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MICROPLASTIC WATER POLLUTION SPANNING THE WILDLAND TO URBAN GRADEINT Of RED BUTTE CREEK, SALT LAKE CITY, UTAH

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Abstract

Anthropogenic activities contribute to the presence and abundance of microplastics in aquatic habitats. Microplastic pollution poses risks to the health of humans, wildlife, and ecosystems, acting as vectors that carry harmful toxins and disease. However, there is relatively little research on the extent to which microplastics pollute Utah's water systems and how anthropogenic activity impacts the presence and distribution of microplastics throughout catchments. The primary aim of this study was to quantify the abundance of microplastic pollution at five locations along Red Butte Creek, a tributary of the Jordan River that flows through the Salt Lake Valley of central Utah, and three impoundments located along the creek's flow-path. Secondary goals were to correlate microplastic pollution to existing Red Butte Creek water quality data and utilize publicly available hydrologic data to estimate microplastic particle loads on the scale of mean daily discharge at each stream study site. Red Butte Creek, a third order stream that originates from the Wasatch Mountains, flows from a relatively undisturbed US Forest Service Research Natural Area (RNA) through the campus of the University of Utah and densely urbanized areas before ultimately discharging into the Jordan River. This geographic setting allows us to observe changes in microplastic abundance along a distinct wildland to urban land-use gradient, as well as compare differences in microplastic abundance between lotic versus lentic parts of the catchment. It was hypothesized that microplastic concentrations would increase moving further down the urbanization gradient, and that microplastics would collect in lentic habitats more than in lotic habitats. Microplastic pollution did not follow the urbanization gradient as expected; however, microplastics were found to be ubiquitous and present at all sites sampled in the Red Butte Creek and follow trends of water quality measurements of particles in the water column. Overall, our findings suggest that Red Butte Creek experiences "urban stream syndrome" in terms of both water quality variables and microplastic pollution.

Introduction

Plastics have increasingly become an inevitable part of everyday life as society has integrated and developed a dependency on plastics. Since World War II, plastic use has been on the rise and has skyrocketed in recent decades (Gangadoo et al., 2020; Geyer et al., 2017). Within the last decade, it is estimated that there were more plastics manufactured and used worldwide than in the entire previous century, with approximately 50% of plastic consumption consisting of disposable and single-use applications (Laskar & Kumar, 2019). According to current estimates, 260 million tons of plastics are consumed per year, accounting for 10% of the total global waste (Gangadoo et al., 2020). With the continual waste stream of single-use plastics in our society, plastics are often not disposed of properly and end up polluting and degrading ecosystems and the environment worldwide. This problem has become ubiquitous and so pervasive that plastics are commonly detected in the oceans, freshwaters, soils and sediment, and the atmosphere (Brahney et al., 2020; Hoellein et al., 2019).

1.1. Plastics and Plastic Degradation

Plastic is a synthetic manufactured material composed of long-chain polymeric molecules that are often extracted and derived from fossil fuels, with chemical additives to alter structural characteristics (Shah et al., 2008). Although plastics are theoretically degradable, degradation occurs at an exceptionally slow rate (Wong et al., 2020). Therefore, plastics are generally not considered to be naturally biodegradable (Webb et al., 2013). Due to the durability and stability of plastic polymers, it can take thousands of years for large macroplastics to break down into smaller microplastics and eventually nanoplastics (Webb et al., 2013). This timeframe is dependent on environmental conditions that impact the effectiveness of the mechanisms for plastic degradation, which also vary based on the plastic type, determined by the character of the polymer backbone (Gangadoo et al., 2020). Despite their resistance to degradation, plastics in natural environments can degrade through four different biotic and abiotic mechanisms, including photodegradation, thermo-oxidative degradation, hydrolytic degradation, and biodegradation (Fig. 1; Gangadoo et al., 2020; Shah et al., 2008; Webb et al., 2013).

Plastic polymers are sensitive to ultraviolet light and radiation, which trigger polymer breakdown via photodegradation (Shah et al., 2008). Once this process has begun, thermo-oxidative degradation more easily follows. Due to high temperatures, polymer integrity deteriorates, and the backbone of the long-chain polymers begin to separate (Shah et al., 2008). The effectiveness of photodegradation and thermo-oxidative degradation depends on environmental conditions as they require significant levels of UV radiation and high heat. Both photodegradation and thermo-oxidative degradation reduce the integrity of the plastic, decreasing the molecular weight and causing it to fracture into smaller pieces (Shah et al., 2008; Webb et al., 2013). Once these particles are small enough and have a low enough molecular weight, the processes of hydrolytic degradation and biodegradation can begin. Depending on the type of plastic, different bacterial and fungal microorganisms metabolize the particles (Shah et al., 2008). These microorganisms convert plastic particles into monomers that are further mineralized and transformed into carbon dioxide or biomolecules (Shah et al., 2008; Webb et al., 2013). The four modes of plastic degradation are time-consuming, and effectiveness is dependent on environmental conditions. As a result, plastics and plastic particles can accumulate in the environment, impacting the health of biota and ecosystem processes.

Plastic pollution is categorized by three size classes of particles. Macroplastics, defined as any plastic greater than 5 mm in size, are most commonly from single-use items including plastic bags, bottles, and commercial packaging (Gangadoo et al., 2020). Microplastics are defined as any plastic polymer in the range of 1μm to 5 mm (Cera et al., 2020). Nanoplastics are intentionally-engineered or fragmented microplastics particles with a size of 1 nm or less, and are typically manufactured, or form as a result of weathering and deterioration of plastics in the environment (Gangadoo et al., 2020; Laskar & Kumar, 2019). As microplastic, and specifically nanoplastics, are so small, they can easily pass through filters and evade filtration through normal water purification processes (Laskar & Kumar, 2019). Both microplastics and nanoplastics end up polluting and contaminating many water sources where they can become embedded in algae and microorganisms that are consumed by higher order aquatic organisms, resulting in trophic transfer of plastics and bioaccumulation within tissues (Gangadoo et al., 2020).

