 5 pieces of rubber, and 19 pieces of litter categorized as "other" (Figure 13). The "other" category included three band-aids, one water shoe, one mask, 10 pieces of cloth, one plastic glove, one piece of concrete, one piece of foam, and one piece of duct tape. This location had the most litter found. Macroplastic pieces consisted of 66.35% of litter found at Hopkins Bridge, followed by intact plastic films with 10.12% of the samples. 83.52 percent of the total litter collected consisted of plastic.

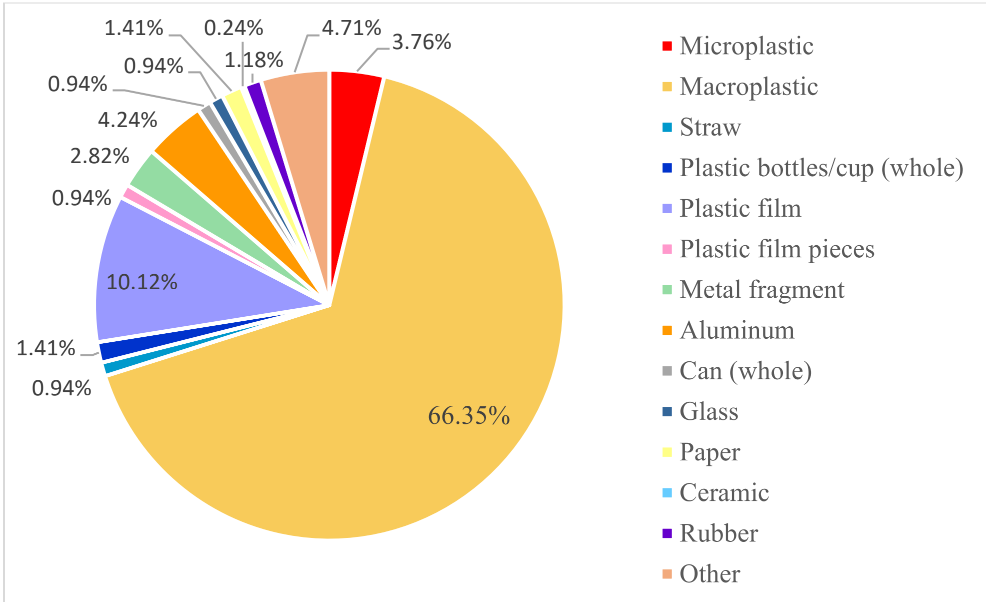

Figure 13. Composition of All Litter Found at Hopkins Bridge.

3.4 Stokes Park

Stokes Park contained the least amount of litter. Items found included 5 macroplastic pieces, 1 intact plastic cup, 5 metal fragments, 1 whole aluminum can, 51 pieces of glass, 1 piece of ceramic, and three items categorized under "other" (Figure 14). The "other" category included one piece of cloth, one flip phone cell phone case comprised of plastic and cloth, and a plastic vape pen. Glass was the majority of litter found at Stokes Park with 73.91% of samples, followed by macroplastic pieces with

8.70% of samples found. 11.6 percent of litter found was plastic.

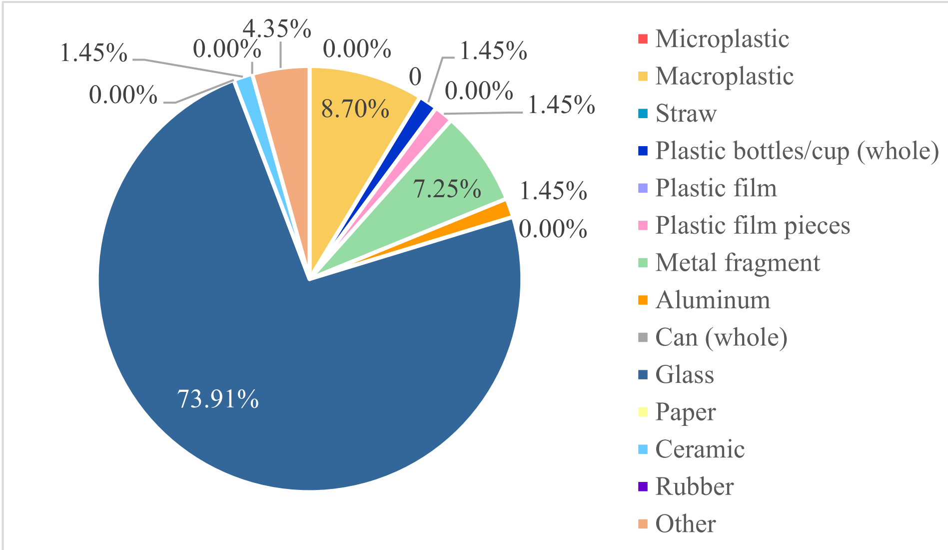

Figure 14. Composition of All Litter Found at Stokes Park.

3.5 Spatial and temporal variations in litter

I collected litter on June 4, June 30, July 10, July 31, August 6, August 29, September 11, September 25, October 3, and October 31. At City Park, 53 percent of samples contained litter. Hopkins Bridge had litter in 97 percent of samples and Stokes Park contained litter in 47 percent of samples (Figure 15).