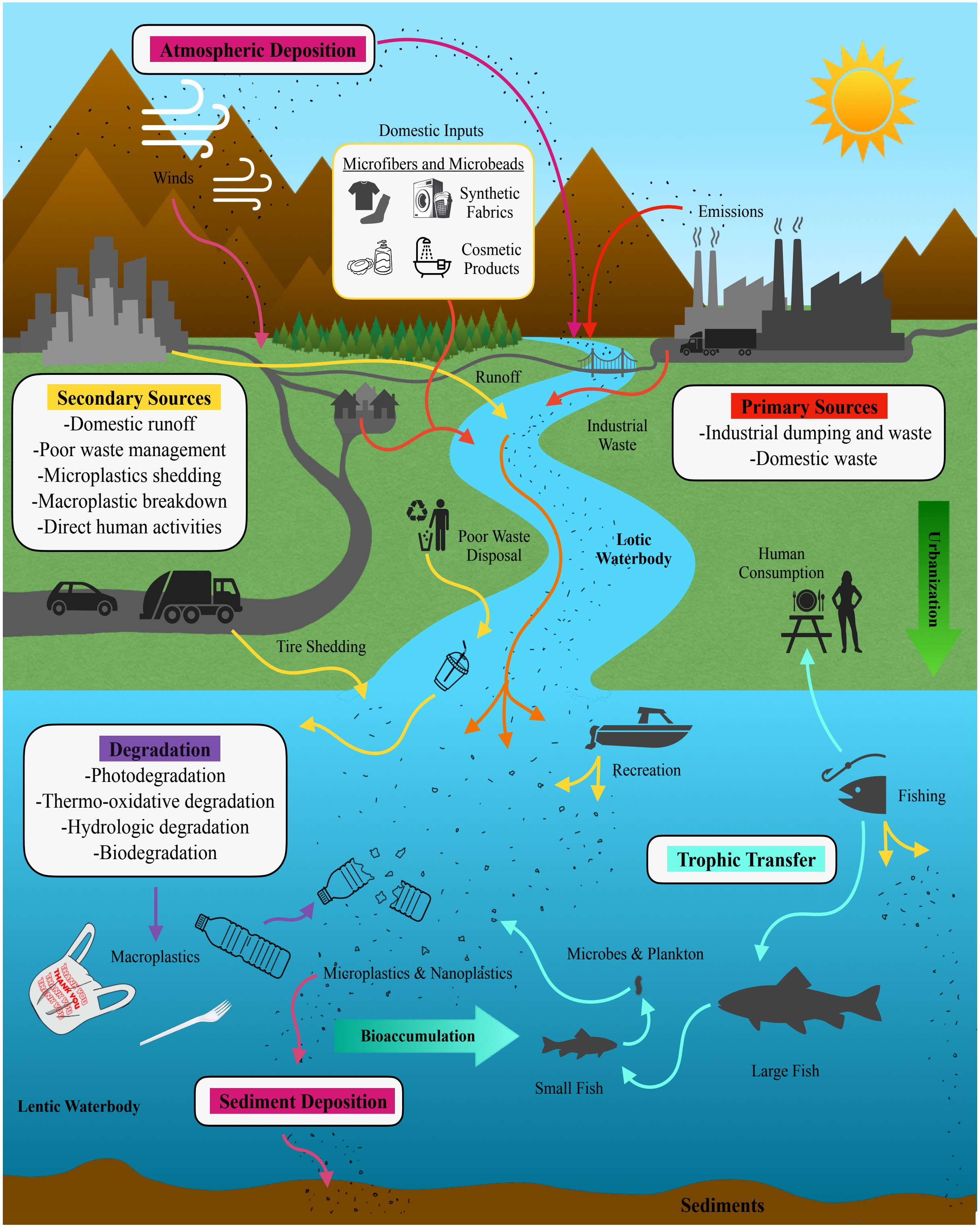

Figure 1. Schematic diagram showing the sources and fate of plastics and microplastics in aquatic environments, and factors contributing to microplastic concentrations (Gangadoo et al., 2020).

1.2. Microplastics in Aquatic Ecosystems

Plastics enter the water column of aquatic ecosystems through the discharge of industrial waste, domestic inputs, runoff, the degradation of large plastics, and atmospheric deposition of plastics via aerosols and precipitation (Fig. 1; Brahney et al., 2020; Yu et al., 2020). These inputs are split into two categories of primary or point pollution and secondary or non-point pollution sources (Dikareva & Simon, 2019). Primary sources of microplastic pollution are the byproduct of industrial production and domestic waste, including microplastic dusts from construction, particulate emissions, and microbeads in cosmetics, personal care products, and laundry detergents (Cera et al., 2020; Gangadoo et al., 2020; Laskar & Kumar, 2019; McCormick et al., 2016). Secondary sources are a result of the breakdown of larger macroplastics that enter aquatic ecosystems through domestic inputs and runoff from land-based degradation due to poor waste management (Laskar & Kumar, 2019).

Although the study of microplastics has primarily focused on the marine environment and microplastics in the ocean, research focused on the effects of microplastic pollution in freshwater ecosystems is growing (Mason, 2019; McCormick et al., 2016; Moore, 2008; Shahul Hamid et al., 2018). In fact, rivers are presumed to be a significant pathway for microplastic deposition in the ocean (Peng et al., 2017). Furthermore, freshwater ecosystems, like rivers, are presumed to have higher concentrations of microplastics than a comparable volume of seawater because less water is available to dilute particle concentrations (McCormick et al., 2016). In freshwater systems, environmental factors as well as anthropogenic influences have been found to impact the abundance and distribution of microplastic pollution within the water column (Yu et al., 2020). These factors include storms, winds, dams, emissions, and direct human activity, which contribute to particle counts and influence particle circulation and spatial variability (Yu et al., 2020).

Human behavior, domestication, and urbanization increase the abundance of microplastic pollution (Shahul Hamid et al., 2018). Increasing consumerism and excessive consumption of plastics result in more plastics in the environment, especially where waste is mismanaged (Gangadoo et al., 2020; Webb et al., 2013). In addition, common household practices can exacerbate microplastic pollution. For example, washing a singular garment in a domestic washing machine can result in over 1,900 microplastic fibers in the residual wastewater, given that many articles of clothes are comprised of synthetic nylon or polyester (Peng et al., 2017). While wastewater treatment plants often remove the majority of these microplastic particles from municipal effluent, substantial quantities remain after treatment because a fraction are small enough to evade capture by filters (McCormick et al., 2016; Peng et al., 2017). The effect of microplastics is thus magnified by the sheer volume of treated wastewater discharged from wastewater treatment facilities into surface waters (Peng et al., 2017). Consequently, sewage and wastewater treatment plants have been identified as a major source of microplastic discharge (McCormick et al., 2016; Wong et al., 2020). Other common activities, such as outdoor recreation and tourism, increase plastic usage that contribute to pollution. Additionally, fishing has been linked to an increased presence of microplastic particles in waterways from net and equipment degradation, loss, and pollution (Shahul Hamid et al., 2018; Webb et al., 2013).

Microplastic concentrations in surface waters vary spatially based on nearby land-use (Watkins et al., 2019) and variation in human population size (Yu et al., 2020). Streams and rivers are major collection points for runoff, and associated microplastic pollutants (Lechner, 2020). For example, streams and rivers adjacent to roadways have increased levels of microplastic abundance due to the shedding of microplastics from tires (Tian et al., 2020). These microplastics can be amassed and carried throughout catchments to be deposited into lentic water bodies (Nel et al., 2018).

The shape, size, and density of microplastics influence the fate of the particles in aquatic ecosystems (Besseling et al., 2017; Gangadoo et al., 2020). Heavier and denser particles tend to have higher deposition rates, which can be augmented by the growth of biofilms (heterogeneous communities of bacteria, algae, and fungi) on the surface of microplastic (Hoellein et al., 2019; Watkins et al., 2019). Consequently, benthic sediments have higher microplastic concentrations relative to the overlying water column (Hoellein et al., 2019). Lighter and low-density particles are more buoyant and easily carried throughout waterbodies and remain in the surface waters of the water column (Hoellein et al., 2019), unless they are intercepted by man-made structures or other obstructions where microplastics are known to accumulate (Watkins et al., 2019).

Water residence time and velocity can interact with physical characteristics of microplastics to control their spatial distribution in aquatic ecosystems. The high residence time of water in lentic environments, such as lakes and reservoirs, leads to concentration and retention of microplastics, promotes particle fragmentation due to weathering, and results in a significant fraction of microplastics in the water column to settle onto benthic sediment (Hoellein et al., 2019; Lechner, 2020; Nel et al., 2018). Lentic water bodies thus act as sinks for microplastics (Nel et al., 2018). However, increased particle abundance and residence time in lentic ecosystems increases the likelihood of ingestion by fish and other aquatic organisms (Lechner, 2020).

1.3. Risks to Human, Wildlife, and Ecosystem Health

Plastics contain a wide variety of chemical additives that alter and change the structural characteristics (Choudhury et al., 2018; Peng et al., 2017). These additives are incorporated during manufacturing and include plasticizers, flame retardants, cross-linking additives, antioxidants and other stabilizers, sensitizers, surfactants, inorganic fillers, and colorants/pigments, many of which are toxic to humans (Choudhury et al., 2018; Peng et al., 2017). Two of the most common and hazardous plasticizers are phthalates and Bisphenol A (BPA), both of which are toxic compounds. Phthalates are an additive used to create flexibility in plastics while BPA is used as a hardener. Absorption of these chemicals due to physical exposure to plastics containing these compounds can be detrimental to human health and childhood development. Phthalates and BPA are endocrine-disrupting and carcinogenic chemicals that have been linked to preterm births, impaired neurodevelopment, type 2 diabetes, breast cancers, and prostate cancers (Kay et al., 2013; Smith et al., 2018; Webb et al., 2013).

Microplastic pollution has a lipophilic nature, lending to bioaccumulation and biomagnification in the tissues of organisms that ingest microplastics (Naik et al., 2019; Webb et al., 2013). Thus, microplastics have become a mechanism to successfully introduce toxic pollutants into the food web through trophic transfer (Watkins et al., 2019), including chemicals such as DDT and hexachlorobenzene (Laskar & Kumar, 2019). These chemicals are toxic to aquatic organisms and humans. Consumption of microplastics has been linked to changes in human chromosomes associated with infertility, obesity, and cancer (Laskar & Kumar, 2019). Biofilm formation increases the probability of consumption by aquatic biota, exacerbating trophic transfer potential (McCormick et al., 2016). As these particles and resulting toxins end up in many different aquatic species, there are many ways in which trophic transfer can occur, ultimately posing a long-term risk to human health (Webb et al., 2013).

Plastics in all shapes and sizes have become a ubiquitous surface for microbial colonization and vector transporting toxins and disease (Rummel et al., 2017). Upon introduction of microplastics into an aquatic environment, within 1-2 weeks distinct biofilms will form on the particles (Miao et al., 2019). Microbial assemblages formed on microplastics are different from those found on natural sources of carbon in freshwaters (Hoellein et al., 2019; McCormick et al., 2016). The formation of these unique biofilms alters the physical characteristics of the plastic and creates a surface that is more suitable for the absorption of toxic chemicals and heavy metals, amplifying bioaccumulation and biomagnification (Shahul Hamid et al., 2018). Biofilms play an important role in facilitating plastic degradation, but also in releasing toxic contaminants in the environment (Rummel et al., 2017). Due to the nature of these plastics to absorb and transfer toxic pollutants and their persistence in the environment, plastics have been classified as a “hazardous” material in some instances (Gangadoo et al., 2020).

1.4. Existing Plastic and Microplastic Legislation in the United States

In 2015, the Microbead-Free Waters Act was signed into law by President Obama (Kettenmann, 2016). Microbeads are small plastic particles that fall into the category of microplastics from a primary source. In the cosmetics industry, microbeads are often used as an exfoliant in products such as face and body cleansers, scrubs, toothpaste, and other personal hygiene products (Kettenmann, 2016). This law prohibits the manufacturing and production of microbeads for cosmetic purposes that will be washed off and inevitably be rinsed down the drain, and in over-the-counter drugs containing microplastics (Kettenmann, 2016). However, this policy does not ban microbeads in products that are not intended to be directly washed down the drain or for other purposes such as lotions and deodorants (Kettenmann, 2016). Although the microbead ban is a step in the right direction towards decreasing microplastic water pollution, there are still many primary sources of microplastics, not to mention secondary sources of microplastics that pollute our water systems worldwide.

Outside of the 2015 Microbead ban in the United States, there has been no other comprehensive policy to address plastic pollution, and legislation has been left up to direct democracy and individual state, county, and/or city discretion. With this bottom-up approach, policies have focused on addressing single-use consumer plastics including plastic bags and straws (O’Neill, 2019). The bottom-up approach uses plastic bans that charge consumers for disposable plastic products. This places the financial responsibility and choice on the consumer, rather than addressing the root of the problem, which is the harmful chemicals, availability of plastics, and excessive production. Unless regulations require otherwise, companies will continue to produce virgin plastics and excessively package products in plastics.

Aim

Situated in the Wasatch Mountains, Red Butte Creek is a tributary of the Jordan River that faces increasing anthropogenic pressures and urbanization impacts as it flows through the Salt Lake Valley of central Utah (Fig. 2b). Originating from a US Forest Service Research Natural Area (RNA), this third-order creek runs through a relatively undisturbed natural area before passing through the campus of the University of Utah and increasingly urban landscapes of Salt Lake City, until ultimately discharging into the Jordan River (Gabor et al., 2017). This geographic setting allows us to observe changes in microplastic abundance and water quality along the wildland to urban land-use gradient, as well as differences in lotic versus lentic parts of the creek.

Due to anthropogenic and urbanization influence, the Jordan River is listed as impaired by the EPA due to the high levels of toxic organic and inorganic pollutants, including low dissolved solids, high suspended sediments, and *E. coli* contaminating the waterway (Follstad Shah et al., 2019; SWCA Environmental Consultants, 2013). Causes of impairment are a result of population size, growth rate, contaminated wastewater effluent from three different water reclamation facilities, groundwater discharge from polluted aquifers, discharge from complex systems of canals, storm drain inputs, and seven tributaries that collect pollution from the Salt Lake Valley, and drain into the Jordan River (Follstad Shah et al., 2019; SWCA Environmental Consultants, 2013).

Microplastic pollution has yet to be studied in the context of the Jordan River and the Red Butte Creek. The Red Butte Creek discharges into the Jordan River and the creek and adjacent impoundments are popular recreation spots for people, often with pets. Additionally, the Red Butte Reservoir is used as a rearing location for fish distributed to streams and rivers around the state. Therefore, it is important to know how microplastics are impacting the ecosystem. The Jordan River is used by humans for various purposes, including recreational boating and fishing. One popular fishing spot is located at the confluence of Red Butte Creek. For these reasons, it is essential to know the influence of microplastics from the stream to the mainstem Jordan River. The primary aim of this study was to quantify the abundance of microplastic pollution at several sites along Red Butte Creek, Utah, USA, and three impoundments located along the creek's flow-path (Fig. 2, Table 1). Secondary goals were to correlate microplastic pollution with existing Red Butte Creek water quality data and utilize publicly available hydrologic data to estimate microplastic particle loads on the scale of mean daily discharge at each stream study site. It was hypothesized that (a) microplastics will be elevated at more urban sites in the catchment and will be more concentrated in the reservoirs and ponds relative to stream sites; and (b) increased microplastic pollution levels will be correlated with indices of poor water quality.

Methods

2.1. Site description

This study was conducted at eight sites along Red Butte Creek, a third-order stream running through Salt Lake City, Utah (Fig. 2). Samples were collected in October 2020 at five stream sites (including one storm drain), one reservoir, and two ponds. Study site names, locations, and site characteristics are summarized in Table 1. These sites were classified as lotic or lentic water bodies and are listed in order from least anthropogenic/urban influence (Red Butte Canyon RNA) to most anthropogenic/urban influence (Jordan River Confluence). Generally, urbanization increases from East to West. At lotic sites, samples were collected downstream of hydrologic gages managed by either the U.S. Geological Survey or the Wasatch Environmental Observatory (WEO). Sites managed by WEO were also equipped with water quality sensors (YSI Exo2 sondes). At lentic sites, samples were collected as close to the outlet as possible, where access was available.

The stream site in the Red Butte Canyon RNA was the most upstream, least urbanized sampling location. It drains to the Red Butte Canyon Reservoir, situated 0.46 km downstream. The stream flows from the outlet of the reservoir to the second stream site located at the boundary between the RNA and the Red Butte Garden arboretum. The creek is then diverted into a pond within the garden (Red Butte Garden Pond), which has a two-tiered structure. The larger tier resides above the smaller tier and the two are connected by a small waterfall. The samples at this site were taken from the smaller tier adjacent to the outlet diverting water back to Red Butte Creek. The stream then flows past the University of Utah campus. The third stream site was located at the western border of campus, adjacent to the Dentistry Building. The fourth stream site was situated at 1300 East in Salt Lake City, just downstream of a restored portion of the creek that is part of the popular Miller Park complex. At the 1300 East stream site, a pool of water surrounded the hydrologic gage where the water discharges from Miller Park through a culvert beneath a road crossing. The sample at Miller park was taken just below this pool where the water had greater velocity. Red Butte Creek flows into a buried culvert at 1100 South and resurfaces at Liberty Park Pond. This culvert also collects flow from two additional tributaries, Parley's Creek and Emigration Canyon. At Liberty Park, pumps circulate water between the inlet and outlet of the pond, where it is again is diverted to a buried culvert until flow from the three creeks discharge into the Jordan River (Fig. 2). Samples of water from Jordan River were collected slightly downstream of the three creek confluence because construction limited access to the site. Here, a short length of the culvert has been unburied and rehabilitated in a process called 'daylighting'. Therefore, the Jordan River Confluence is not actually within the Red Butte Creek catchment.

2.2. Sampling Procedure

2.2.1. Microplastic Sample Collection and Quantification

A total of three microplastic samples were collected on ashed and pre-weighed 47mm Whatman glass microfiber filters (1.2 µm nominal pore size) at each site using a drill-pump. Equipment was rinsed with stream water prior to sample collection, downstream of the collection point. Up to five-liters of water were filtered, unless lesser volumes caused the filter to clog. Filtered water was collected in a bucket to measure water volume post-filtration using a 1-L graduated cylinder and then discarded into the water body where it was collected after the volume was recorded. Filters were stored in aluminum foil packets and immediately placed into a cooler on ice for transport to the laboratory where they were dried in their foil packets in a drying oven set at 60 °C for at least 24 hours.