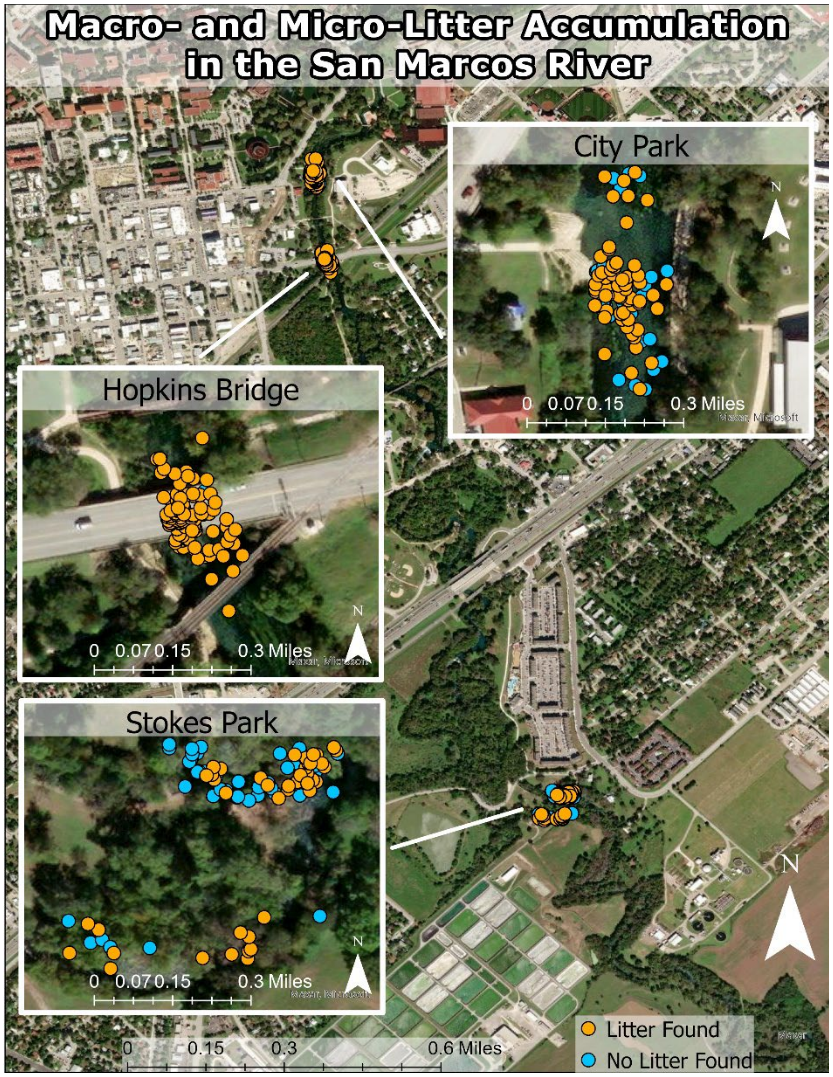

Figure 15. Primary Litter Collection Samples.

3.6 Daily litter collection data

3.6.1 June 4, 2021

City Park included a total of 10 pieces of litter on the first collection day. The most common items were pieces of metal tabs from cans. These tabs were detachable and used before manufacturers implemented tabs that remain attached after the can was opened. 3 out of 10 samples contained litter. Hopkins Bridge contained a total of 36 pieces of litter. The most common item were macroplastics. A notable item this day was a water shoe. This likely originated from recreation. All ten samples contained litter. Stokes Park had a total of 12 pieces of litter (Figure 16). The most common item was glass. Two out of ten samples contained litter.

Figure 16. Stokes Park Litter Collected 6/4/2021.

3.6.2 June 30, 2021

City Park included a total of six pieces of litter on this day. Four pieces were metal fragments, likely from old can tabs. I also found a single-use mask. Six out of ten samples contained litter. Hopkins Bridge included a total of 35 pieces of litter. The most common item were macroplastics. All ten samples contained litter. Stokes Park had a total of six pieces of litter. The most common item found were metal pieces. Six out of ten samples contained litter.

3.6.3 July 10, 2021

City Park had a total of six pieces of litter collected. Four pieces were from metal can tabs. Six out of ten samples contained litter. Hopkins Bridge had a total of 61 pieces of litter. The most common item were macroplastics, with nearly 74% of the total from this day. All ten samples contained litter. Stokes Park resulted in a total of five pieces of litter (Figure 17). Pieces of a plastic cup were the most common. Two out of ten samples contained litter.

Figure 17. Stokes Park Litter Collected 7/10/2021.

3.6.4 July 31, 2021

City Park contained four pieces of litter (Figure 18). Three were from metal can tabs. Two out of ten samples contained litter. Hopkins Bridge had 15 pieces of litter. All pieces were plastic of various sizes, including a car gas cap. All ten samples contained litter. Stokes Park had three pieces of litter. Two out of three were glass. Two samples contained litter.

Figure 18. City Park Litter Collected 7/31/2021.

3.6.5 August 6, 2021

City Park resulted in 14 pieces of litter. Metal fragments from a can tab and macroplastic tied as the most common items. Eight out of ten samples contained litter. Hopkins Bridge comprised of 16 pieces of litter. 87.5% of items were plastic. Nine out of ten samples contained litter. Stokes Park had three pieces of litter (Figure 19). Two pieces were glass. Two out of ten samples contained litter.

Figure 19. Stokes Park Litter Collected 8/6/2021.

3.6.6 August 29, 2021

City Park had 33 pieces of litter on this day. This was the largest amount of litter found at this location during the entirety of the collection period. The most common item were macroplastics. Nearly 88% of litter was plastic. Six out of ten samples contained litter. Hopkins Bridge resulted in a total of 28 pieces of litter (Figure 20). The most common items were macroplastics. Over 71% of litter was plastic. All ten samples contained litter. Stokes Park contained a total of ten pieces of litter. All were pieces of glass. Nine out of ten samples contained litter, the highest number of samples to contain litter during the entirety of the study.

Figure 20. Hopkins Bridge Litter Collected 8/29/2021.

3.6.7 September 11, 2021

City Park contained nine pieces of litter. Macroplastic was the most common item found. Six out of eight samples contained litter. Hopkins Bridge had 37 pieces of litter. The most common type of litter were macroplastics. Over 75% of litter was plastic. All ten samples contained litter. Stokes Park had three pieces of litter. These items were a piece of glass, a plastic bottle cap, and a piece of ceramic. Three out of ten samples contained litter.

3.6.8 September 25, 2021

City Park included 26 pieces of litter (Figure 21). The most common item found was glass with ten pieces. Nine out of ten samples contained litter. Hopkins Bridge had 79 pieces of litter. The most common type of litter were macroplastics. Over 88% of litter found was plastic. All ten samples contained litter. Stokes Park had a total of 30 pieces of litter found. The most common item found was glass that resulted in over 93% of litter found. Eight out of ten samples contained litter.

Figure 21. City Park Litter Collected 9/25/2021.

3.6.9 October 3, 2021

City Park resulted in 19 pieces of litter. The most common item found were pieces of metal wire. Seven out of ten samples contained litter. Hopkins Bridge included 96 pieces of litter (Figure 22). The most common type were macroplastics. This site also had two whole cans, two whole plastic cups, and two whole plastic bottles. This was unusual to find, as most litter collected were pieces of larger objects. Plastic litter was almost 82% of litter found this collection day. All ten samples contained litter. Stokes Park included 4 pieces of litter. Glass constituted half of the total. 4 out of 10 samples contained litter.

Figure 22. Hopkins Bridge Litter Collected 10/3/2021.

3.6.10 October 31, 2021

City Park had eight pieces of litter. The most common item found was glass. Six out of ten samples contained litter. Hopkins Bridge contained 24 pieces of litter. The most common item found were macroplastics. Over 83% of litter on this day was plastic. All ten samples contained litter. Stokes Park had 15 pieces of litter. The most common type of litter found was glass at over 73% of the total. Eight out of ten samples contained litter.

3.7 Culvert and precipitation data

There are a total of 14 culverts that lead into the San Marcos River from the spring-fed headwaters at the Meadows Center to Stokes Park (Figure 1). There are culverts at City Park and three at or directly upstream of Hopkins Bridge. Stokes Park does not have culvert outputs nearby.

A total of 55.42 cm of rain fell between May 30th (five days before the first survey collection day) and October 31 (Figure 23). June had a total of 5.39 cm of rain, July totaled 11.51 cm, August had 7.19 cm, September resulted in 11.86 cm, and October totaled the most rainfall of all survey months with 19.13 cm. It rained on three out of ten data collection days, either before or after data collection, but never during collection.

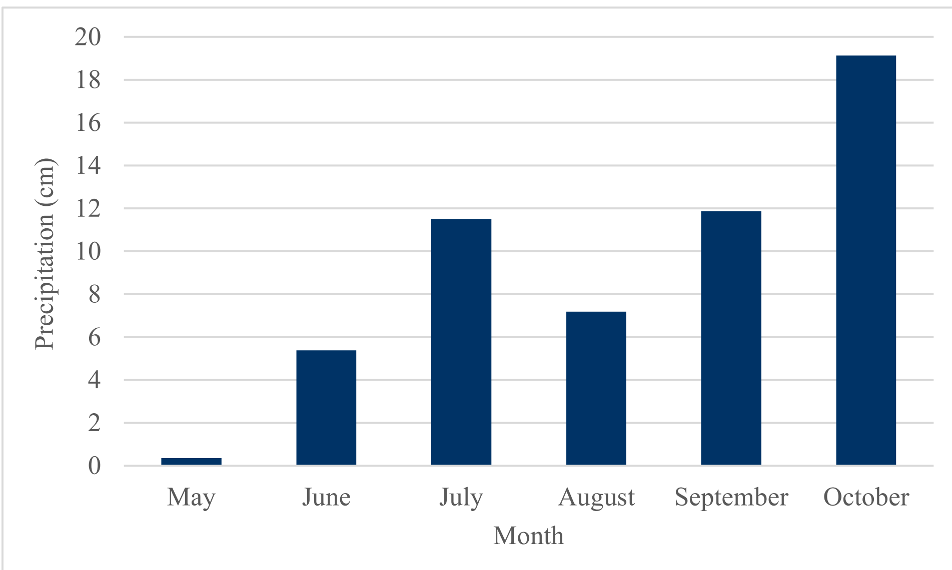

Figure 23. Monthly Precipitation Totals from May 30, 2021 to October 31, 2021.

Precipitation events occurred in between collection dates nine out of ten times. From the sampling event on September 11 to the sampling event on September 25, no rainfall occurred. There was 3.35 cm of rain total between May 30 and June 4 and 2.39 cm between June 5 and June 30. 4.06 cm of rain fell between July 1 and July 10 and 7.44 cm between July 11 and July 31. There was 2.82 cm on or between August 1 and August

6 and 0.20 cm between August 7 and August 29. There was 5.28 cm of rain between August 30 and September 10. No precipitation occulted between September 11 and September 25. There was 13.84 cm of rain between September 26 and October 2. Lastly, there was 15.98 cm of rain between October 4 and October 31.

IV. DISCUSSION

4.1 Primary data collection

The San Marcos River has persistent litter entering the water from urban runoff, culvert outputs, recreation, wind, and other sources. Throughout the study, the weather, seasonality, and recreators influenced the types and abundance of litter found in the river. Following high flow events, litter increased at the Hopkins Bridge site. This location captured the most litter out of all three sites due to the type of substrate that differs. The velocity was lowest here, allowing for litter to become easily deposited and lodged in riverbed sediments.

The study began during the recreational season in June and concluded after the end of the season in October. The amount of litter increased during the duration of collection. Possible explanations for the litter increase could be the rise in recreators on the river and in the parks, more car and foot traffic in the watershed, and the rainfall amounts throughout the period.

Sources of litter cannot be fully determined based on litter collected due to many variables. Much of the litter collected is only a piece that broke off from the original object. Small fragments are almost impossible to identify if there is no logo or brand from the original manufacturer.

Peak recreational season in San Marcos is between Memorial Day and Labor Day. During this time, there are typically tens of thousands of recreators on the river and in the surrounding parks. Unless there was a rainfall event that led to runoff, I assumed that most litter originated from recreation or natural sources of transportation in the watershed. In the case of Hopkins Bridge, I assumed most litter was from recreation and the above street.

4.2 Monthly litter collection data

4.2.1 June 2021

Based on the seasonality and precipitation, much of the litter on the June 4th sample day likely originated from recreational sources and possibly runoff. Broken glass, water shoes, and can tabs are common items taken to the river for recreation, although glass is not allowed per a city ordinance. There was 2.39 cm of rainfall between June 5th and June 30th. The litter collected on June 30th likely sourced from recreation or became stuck in the substrate from a previous runoff event.

4.2.2 July 2021

There was 4.06 cm of rainfall between June 30th and July 10th, including rain the two days prior and the day of collection. City Park and Stokes Park litter likely derived from recreational sources due to metal can tabs and plastic cups frequently used by recreators. Hopkins Bridge can be a mix of recreational litter and runoff from the above road. 7.44 cm of rainfall occurred from July 11th to July 31st. Items such as the gas cap indicate a major source of litter on this day were from the above street or surrounding urban environment.

4.2.3 August 2021

2.87 cm of rain fell between August 1st and August 6th. Some of the litter may have been from runoff flowing in the river or culvert outputs. Recreation is likely a source as well since the sampling occurred at the beginning of August and the types of materials found, including a plastic cup. There was only 0.20 cm of rainfall between August 7th and August 29th. This likely means most of the litter derived from recreation.

4.2.4 September 2021

5.28 cm of rain occurred between August 30th and September 11th. Litter could derive from the small runoff event and a large number of recreators on the river and in the surrounding parks. There was no rainfall between September 12th and September 25th, meaning that recreation was likely the main source of litter for this collection day, especially at Stokes Park. Glass was a common item.

4.2.5 October 2021

13.84 cm of rain fell between September 26th and October 3rd. The large rainfall event contributed to the majority of litter found on this day. This can explain the whole bottles, cans, and cups. Precipitation as an agent can move larger litter items from the watershed to the river. Almost 15.98 cm of rain fell between October 4th and October 31st. Since the peak recreation season ended in early September and there was a large rainfall event early in October, it is likely the runoff carried a large amount of litter that entered the river.

4.3 Cross-site analysis

Litter types and abundance among survey sites varied, but patterns emerged through analysis. The most common type of litter found at each location can provide us with insight into surrounding activities. For example, if cans are the most common litter found in a location, we can assume that the area has high recreational use.

4.3.1 Types of litter

Small pieces of litter, typically broken off from a larger object were most common at all sites. City Park frequently contained small metal litter and macroplastic pieces. Hopkins Bridge mainly consisted of marcoplastic pieces and contained the widest variety of litter at all sites. I found few microplastics, but studies show that sediments contain the majority of microplastics, followed by surface water (Alam et al. 2021). Microplastics are the most abundant near urban areas (Toumi et al. 2019). From this, I assume City Park and Hopkins Bridge have the most microplastics from the three sites.