Once dry, filters were removed from the drying oven and examined under a dissection microscope at 40x magnification. Algae and sediment were very abundant and adhered to the filter, so a subsampling approach was used for identification. For each sample, three smaller random subsamples (a total of 6.6 % of the filter area) were punched out using a metal straw, then examined under the microscope, and the number of microplastic particles were recorded. Microplastics were identified using the guide to microplastic identification described by Chen et al., (2020). The number of particles present in the three subsamples was scaled up in proportion to the area of the whole filter and normalized to one liter of water filtered to determine microplastic abundance (particles per liter) at each site.

2.2.2 Water Quality Measures and Hydrology Data

Water quality analyses were conducted using an existing dataset compiled over three years of sampling (2014, 2015, and 2016) at the respective lotic sites (iUTAH, 2016). This dataset included concentrations (all mg/L) of total dissolved solids (TSS), dissolved organic carbon (DOC), total nitrogen (TN), and chloride (Cl^-) obtained from grab samples of water collected on a biweekly basis by a technician associated with the iUTAH program (iUTAH EPSCoR, n.d.). These samples were analyzed at the Aquatic Biochemistry Laboratory at Utah State University following standard protocols for each constituent. Data were isolated for the month of October in each and used for further statistical analysis because this month corresponded to the dates when microplastic samples were collected in 2020. Discharge data were obtained from hydrologic gages that record stage height at 15-minute intervals and translated to discharge volume using established rating curves. Discharge data were downloaded for the day microplastics were sampled at the respective lotic study sites from repositories accessible to the general public (Salt Lake County, 2020; University of Utah--Wasatch Environmental Observatory, 2021)

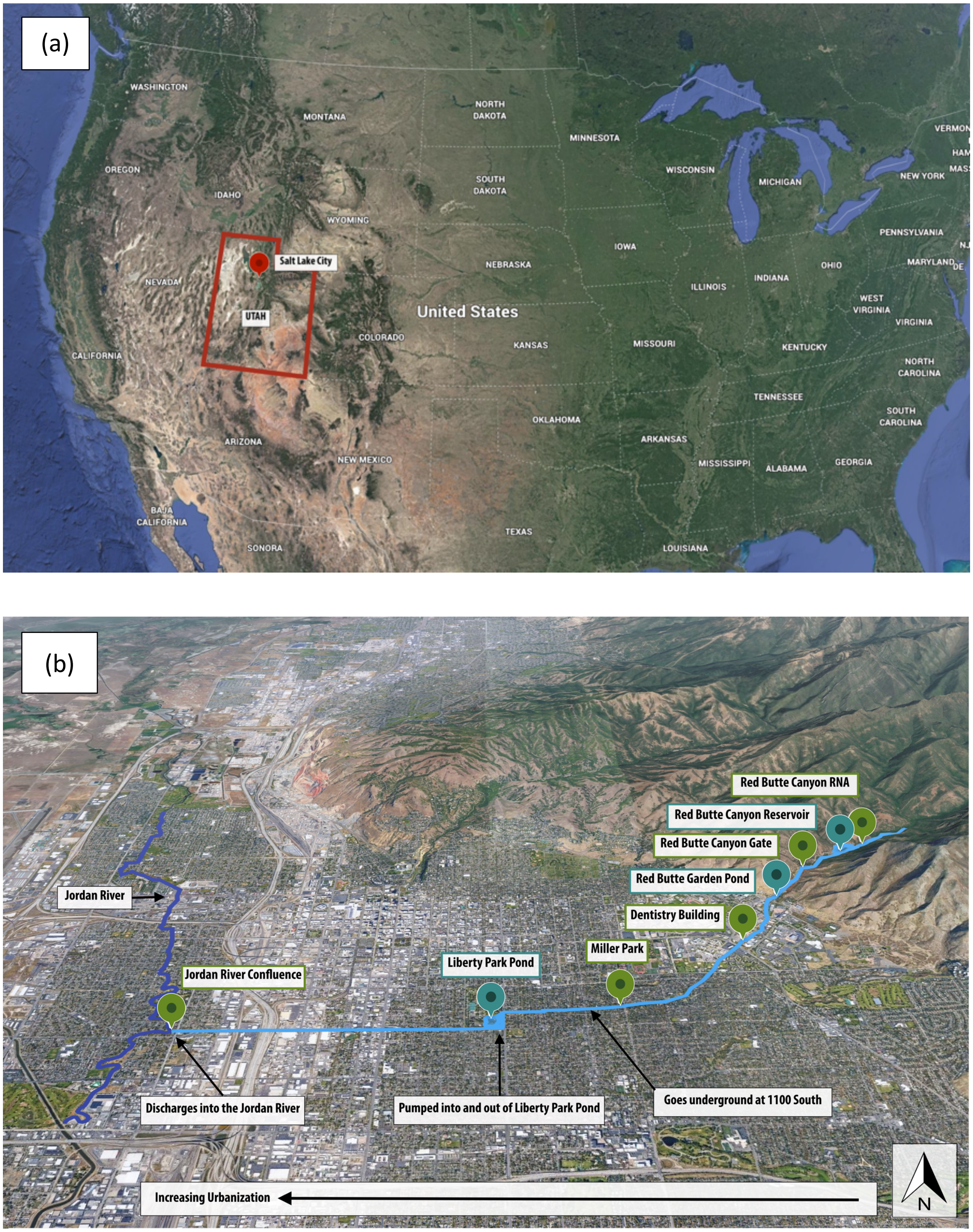

Figure 2. Location of Salt Lake City, Utah (a) and sample site locations within the Red Butte Creek catchment (b). Green symbols denote lotic sites. Turquoise symbols denote lentic sites. The urbanization gradient increases from East to West following Red Butte Creek. Site characteristics and information can be found in Table 1.

Table 1. Summary of study site names, geographic coordinates, habitat type, distance from headwater source, and elevation. Site names correspond to those shown in Fig. 2.

	Site Name and ID	Latitude, Longitude	Habitat Type	Distance Along Stream (km)	Elevation (m)
1.	Red Butte Canyon RNA	40.779602, -111.806669	Lotic	4.76	1645
2.	Red Butte Reservoir	40.778576, -111.809903	Lentic	5.22	1636
3.	Red Butte Canyon Gate	40.774228, -111.817025	Lotic	6.02	1582
4.	Red Butte Garden Pond	40.767134, -111.825516	Lentic	6.94	1525
5.	Dentistry Building	40.757225, -111.833722	Lotic	8.31	1449
6.	Miller Park	40.744995, -111.854441	Lotic	10.72	1353
7.	Liberty Park Pond	40.743486, -111.872984	Lentic	12.27	1299
8.	Jordan River Confluence	40.7416, -111.9176	Lotic	16.29	1289

2.3 Data and Statistical Analysis

Data were collated and analyzed using Excel and RStudio running version 1.3.1093 of R. To determine the distribution of the data, density plots and descriptive statistics were calculated, and a Shapiro-Wilk test was run to see if the data was normally distributed (p > 0.05, data is normally distributed). Where the data were abnormally distributed, further analyses were conducted using non-parametric statistical tests in RStudio.

To explore differences in microplastic distribution, abundance in total microplastics among sites, and differences among habitat types, statistical analyses to test for significance were conducted using base functions and the PCMR package in R. One-way analysis of variance (ANOVA) was used on normally distributed subsets of data. Kruskal-Wallis analyses were completed for abnormally distributed subsets of data. Post hoc comparisons were conducted using the Bonferroni (abnormal distribution) and Tukey (normal distribution) approach, to adjust for the number of comparisons. Due to a known sampling error resulting in a broken filter, the sample size (n = 2) of data obtained from Jordan River Confluence prevented the calculation of the standard error of the mean. The remaining two data points had elevated microplastic counts which skewed the distribution of observations across all sites. For these reasons, data from the Jordan River Confluence were excluded from statistical analysis. Additionally, the samples at the Jordan River Confluence were taken from within the Jordan River, not the Red Butte Catchment but downstream of where Red Butte Creek discharges into the Jordan River.

A correlation matrix was created for lotic sites to examine the strength and direction of correlations between water quality variables and microplastic abundance, Pearson *r*-values were calculated using the PSYCH package in R. However, this analysis could only be conducted using mean values for microplastic counts and water quality parameters, due to an uneven number of replicates across factors and the fact that water quality measurements were collected over a number of years. Sample sizes ranged from n=2 to n=6 among the different variables and sites. The Jordan River Confluence was included in this analysis using the average value for two samples collected at this site. This analysis was based on an assumption that water quality variables are relatively similar within the same month, from year to year. Water quality measurements were made within Red Butte Creek just upstream of the confluence with the Jordan River while microplastic samples were taken slightly downstream of the confluence due to construction blocking access to the site.

Discharge data were used to scale mean values of microplastic counts per liter to daily loads of microplastics at each lotic study site. The average daily discharge was calculated for each site on the respective date microplastic samples were collected. Discharge data units were converted from cubic feet per second to liters per second (L/s) and then multiplied by the mean number of microplastic particles per liter at the corresponding site to yield microplastics particle count per second. The resulting value was multiplied by the number of seconds per day (86400) to provide an estimate of microplastic particle load per day. The Dentistry Building was excluded from this analysis as hydrological data for this site had not undergone quality control review to assure accuracy. The Jordan River Confluence was included in this analysis, as average microplastics per liter was used for this calculation. These resulting values do not represent a definitive count of daily particle loads as the calculations are based on a limited number of observations and rest on two assumptions: 1) both discharge and microplastic pollution levels are constant, and 2) microplastic loads are constant and uniformly distributed throughout the water column. However, this estimate has utility, as it provides context to the scale of the issue and yields an approximation of microplastic loads on the date sampled.

Results

3.1. Microplastic Abundance and Distribution throughout the Catchment

3.1.1 Microplastics Along the Wildland to Urban Gradient

Table 2. Descriptive statistics for total microplastic pollution at each site within the Red Butte Creek catchment, Salt Lake City, Utah. *Indicates lentic sites.

Site Name	n	Min	Max	Mean	Standard Error
Red Butte Canyon RNA	3	4.9	12.0	7.6	2.2
Red Butte Canyon Reservoir*	3	6.0	22.4	13.1	4.9
Red Butte Canyon Gate	3	6.0	34.3	16.4	9.0
Red Butte Garden Pond*	3	8.6	20.0	12.7	3.7
Dentistry Building	3	9.0	22.3	14.4	4.1
Miller Park	3	3.0	9.4	6.1	1.9
Liberty Park Pond*	3	24.2	37.6	30.1	3.9
Jordan River Confluence	2	90.2	90.2	90.2	0.0

Microplastics were found in every sample collected within the Red Butte Creek catchment and from the Jordan River. Microplastic concentrations were higher at the most urbanized sites at the terminus of the catchment (Jordan River, Liberty Park) relative to upland sites (Fig. 3a). Microplastic counts varied at upland lotic sites yet were of a similar magnitude at (~12 particles/L) at upland lentic sites. Microplastic abundance ranged from 3 to 90 artificial particles per 1-liter water sample throughout all sites (Table 2). On average, concentrations ranged from 6.1 ± 1.9 to 90.2 ± 0 (30.1 ± 3.9 in the Red Butte Creek) particles per liter (Fig. 3, Table 2). The Jordan River Confluence had the highest levels of microplastics present in the surface water, with an average of 90.2 ($n = 2$) particles per liter (Fig. 3a,b, Table 2). Of the lentic sites, Liberty Park Pond had the highest mean microplastic concentration with 30.1 ± 3.9 particles per liter (Fig. 3a,c, Table 2). The site with the lowest level of microplastic pollution was Miller Park, with an average of 6.1 ± 1.9 particles per liter (Fig. 3a,b, Table 2).

The magnitude of change in microplastic abundance among sites is striking. Microplastic concentration increased 71% from the Red Butte Canyon RNA (the least urbanized site) to the Red Butte Canyon Reservoir. Particle concentration more than doubled between the RNA and the next lotic site (Red Butte Canyon Gate), with a 114% increase. The abundance of microplastics remained relatively constant from Red Butte Canyon Gate to Miller Park (the last lotic site in the catchment), where average particle abundance decreases by 57% as compared to the mean concentration observed at the Dentistry Building. From Miller Park to Liberty Park Pond, average microplastic presence then increased by 110%. The total mean microplastic abundance across both lentic and lotic sites within the Red Butte Creek catchment was 14.3 ± 2.2 particles per liter. In comparison, microplastic abundance was 531% greater in the Jordan River.

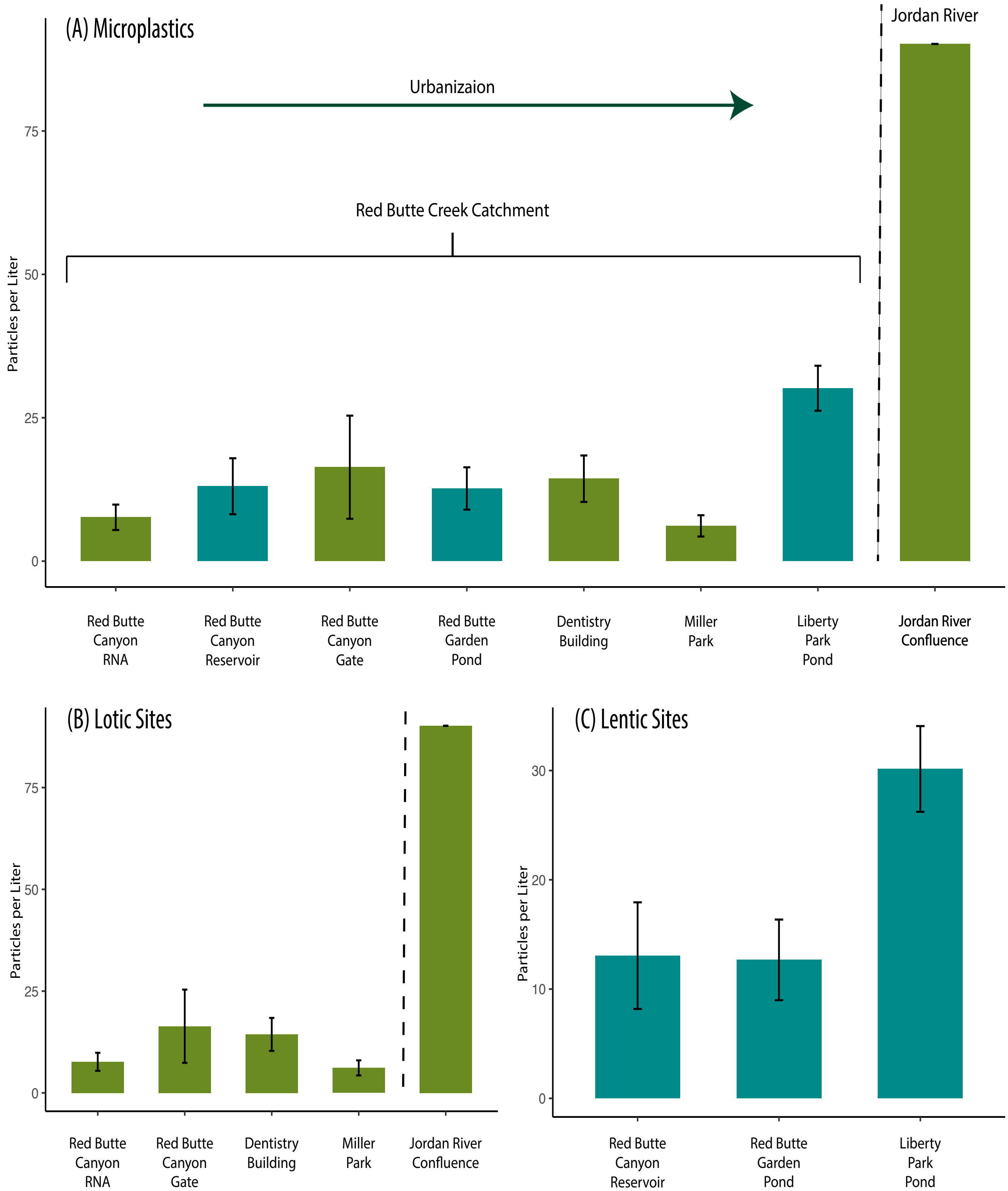

Figure 3. (A) Average number of microplastics per one-liter water sample at eight study sites along the Red Butte Creek, ending at the Jordan River, Salt Lake City, Utah, including both lotic and lentic habitat types, (B) Lotic (flowing) sites along Red Butte Creek, including the Jordan River, downstream of the confluence, (C) Lentic (still) sites. Sites are listed following the urbanization gradient from left to right. Green denotes lotic sites; turquoise denotes lentic sites. Error bars indicate standard error.