The majority of litter from Stokes Park was glass. Macroplastics and metal fragments were also prominent. Larger litter occurred as well, such as a shotgun shell casing at City Park (Figure 24), whole bottles and cans at Hopkins Bridge, and large pieces of glass at Stokes Park. Larger litter typically occurred near the bank and in areas recreators do not frequent.

Figure 24. Bullet Casing Found at City Park.

Location, activities surrounding each site, and proximity to urban areas can predict types of litter in specific areas of the river. Multiple sources of litter results in a wider variety of categories of litter. Like my research, a study done on a coastal lagoon and a large river found a variety of types of litter throughout the study area that varied on the source (Velez et al. 2020) and proximity to urban areas (Bruge et al 2018). Locations close to large impermeable surfaces, high foot traffic, and many culvert outputs, i.e., urban areas, will likely contain a wide variety of litter (Carson et al. 2013; Cowger et al. 2019; Moore et al. 2011; Rech et al. 2015). Locations with surrounding green spaces that are more remote and lack foot traffic have less variety of litter. Location and sources of litter greatly impact types and amounts of litter. Much of the litter found in this study was domestic litter sourced from households. Other studies commonly found domestic litter compared to industrial (Blettler et al. 2017; Hoellein et al. 2017).

Hopkins Bridge is accessible to recreators, close to the urban core of the city, has bridge-related car traffic, and multiple culvert outputs upstream. Compared to City Park and Stokes Park, Hopkins Bridge has the most litter sources, resulting in the widest variety of litter. Stokes Park has the least sources of litter—mainly foot traffic/recreators, runoff from the nearby road, and general transport by the river. Stokes Park contained glass more often than other sites. Recreators likely deposited glass in this more secluded park. City Park and Hopkins Bridge rarely contained glass because they are highly trafficked by recreators and park rangers. Remote locations allow visitors to bring glass containers with fewer consequences from city ordinance enforcement. Much of the found glass at Stokes Park was brown, resembling beer bottles, typical of recreational litter

(Figure 25).

Figure 25. Stokes Park Litter Collected 8/29/2021.

It is also important to note that there are dams along the San Marcos River. One is located above my study site at City Park, the Spring lake Dam, another is located downstream of City Park and Hopkins Bridge, Rio Vista Dam, and there is a third downstream of Stokes Park, Cape's Dam. Dams may trap some litter stored in the bed substrates, preventing its downstream transport. On the contrary, a tributary, Willow Springs Creek that connects with the San Marcos River upstream of the Stokes Park survey location transports litter into the river. This creek is close to I-35, collecting litter from the highway and the surrounding area during rainfall events.

4.3.2 Foot traffic and sources of litter

Areas with lower foot traffic tend to retain litter for longer periods due to less substrate disturbance. This is true for the banks of City Park, most of Hopkins Bridge, and more remote areas of Stokes Park. Less recreation combined with the type of substrate can allow litter to remain in place. The opposite occurs for highly trafficked areas of the river such as City Park, where the frequent disturbance of substrate uplifts litter along with sediment, pushing it downstream. Stokes Park lacks heavy foot traffic but is unique with varying depth and velocity from bank to bank. Recreators at this spot are likely to stay at the bank with lower velocity, limiting the scale of substrate disturbed.

The culvert outputs leading into City Park transports urban street litter, but it most likely flows downstream. Recreation and urban runoff are the main sources of litter.

4.3.3 Substrate

Type of substrate impacts litter. Gravel and cobble are not able to contain litter like silt. Silt easily traps litter, where the fine particles hold onto it, especially in low velocities. Hopkins Bridge contained more litter for this reason. This location was difficult to move around in compared to the other sites due to the immediate sinking upon pressure to the substrate. Once an object is lodged into silt, it is difficult to remove without pressure. Stepping on litter buries it further into the substrate. City Park and Stokes Park were easily navigable, with a more armored channel bed, allowing movement of litter with the current and not embedded into the substrate. Another possible reason why I found glass frequently at Stokes Park is related to the weight of the substance. Glass is heavier than plastics and small pieces of metal, trapping it against the substrate. Additionally, a lack of ordinance enforcement for glass at Stokes Park plays a role. Hopkins Bridge may contain larger pieces of glass, but silt may trap it under layers of sediment.

4.3.4 Velocity and depth factors

Velocity varies in the San Marcos River and in cross-sections of each survey site. Abundancy and categories of litter are largely dependent on river velocity, as shown in this study. Stokes Park had the highest average velocity and contained the least litter. City Park had the second-highest velocity and amount of litter. Hopkins Bridge had the slowest velocity and contained the most litter.

Stokes Park contained more glass than other litter due to a higher velocity. The river carries lighter pieces of litter downstream in areas with higher velocities, but litter stays put in lower velocity locations such as at Hopkins Bridge. In City Park and Hopkins Bridge, litter was found around Texas wild-rice, but there was no noticeable difference in abundance near vegetation.

4.3.5 Historic litter data

The data provided by the EAHCP illustrates monthly and yearly data from 2013 to 2020. Although not entirely consistent due to 2018 lacking data for many months, (Figure 26)

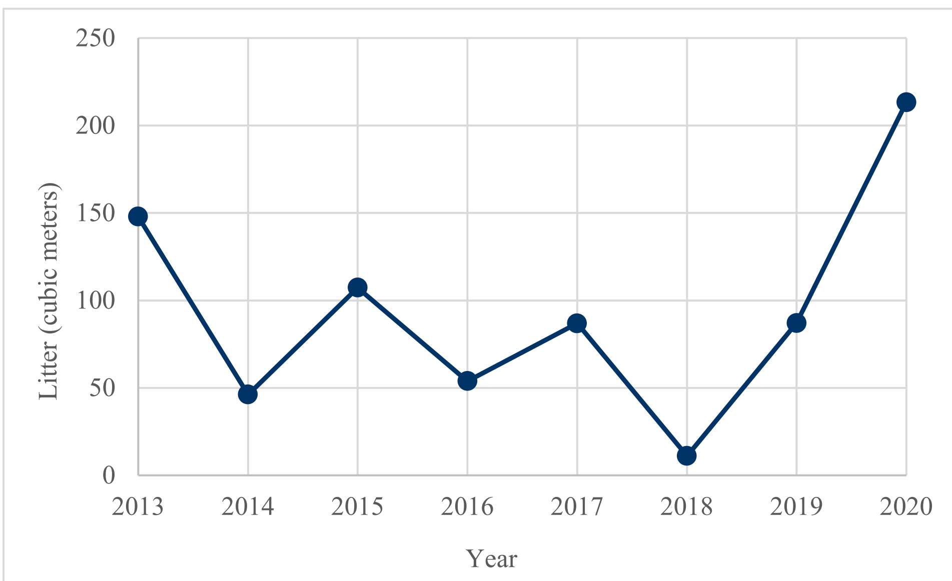

Figure 26. EAHCP 2013-2020 Yearly Litter Totals.