3.1.2 Habitat Type: Lotic versus Lentic Sites.

On average, lotic sites had 67% more particles per liter than lentic sites overall, with 11.1 ± 2.6 particles per liter at lotic sites compared to 18.6 ± 3.6 particles per liter at lentic sites (Fig. 3, Table 3). However, statistical analysis revealed that microplastic abundance was not significantly different (p = 0.08, Table 4) across lotic and lentic locations within the Red Butte Creek catchment (excluding the Jordan River Confluence). Similarly, a Kruskal-Wallis test indicated no differences in microplastic concentration between lotic sites (p = 0.39). In contrast, an ANOVA indicated that microplastic concentration significantly varied among lentic sites (p = 0.04) (Table 4). However, post-hoc tests did not strongly support differences between any two comparisons (Table 5).

Table 3. Descriptive statistics for total microplastic pollution at all sites within the Red Butte Creek and at lotic and lentic sites.

Descriptive Statistics	All Sites (n=21)	Lotic Sites (n=12)	Lentic Sites (n=9)
Mean	14.3	11.1	18.6
Standard Error	2.2	2.6	3.6
Minimum	3.0	3.0	6.0
Maximum	37.6	34.3	37.6

Table 1. p-values for differences in microplastic abundance at lotic and lentic sites. *Indicates normal distribution.

Habitat Type	p-value
Lotic	0.39
Lentic	0.04*
Total:	0.08

Table 5. Tukey values for microplastic abundance comparisons between lentic sites.

Sample Sites	Red Butte Garden Pond	Liberty Park Pond
Red Butte Canyon Reservoir	1.00	0.06
Red Butte Garden Pond		0.06

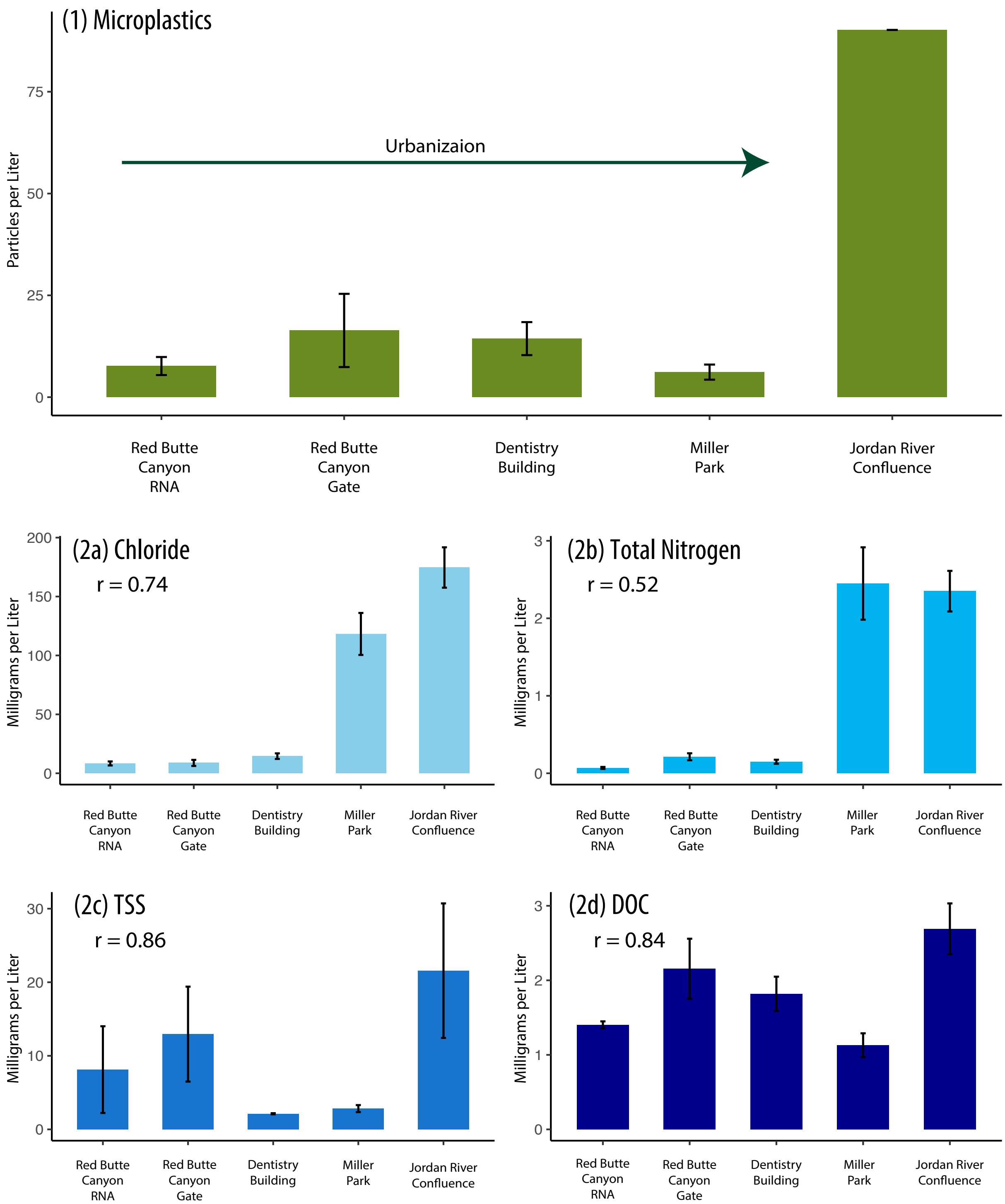

Figure 4. Concentrations of (1) microplastics and (2a-d) four indices of water quality at lotic sites along Red Butte Creek, Salt Lake City, Utah. (1) Average microplastic particle concentrations, (2a) Chloride, (2b) Total Nitrogen, (2c) Total Suspended Solids (TSS), and (2d) Dissolved Organic Carbon (DOC). Pearson correlation coefficients (*r*-values) are displayed on each water quality graph indicating the strength of the correlation to microplastic concentration. Sites are listed following the urbanization gradient from left to right. Error bars indicate standard error.

3.2 Microplastic Abundance and Water Quality

Microplastic counts were positively correlated with all water quality metrics (Fig. 4). Microplastic pollution trends were most closely correlated to the variables that represent the transport of particles within the water column, such as TSS and DOC. Average microplastic particles were most positively correlated to average TSS ($r = 0.86$), followed closely by the correlation with average DOC ($r = 0.84$; Fig. 4.1, 4.2c, & 4.2d). Microplastic pollution concentrations were less positively correlated to TN concentrations (r = 0.54) and Cl^- (r = 0.74) concentrations (Fig. 4.1, 4.2a & 4.2b).

3.3 Catchment Hydrology and Microplastics

Water discharge varied slightly, within less than 5 liters, throughout the day along sites in the Red Butte Creek. Discharge in the Jordan River was more variable. Discharge increased with distance along the land use gradient (Table 6). As average microplastic particle concentrations

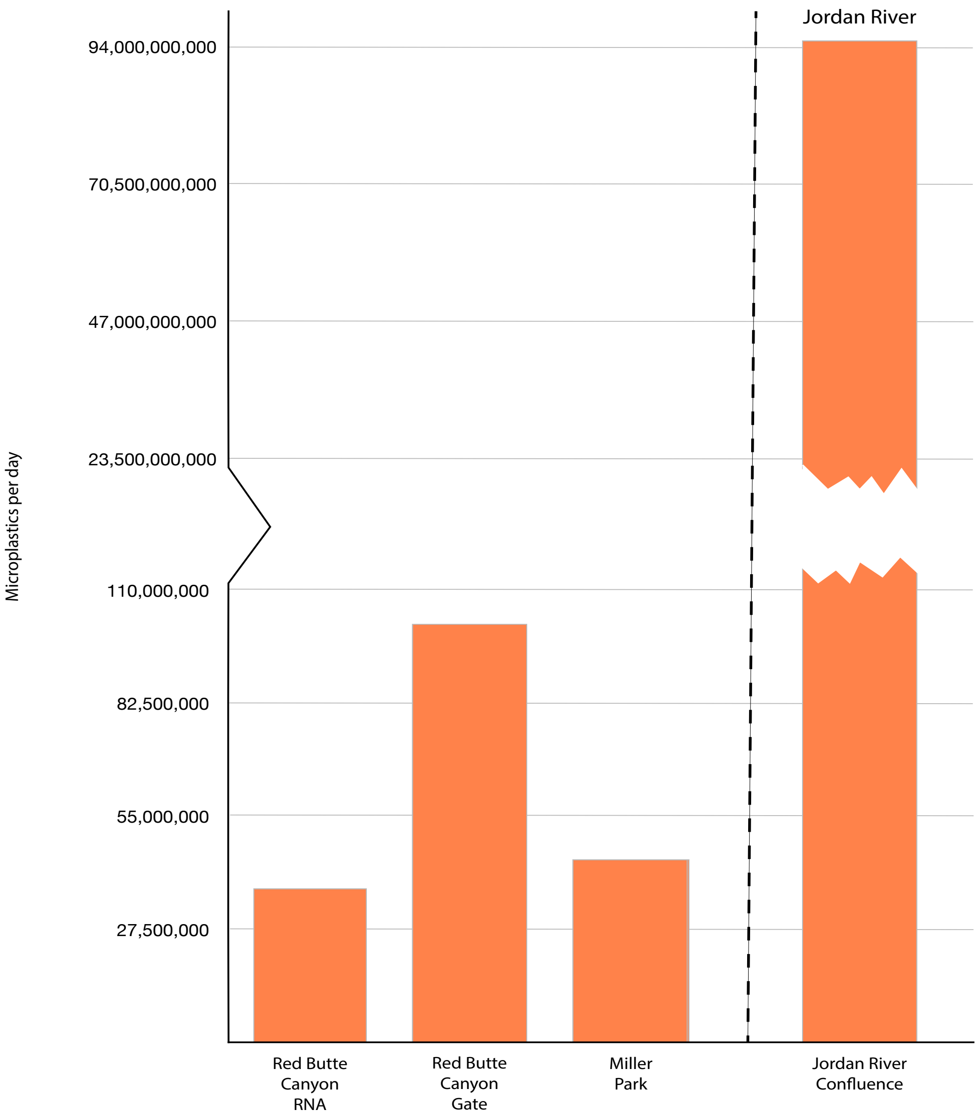

Figure 5. Microplastic load (count/day) at lotic sites, excluding the Dentistry Building, for the date microplastic samples were collected at each study site.

varied between the different sites, microplastic concentrations per day fluctuated between sites rather than uniformly increasing with change in discharge. The Red Butte Creek RNA site had the lowest load of microplastics per day with approximately 3.8 x 10^7 particles flowing through this site on the respective date sampled (Fig. 5, Table 6). With approximately 9.3 x 10^{10} particles on the day sampled, the Jordan River Confluence had the highest load of microplastics per day (Fig. 5, Table 6). This is an increase equal to three orders of magnitude relative to the loads observed at the Red Butte Creek Gate (approximately 1.0 x 10^8 microplastics per day), the site with the highest load of microplastics on the date sampled within Red Butte Creek proper (Fig. 5, Table 6).

Table 6. Average daily stream discharge (L/s), microplastic abundance (count/L), and total microplastic load (count/day) at lotic sites. Dentistry Building is excluded due to missing discharge data.

Site Name	**Average Daily Discharge (L/s)**	**Microplastics per Liter** (± SE)	**Microplastics per day**
Red Butte Creek RNA	22.7	7.6 (± 2.2)	3.6 x 10^7
Red Butte Creek Gate	28.8	16.4 (± 9.0)	1.0 x 10^8
Miller Park	33.5	6.1 (±1.9)	4.5 x 10^7
Jordan River Confluence	4783.7	90.2 (± 0.0)	9.3 x 10^{10}

Discussion

Microplastic pollution is becoming more prevalent in our environment. Although research on this subject is increasing, the focus has primarily been on marine environments rather than freshwater ecosystems (Hoellein et al., 2019). Freshwater ecosystems are certainly impacted by microplastics, as human impacts and activity influence microplastic pollution, demonstrated by elevated particle counts in surface waters of densely urbanized areas (Mason, 2019; McCormick et al., 2016; Yu et al., 2020). This study sought to understand spatial patterns in microplastic abundance along a river flowing from pristine headwaters through a densely urbanized lower catchment of Red Butte Creek in Salt Lake City, Utah. It was hypothesized that, if urban land use is an important driver of microplastics in streams, microplastic particle abundance would increase with urbanization. Furthermore, it was hypothesized that if lentic sites serve as sinks of microplastics, microplastics would be more abundant in stream-connected ponds and reservoirs than lotic sites along a lotic stream transect. Microplastics were present at all sites sampled along the Red Butte Creek, Salt Lake City, Utah. Data analysis revealed that there was no significant difference in microplastic concentrations among study sites along the Red Butte Creek. Mean microplastic concentrations in lotic and lentic habitats also were similar. However, microplastic concentrations were most elevated in the low-lying, densely urbanized sites. Furthermore, microplastic concentrations were positively correlated with long-term average TN, Cl^-, DOC and TSS concentrations at each site.

4.1 Urban Stream Syndrome

"Land use in all forms affects water quality" (Leopold, 1968). Urban streams and tributaries acting to drain increasingly urbanized catchments often display ecological degradation due to land use altering the natural processes and water chemistry (Walsh et al., 2005). Symptoms of the urban stream syndrome include "flashier hydrography, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species" in addition to inconsistent responses in suspended solids (Walsh et al., 2005). Not all streams and waterways react in the same way to urbanization; therefore, the degree to which each stream and waterway experiences these symptoms is variable and not confined to specific concentrations. Rather, symptoms of the urban stream syndrome are examined in the context of change in the observed symptom of the specific waterway (Walsh et al., 2005). Red Butte Creek is characterized by many of the features associated with the urban stream syndrome, including a flashier hydrograph and elevated nutrient and salt concentrations in more urban areas (Gabor et al., 2017; Hall et al., 2016).

The distribution of microplastic pollution within the Red Butte Creek fluctuates from site to site in a non-uniform manner. There was no significant difference in microplastic abundance among the sites or habitat types overall (Table 4). This could potentially be attributed to the small sample size of the study, the ubiquity of plastics in all environments (even the relatively pristine Red Butte Creek RNA), or the unique fluvial geomorphology impacting the hydrology of the stream and driving microplastic distribution. There are many complex mechanisms and hydrological processes that contribute to the abundance and distribution of microplastics in the water column. In reality, microplastic pollution is not just a symptom of urbanization as urban land use is not the only indicator of urban water quality impacts and thus microplastics abundance (Gabor et al., 2017).

Given the unique hydrology and geomorphology, direct measurements of total dissolved nitrogen, chloride, total suspended solids, and dissolved organic carbon give a better picture of how the streamwater chemistry changes throughout the urban environment (Leopold, 1968; Walsh et al., 2005). Therefore, multiple variables must be considered when evaluating microplastic abundance throughout the catchment. Specifically, the percent change in microplastic concentrations among sites, despite the lack of statistical significance, revealed interesting patterns that may be related to localized differences in geomorphology and water residence time. Although some changes were unexpected, overall trends suggest the wildland to urban land use gradient is evident. Hence, altered microplastic concentrations in Red Butte Creek may represent another feature of the urban stream syndrome.

4.1.1 Microplastic Abundance and Distribution Throughout the Catchment

Starting at the top of the catchment in the Red Butte Canyon RNA, Red Butte Creek experiences very little direct anthropogenic influence, as access to the RNA is restricted to those with a permit and is mostly reserved for research purposes. While the first sampling site did have microplastics present, they existed in relatively low amounts compared to the concentrations at the bottom of the catchment and the Jordan River. Mean concentration at this site (7.6 particles per liter) is comparable to the average 5.5 particles per liter found in tap water (Table 2; Mason, 2019). The presence of microplastics in the RNA suggests wet or dry deposition of particles from the atmosphere (Besseling et al., 2017; Brahney et al., 2020; Wong et al., 2020). This finding is supported by the work of Brahney et al. (2020) who found microplastic atmospheric deposition rates averaged 132 particles per square meter per day across the intermountain west, including in western U.S. protected lands. From this first lotic site (Red Butte Canyon RNA) to the second lotic site within the catchment (Red Butte Canyon Gate) anthropogenic activity increases, concomitant with a 114% increase in microplastic concentrations. The Red Butte Canyon Gate lies right outside of the RNA. This area is open to the public for recreational purposes including hiking, biking, and walking dogs.