2020 had the highest volume of litter collected from the river and surrounding banks with 213.31 cubic meters. 2018 had the lowest amount of litter collected by the EAHCP with 11.07 cubic meters. The total amount of litter collected from the EAHCP from 2013 to 2020 resulted in 753.49 cubic meters. Historic EAHCP data reported the highest amounts of litter collected during July (Figure 27).

The City of San Marcos KSMB data does not show a trend in the amount of litter

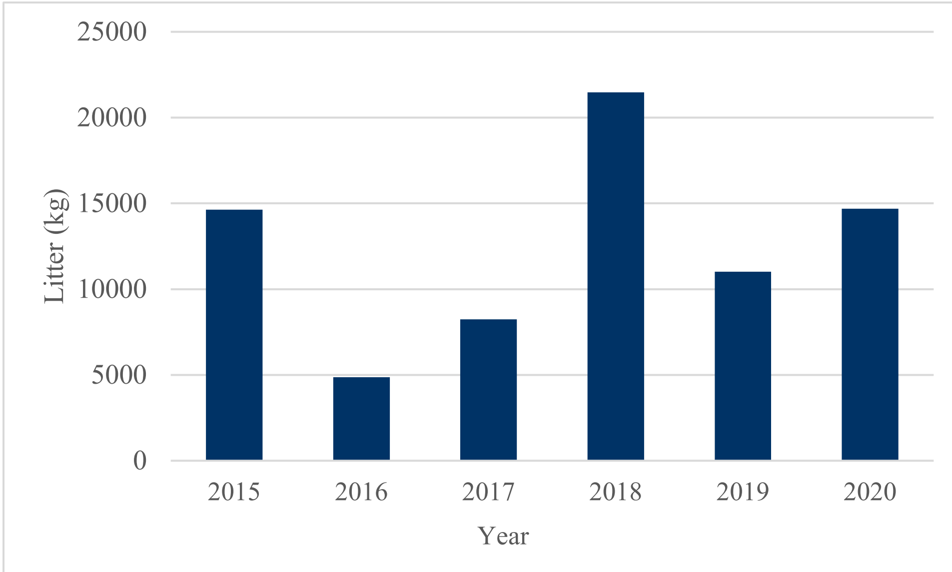

Figure 27. EAHCP 2013-2020 Monthly Totals.

collected (Figure 28). 2016 only had one of the two large river cleanup events in the city, thus a significant decrease in litter was reported compared to other years. 2015 also only had one event, but the amount of litter collected exceeds other years such as 2019 with just the single event. There was a decrease in litter collected from 2018 to 2019. The total amount of litter collected from the Great Texas River Clean-up events from 2015 to 2020

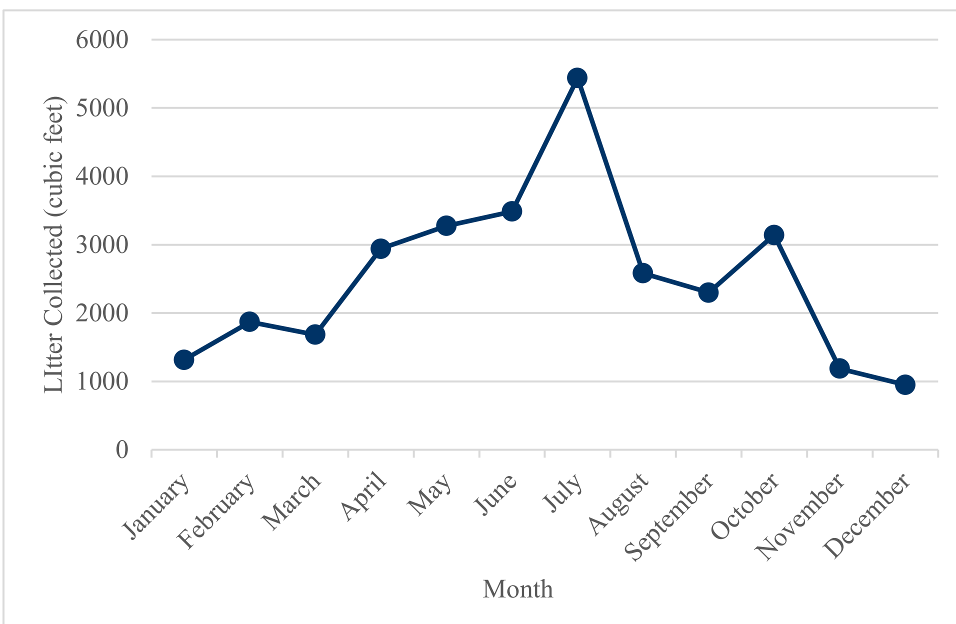

Figure 28. KSMB Litter Collected During River Clean-ups 2015-2020.

was 74,891.34 kg. The City of San Marcos also actively participates in an "Adopt a Spot" program with cleanup locations throughout the watershed, but this data is incomplete for many years and does not capture the true amount of litter collected through the program.

4.3.6 Spatial and temporal patterns of litter

Litter increased throughout the study. September 25th had the largest amount of litter collected, but there was no rainfall since the previous collection day. This litter likely originated from people floating on the river or sitting on the banks. There were two larger rainfall events on September 30th and October 1st, that likely contributed to the increase in litter found in the Hopkins Bridge location. I collected larger litter during this day and saw an increase in whole plastic bottles and cups, rarely seen items throughout the collection period. There was another large rainfall event in mid-October, but the litter collected does not reflect that of the last rainfall event from October 3rd.

A possible explanation of why Stokes Park contained the least amount of litter of the three sites is the green space surrounding the river. Vegetation can stop litter before it enters the river. There is less runoff from the surrounding area flowing into the river as a result of infiltration. Stokes Park located downstream of the urban core of San Marcos showed that litter varies spatially. Figures 22 and 23 show examples of litter found at Stokes Park on June 4 and June 30.

I collected masks four times during the study. Three of these were found at City Park. This type of litter was likely not present before the COVID 19 pandemic. Studies found masks to be a common item found in beach cleanups (Okuku et al. 2021). This is an example of how litter reflects societal behavior and activities. Another example of this is the old can tabs found throughout the study. Pull-off can tabs were phased out in the

1980s yet persist in the environment decades later. This is likely true for other litter found. Plastic, for example, persists in the environment for decades. Plastic comprised of 63.8 percent of litter found in a study from the 1980s. The author estimated the plastic to be decades-old (Lucas 1992). Another study published in 1990 commonly found plastic containers but focused on aluminum cans (Cahoon 1990). Much like Cahoon's study, my study found many partial cans and can tabs. We are observing a consistent presence of legacy litter pollution dating back to at least the 1980s in the San Marcos River. New litter entering the river may remain there for decades for the continued introduction/source of micro-litter.

V. LIMITATIONS

During the early summer, it frequently rained, making it difficult to collect data. The river was turbid, not allowing for sighting and data collection. I was not able to collect all litter within my survey square due to only taking items off the surface of the substrate. Litter could be buried under gravel, pebbles, or buried in mud that I was unable to collect. Some litter may have been too small to see, or the color was difficult to distinguish from the surrounding natural elements. The types of litter slightly changed due to the COVID-19 pandemic, such as masks.

The accuracy of the GPS data for each survey plot may not represent the actual location and may also differ from the Apple Maps® location. I captured the depth and velocity of the river in March 2022. This is not completely representative of the actual conditions during the study, though the relative comparisons among sites using this data were useful.

VI. MITIGATION AND MANAGEMENT IMPLICATIONS

The first step to combatting litter pollution in rivers is to have a basic understanding of *how much* litter, what *kinds* of litter, and *where* it is entering our waterways. A universal data-sharing platform where all individuals and groups collecting litter can report their findings in terms of collected items and where they are located could largely inform communities on the next steps for mitigation techniques.

More baseline studies should be completed in rivers across the United States and the world using the inexpensive resource of citizen science to drive data collection. These events are already happening across communities, such as the Great Texas River Cleanup that many cities in Texas participate in yearly. 5 Gyres Institute is in the process of a major data collection phase across the US. It works with NGOs, cities, and volunteers to collect and categorize litter in an app named Litterati. 5 Gyres Institute completed studies in Los Angeles, Denver, and Austin from 2019 to 2021. The Institute captured the top 10 or 20 litter items and brands (5 Gyres Institute 2022). The City of San Marcos completes litter audits after some clean-up events. It works with Keep Texas Beautiful and received a $400,000 grant to improve litter prevention programming (Corridor News 2020).

Volunteers that participate in the Great Texas River Cleanup collect thousands of kilograms of trash and recycling yearly, making it difficult to audit. I recommend the city perform trash and recycle audits on smaller events, especially involving litter removed from the river. Multiple organizations within the city can participate in removing debris, sorting, and recording items found on an easy-to-use platform. The city should also host events where the primary goal is to collect litter from a variety of locations within the San Marcos River to audit, find trends in litter, and assess potential sources for each site to weigh options for management in the future. This data is crucial for the City of San Marcos to apply for grants and request funding for programs internally.

Best management practices for litter in river systems are still being experimented with, but some successful technologies include implementing netting systems over culverts, storm drain filters, buoy systems, and barriers in stormwater drains. Culverts, transport litter from busy streets and urban areas directly into the San Marcos River. Netting systems attach to culverts and capture medium to large litter, preventing it from entering the water. These are in use around the world to contain litter before it flows downstream (Blanc 2013; Armitage and Rooseboom 2000). Although they are useful, some concerns include wildlife entrapment and increased flooding during reduced water conveyance.

Storm drain filters connect to existing storm drains to collect litter from stormwater and are easily installed, cleaned, and removed (Chittripolu et al. 2011). The removal of litter, sediment, and debris should be done weekly for flooding concerns. Texas State University has three storm drain filters on its campus to collect litter from flowing into the river and has recently started to collect data on items captured.

Another recent technology for litter collection are buoy systems that float in the river and collect litter as it flows downstream, such as the Bandalong Litter Trap engineered by Stormwater Systems (Stormwater Systems 2022). These are effective for capturing larger floating lightweight items such as cans and water bottles but can also capture natural debris such as tree branches.

The City of San Marcos Stormwater Management department recently implemented a pilot program for the SAFL Baffle. This is a technology created by

Upstream Technologies that removes sediment in stormwater to improve water quality (Upstream Technologies 2022). This device can also filter out litter in addition to sediment.

All these management strategies are a step in the right direction but have a similar problem in common—they do not capture micro-litter and microplastics. These items are extremely difficult to clean up due to their size and there are currently no systems designed to capture them. This type of litter needs special attention from volunteers.

Implementing more litter clean-ups and utilizing free help from volunteers is a cost-effective and efficient way of removing litter from waterways and the surrounding basin area. Clean-ups can be done multiple times a year, or as often as needed, and allows for locals to be involved in cleaning up their community. Statewide events such as the Great Texas River Clean-up attract many across the state. The two city-run events per year incentivize volunteers with tee shirts, cups, and free food. Volunteers learn about how litter impacts ecosystems and are encouraged to make smart, sustainable decisions when they are in natural environments.

Education is key when it comes to litter reduction. Many people do not realize the impacts their actions have on the environment and view littering as a minor offense, if one at all. The Texas Litter Abatement Act punishes perpetrators of illegal dumping crimes and litter with fines and even jail time in serious cases. A major setback in prosecuting these types of crimes is a lack of enforcement. City and county officials do not see it as a priority. Officers are more focused on issues such as drugs, domestic violence, and violent crime so environmental crimes are not given priority. Some cities and counties do not even have environmental enforcement. Hiring more environmental investigators and prosecuting attorneys can be a valuable solution to litter pollution in cities and counties. One incentive to increase catching litter perpetrators includes a reward for citizens who call in crimes they see. A city or county can offer a $50 reward if the situation results in prosecution according to Tex. Health and Safety Code § 365.012(m). This encourages proper disposal of litter and makes citizens more aware of environmental crimes and their impacts.

Incentives for recreators to properly dispose of their litter such as a swap program can reduce litter in the river from recreation. Tubing is one of the main activities on the San Marcos River and some companies that rent out tubes provide recreators with a mesh bag to store litter in to properly dispose of it after they float. If tubing companies partner with local businesses and restaurants to provide coupons for recreators that use their mesh bags for storing litter, they can swap their bag for a coupon to a local business in town. It incentivizes proper disposal of litter, increases cleanup efforts and awareness, promotes local businesses, and can boost the local economy by recreators spending money at local restaurants and businesses.

A combination of technologies, citizen science, policy, education, and incentives for recreators will create the most comprehensive solution for mitigating litter from entering the San Marcos River. The community needs to be involved in the clean-up of the San Marcos River and the surrounding watershed because they are the source of litter that travels to the river. Policy and enforcement are major players in litter prevention, but the fundamental issue is human behavior. Citizen science and education in this case are steps for the community to become involved in science and realize the implications of their actions.

VII. CONCLUSION

Litter pollution in the San Marcos River is a nuisance brought on by activities in urban areas, culvert outputs, and recreation. There are laws in place to prevent litter from entering waterways such as the Solid Waste Disposal Act, the Texas Litter Abatement Act, the Texas Water Code, and the local ordinances created by the City of San Marcos, but there is simply not enough enforcement to combat the problem. The conclusion is that we do not know *how much* litter is in the San Marcos River due to a lack of data from organizations collecting litter from the river, and minimal studies on litter pollution, especially in the San Marcos River.

From the study, I can conclude that the surrounding environment impacts the types and amounts of litter in various locations in the river. Areas with high recreation will see different types of litter than those with street traffic or a lower number of visitors. For example, Hopkins Bridge had the most amount and the greatest variety of litter. This location has the most sources of litter, including recreation, culverts, the above street, and urban runoff. The same can be said for areas close to an urban area or green space. The type of litter found greatly depends on the originating source. For Stokes Park, the majority of litter comes from recreation, hence the large quantity of glass from beer bottles.

The substrate and flow of the river also impact the types and quantity of litter. Areas with a high velocity saw less litter than areas with low velocity. Substrates comprised of gravel and pebbles were less likely to hold onto litter compared to silt, where litter can be held for periods of time.

Floods and precipitation can impact the types of litter found as well. Rainfall events can transport larger items from the watershed into the river. Seasonality can affect types of litter based on the activities in the watershed and around the river. Recreational litter is likely to decrease in the offseason.

From this research, I found a legacy of litter in the three survey sites. Litter dating back to at least the 1980s is still prominent in the river. New items entering the river may remain there for decades, joining old litter. Immediate steps need to be taken to mitigate future impacts of litter pollution.

A key strategy for quantifying litter includes creating a data tracking platform for organizations, businesses, and volunteers to record litter data from clean-ups. Consistency is crucial for data tracking and analysis. Education is a critical tool for decreasing the amount of waste produced and improperly disposed of. All citizens, especially recreators, need education on the impacts litter pollution has on fragile environments like the San Marcos River. People need to understand that their decisions can make positive and negative impacts.

New practices and technologies continue to develop, but laws, enforcement, data tracking, education, and incentives are today’s most favorable implementation strategies. The fate of the San Marcos River rests in our hands. To what lengths will policymakers, the city, residents, recreators, and businesses go to protect it?

REFERENCES

5 Gyres Institute. TrashBlitz. 2022. Trashblitz — 5Gyres.org.

Abdul-Rahman, F. Reduce, Reuse, Recycle: Alternatives for Waste Management. 2014. *New Mexico State University College of Agriculture, Consumer and Environmental Sciences.* :4.

Alam, F. C., E. Sembiring, B. S. Muntalif, and V. Suendo. 2021. Microplastic distribution in surface water and sediment river around slum and industrial area (case study: Ciwalengke River, Majalaya District, Indonesia). *Chemosphere* 224:637–645.

Armitage, N., and A. Rooseboom. The removal of urban litter from stormwater conduits and streams: Paper 1 - The quantities involved and catchment litter management options. April 2000. *Water SA*. :8.

Baldwin, Austin K., Corsi, Steven R., Mason, Sherri A., Plastic Debris in 29 Great Lakes Tributaries: Relations to Watershed Attributes and Hydrology. 2016. *American Chemical Society.* https://pubs.acs.org/doi/full/10.1021/acs.est.6b02917.

Blanc, Janice. An analysis of the impact of trash screen designs on debris related blockage at culvert inlets. March 2013. *Heriot-Watt University.*

Blettler, M. C., M. A. Ulla, A. P. Rabuffetti, and N. Garello. 2017. Plastic pollution in freshwater ecosystems: Macro-, meso-, and microplastic debris in a floodplain Lake. *Environmental Monitoring and Assessment* 189 (11).

Bruge, A., C. Barreau, J. Carlot, H. Collin, C. Moreno, and P. Maison. 2018. Monitoring Litter Inputs from the Adour River (Southwest France) to the Marine Environment. *Journal of Marine Science and Engineering* 6 (1):24.

Cahoon, L. B. 1990. Aluminum Cans as Litter in Masonboro Sound, North Carolina. *Journal of Coastal Research* 6 (2):479–483.

Carson, H. S., M. R. Lamson, D. Nakashima, D. Toloumu, J. Hafner, N. Maximenko, and K. J. McDermid. 2013. Tracking the sources and sinks of local marine debris in Hawaiʻi. *Marine Environmental Research* 84:76–83.

Chittripolu, R., Lau, T. L., and A. Ab. Ghani. 2012. Sustainable solutions for global crisis of flooding, pollution and water scarcity. *International Journal of River Basin Management* 10 (2):137–138.

City of San Marcos. 2018. San Marcos Parks, Recreation, and Open Space Master Plan.

City of San Marcos. 2022. Public Facilities, Parks and Recreation. Chapter 58 - PUBLIC FACILITIES, PARKS AND RECREATION | Code of Ordinances | San Marcos, TX | Municode Library.

Corridor News. 2020. Keep san marcos beautiful to share in $400,000 grant award. *Corridor News*. https://smcorridornews.com/keep-san-marcos-beautiful-to-share-in-400000-grant-award/#:~:text=T%20he%20City%20of%20San%20Marcos%20is%20excited,recent%20%24400%2C000%20grant%20award%20to%20Keep%20Texas%20Beautiful.

Cowger, W., A. B. Gray, and R. C. Schultz. 2019. Anthropogenic litter cleanups in Iowa riparian areas reveal the importance of near-stream and watershed scale land use. *Environmental Pollution* 250:981–989.

Davila, E. 2016. Spatiotemporal river use patterns and implications for Texas wild-rice distribution in the San Marcos River (Texas, USA) for summer 2016. :25–25.

Davis, H. Life & Death in the Anthropocene: A Short History of Plastic. :12.

Dikareva, N., and K. S. Simon. 2019. Microplastic pollution in streams spanning an urbanisation gradient. *Environmental Pollution* 250:292–299.

Edwards Aquifer Authority. 2021. Covered species. *Edwards Aquifer Authority*. https://www.edwardsaquifer.org/habitat-conservation-plan/about-eahcp/covered-species/.

Edwards Aquifer Authority. 2021. Net Disturbance and Incidental Take. *Edwards Aquifer Authority*. https://www.edwardsaquifer.org/habitat-conservation-plan/about-eahcp/covered-species/.

Edwards Aquifer Habitat Conservation Plan. 2014. Edwards Aquifer Habitat Conservation Plan 2013 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2015. Edwards Aquifer Habitat Conservation Plan 2014 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2016. Edwards Aquifer Habitat Conservation Plan 2015 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2017. Edwards Aquifer Habitat Conservation Plan 2016 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2018. Edwards Aquifer Habitat Conservation Plan 2017 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2019. Edwards Aquifer Habitat Conservation Plan 2018 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2020. Edwards Aquifer Habitat Conservation Plan 2019 Annual Report.

Edwards Aquifer Habitat Conservation Plan. 2021. Edwards Aquifer Habitat Conservation Plan 2020 Annual Report.

Environment, U. N. 2017. Global Partnership on Marine Litter. *UNEP - UN Environment Programme*. http://www.unep.org/explore-topics/oceans-seas/what-we-do/addressing-land-based-pollution/global-partnership-marine.

Free, C. M., O. P. Jensen, S. A. Mason, M. Eriksen, N. J. Williamson, and B. Boldgiv. 2014. High-levels of microplastic pollution in a large, remote, mountain lake. *Marine Pollution Bulletin* 85 (1):156–163.

Gersberg, R.M., Novotny, T.E., Rudolph, Slaughter, J., Stransky E.C., and Watanabe K. 2011.Toxicity of cigarette butts, and their chemical components, to marine and freshwater fish. *Tobacco Control* 20 (Suppl_1):i25–i29.

Geyer, R., J. R. Jambeck, and K. L. Law. 2017. Production, use, and fate of all plastics ever made. *Science Advances* 3 (7):e1700782.

Health and Safety Code. Chapter 361. Solid Waste Disposal Act. n.d. https://statutes.capitol.texas.gov/docs/HS/htm/HS.361.htm.

Hoellein, T. J., M. Westhoven, O. Lyandres, and J. Cross. 2015. Abundance and environmental drivers of anthropogenic litter on 5 Lake Michigan beaches: A study facilitated by citizen science data collection. *Journal of Great Lakes Research* 41 (1):78–86.

Julian, J., G. Daly, and R. Weaver. 2018. University students' social demand of a blue space and the influence of life experiences. *Sustainability* 10 (9):3178.

Kiessling, T., K. Knickmeier, K. Kruse, D. Brennecke, A. Nauendorf, and M. Thiel. 2019. Plastic Pirates sample litter at rivers in Germany – Riverside litter and litter sources estimated by schoolchildren. *Environmental Pollution* 245:545–557.

Lebreton, L. C. M., J. van der Zwet, J.-W. Damsteeg, B. Slat, A. Andrady, and J. Reisser. 2017. River plastic emissions to the world's oceans. *Nature Communications* 8 (1):15611.

Lidia, S.-I., and D. Fischer. 2003. Quantification and classification of marine litter on the municipal beach of Ensenada, Baja California, Mexico. *Marine pollution bulletin* 46:132–8.

Lucas, Z. 1992. Monitoring persistent litter in the marine environment on Sable Island, nova scotia. *Marine Pollution Bulletin* 24 (4):192–199.

Martin, K. M. 2018. Quantifying and characterizing the Mississippi River's contribution of microplastic debris to the Gulf of Mexico. https://tamuccir.tdl.org/handle/1969.6/87095.

Meadows Center for Water and the Environment. About. 2021. //www.meadowscenter.txstate.edu/About.html.

Meadows Center for Water and the Environment. Endangered Species. 2020. //www.meadowscenter.txstate.edu/ExploreSpringLake/EndangeredSpecies.html.

Moore, C. J., G. L. Lattin, and A. F. Zellers. 2011. Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. *Revista de Gestão Costeira Integrada* 11 (1):65–73.

National Centers for Environmental Information (NCEI). 2022. Daily summaries station details. *Daily Summaries Station Details: SAN MARCOS, TX US, GHCND:USC00417983 | Climate Data Online (CDO) | National Climatic Data Center (NCDC)*. https://www.ncdc.noaa.gov/cdoweb/datasets/GHCND/stations/GHCND:USC00417983/detail.

Okuku, E., L. Kiteresi, G. Owato, K. Otieno, C. Mwalugha, M. Mbuche, B. Gwada, A. Nelson, P. Chepkemboi, Q. Achieng, V. Wanjeri, J. Ndwiga, L. Mulupi, and J. Omire. 2021. The impacts of covid-19 pandemic on marine litter pollution along the Kenyan Coast: A synthesis after 100 days following the first reported case in Kenya. *Marine Pollution Bulletin* 162:111840.

Rech, S., V. Macaya-Caquilpán, J. F. Pantoja, M. M. Rivadeneira, C. K. Campodónico, and M. Thiel. 2015. Sampling of riverine litter with citizen scientists — findings and recommendations. *Environmental Monitoring and Assessment* 187 (6).

Rosevelt, C., M. Los Huertos, C. Garza, and H. M. Nevins. 2013. Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA. *Marine Pollution Bulletin* 71 (1):299–306.

San Marcos Convention & Visitor Bureau. 2022. San Marcos, TX history: Attractions & Sight Seeing. *San Marcos, TX History | Attractions & Sight Seeing*. https://www.visitsanmarcos.com/plan-your-visit/about-san-marcos/history/.

Stormwater Systems. Bandalong Litter Trap. 2022. Bandalong The Original Litter Trap - Storm Water Systems (last accessed 6 March 2022). Surrounding towns put pressure on San Marcos to ban disposable containers | News | universitystar.com.

Timia Cobb. Surrounding towns put pressure on San Marcos to ban disposable containers. 19 October, 2021. *The University Star.*

Texas State University. facts-and-data. 2021. Facts & Data. //brand.txstate.edu/facts-and-data.html.

Texas State University. 2020. Sewell Park. *Texas State University: Texas State University*. https://www.txstate.edu/about/history-traditions/sewell-park.html#:~:text=On%20a%20hot%20summer%20day%20in%201916%2C%20Dr.,college%20four%20acres%20of%20land%20along%20the%20river.

Texas Water Code. Chapter 7. Texas Water Code Section 7.145 - Intentional or Knowing Unauthorized Discharge (public.law).

Toumi, H., S. Abidli, and M. Bejaoui. 2019. Microplastics in freshwater environment: The first evaluation in sediments from seven water streams surrounding the lagoon of Bizerte (northern Tunisia). *Environmental Science and Pollution Research* 26 (14):14673–14682.

Upstream Technologies. SAFL Baffle. 2022. SAFL Baffle (upstreamtechnologies.us).

U.S. Census Bureau QuickFacts: San Marcos city, Texas. https://www.census.gov/quickfacts/sanmarcoscitytexas.

USGS 08170500 San Marcos Rv at San Marcos, TX. https://waterdata.usgs.gov/nwis/inventory/?site_no=08170500&agency_cd=USGS.

van der Velde, T., D. A. Milton, T. J. Lawson, C. Wilcox, M. Lansdell, G. Davis, G. Perkins, and B. D. Hardesty. 2017. Comparison of marine debris data collected by researchers and citizen scientists: Is citizen science data worth the effort? *Biological Conservation* 208:127–138.

Velez, N., K. R. Nicastro, C. D. McQuaid, and G. I. Zardi. 2020. Small scale habitat effects on anthropogenic litter material and sources in a coastal lagoon system. *Marine Pollution Bulletin* 160:111689.

Wagner, M., C. Scherer, D. Alvarez-Muñoz, N. Brennholt, X. Bourrain, S. Buchinger, E. Fries, C. Grosbois, J. Klasmeier, T. Marti, S. Rodriguez-Mozaz, R. Urbatzka, A. D. Vethaak, M. Winther-Nielsen, and G. Reifferscheid. 2014. Microplastics in freshwater ecosystems: what we know and what we need to know. *Environmental Sciences Europe* 26 (1):12.