Although the Red Butte Canyon Reservoir lies within the RNA, it had microplastic concentrations more similar to the Gate site rather than the RNA lotic site (Fig. 3A, Table 2). Here, lentic water body processes must be considered. Reservoirs are known to have elevated counts of microplastics, as they concentrate and trap pollutants (Lechner, 2020; Nel et al., 2018). This finding is consistent with observations within the RNA, as microplastic concentrations are lower in the waters above the reservoir, yet sources of microplastic inputs are similar between the two sites. Additionally, reservoirs are formed by dams, human-made structures that can aggregate and contribute to particles in the water column (Watkins et al., 2019).

Past the Gate site, Red Butte Creek flows into two connected ponds within Red Butte Garden. At this site, we see slightly decreased microplastic concentrations from the Red Butte Canyon Gate (Fig. 3A, Table 2). Although this is a lentic water body and would be expected to have increased concentrations of microplastic pollution from the lotic site above, it is likely the larger pond that resides above the sampling location that displays this characteristic, trapping the particles and decreasing microplastic input in the lower pond where the samples were taken (Lechner, 2020). However, these results are still surprising given the number of people visiting the garden and pond. However, it is possible that the regular management and pollution control in the garden decreases plastic and microplastic sources from entering the pond.

After exiting the Red Butte Garden ponds, the creek flows through the University of Utah campus. Microplastic concentrations increased again at the Dentistry Building, situated at the downstream boundary of campus. Miller Park is the last and most urbanized lotic site within the Red Butte Creek catchment. However, despite Miller Park's location within the catchment and the increasing anthropogenic pressures, this site had the lowest concentrations of microplastic pollution of all eight sampling locations (Fig. 3A, Table 2). The low concentrations at this site are possibly due to the natural circulation of particles and hydrology within this site. These samples were taken from a portion of the stream with high velocity. However, there was a pool of still water just upstream of the sampling location. The low levels of particles present in the Miller Park samples may have been due to the pool collecting the water and concentrating particles, potentially further depositing them in the stream sediments (Hoellein et al., 2019).

After exiting Miller Park, Red Butte Creek goes underground, via a culvert parallel to 1300 South, until it is piped into Liberty Park Pond. Liberty Park Pond was the final sampling site within the Red Butte Creek catchment and had the highest concentration of microplastics amongst all study sites (Fig. 3A, Table 2). This result was expected because Liberty Park receives water from two other streams and is the most urbanized site, with the high recreational use and pond habitats concentrate and trap microplastic particle pollution (Lechner, 2020).

Exiting Liberty Park Pond, Red Butte Creek is re-diverted underground until it is fed into the Jordan River at the confluence. While the Jordan River Confluence was not included in statistical analyses due to a limited sample size, this site displays a large increase (531% increase) in microplastic particle abundance, from an average of 30.1 (± 3.9) particles per liter at Liberty Park Pond to 90.2 (± 0) particles per liter (Fig. 3A, Table 2). Again, elevated microplastic pollution was expected. The Jordan River is a compromised waterbody that is listed as impaired by the EPA due to high levels of toxic organic and inorganic contaminants and pollutants (Follstad Shah et al., 2019; SWCA Environmental Consultants, 2013). As microplastics are a form of pollution, it would be expected that the Jordan River carries a higher load of microplastic particles, especially when compared to Red Butte Creek.

The Jordan River is fed by seven tributaries throughout the Wasatch Mountains, including Red Butte Creek. Not only are the canyons and tributaries popular places for recreation, but the waterways subsequently flow through the dense urbanization of Salt Lake City, collecting microplastics that will inevitably be deposited into the Jordan River. Additionally, the Jordan River receives water inputs from storm drains, canal inputs, and wastewater treatment facilities, further contributing to microplastic loads (Follstad Shah et al., 2019). There are three wastewater treatment plants that discharge into the Jordan River above the sampling location (Follstad Shah et al., 2019). Although wastewater treatment plants have a removal rate of approximately 95%, the volume of water processed at these facilities results in a significant amount of microplastic discharge into the environment (Peng et al., 2017). One study found that an average of 8.6 (±2.5) microplastic particles per liter managed to evade filtration, totaling to 65 million particles per day (Peng et al., 2017). Therefore, the Jordan River is a major collection point for pollution throughout the Wasatch.

In summary, microplastic abundance did not increase along an urbanization gradient within the Red Butte Creek as expected; however, the concentrations of microplastics were correlated with other water quality indicators. While there was no significant difference overall among habitat type and within lotic sites, there was a significant difference in microplastic abundance across lentic sites, as Liberty Park was higher than both Red Butte Canyon Reservoir and Red Butte Garden Pond (Fig. 3C, Table 4). This makes sense, given that the reservoir and garden pond are situated upstream of most of the anthropogenic and urban pressures. Although the microplastic concentrations in these two lentic sites were similar to those of lotic sites, the residence time of water trapping particles is potentially what is driving the observed distribution (Lechner, 2020). It is possible that these lentic sites are keeping microplastics from compounding from site to site moving further down in the catchment and creating the fluctuations in particle abundance. Other possible explanations for the observed distribution include differences in water inputs into the stream including groundwater upwelling (Gabor et al., 2017).

4.1.2 Microplastics and Water Quality Variables

Microplastic concentrations were positively correlated with all water quality variables (Fig. 4). Microplastic pollution trends were most closely correlated with TSS, and DOC concentrations. TSS and DOC are measures associated with the transport of particles and organic matter. Microplastic pollution can contribute to both TSS and DOC loads, as they are C-rich particles suspended in the water column. When compared to variables of water chemistry, microplastic pollution was less correlated with concentrations of TN and Cl^-.

Total nitrogen and chloride concentrations were relatively low in the upper part of the catchment and down past the University. It is not until Miller Park that we see these large spikes in TN and Cl^-, which are traditionally indicative symptoms of urban stream syndrome (Fig. 4.1, 4.2a & 4.2b). One of the principal effects of urbanization on water quality is the increase in waste material due to increasing urbanization, resulting in an influx of dissolved-solids and in general, poorer water quality (Leopold, 1968). Dissolved-solids include Cl^-, TN, TSS, and DOC. Additionally, water chemistry is altered by increased concentrations and loads of chemical pollutants, even at low levels of catchment urbanization (Walsh et al., 2005). Cl^- is a conservative tracer, as once it is introduced into the water column, it does not react. Therefore, increasing Cl^- concentrations are a good indicator of urbanization, as Cl^- often comes from road salts. For this reason, it is surprising there is not a stronger correlation between microplastic concentrations and Cl^-. In terms of TN, some forms of nitrogen are very reactive, meaning it can be taken up by plants and microbes with some being lost in gaseous forms. For this reason, we would not expect there to be a strong correlation between TN and microplastics.

One factor to consider to explain the increase in Cl^- and TN is the impact of groundwater springs discharging potentially contaminated water into the creek. A recent synoptic study of water quality and water sources (Gabor et al., 2017) found a similar trend in surface water chemistry. The concentration of solutes, specifically chloride and nitrogen, remained relatively un-impacted until further down in the catchment where they once again spiked around Miller Park. Their results suggest that contaminated base flow from aquifers is a major driver in surface water chemistry through groundwater discharge (Gabor et al., 2017). However, groundwater discharge should theoretically not contain microplastics and add to particle counts.

Another potential explanation for this phenomenon is total catchment imperviousness, which might be a driver of the observed differences between particle transport (TSS and DOC) and water quality (Cl^- and TN) response in the upper part of the catchment where urbanization increases at the Red Butte Canyon Gate. Increased catchment imperviousness is often correlated with more severe symptoms of urban stream syndrome (Walsh et al., 2005). In the upper part of the catchment by the Red Butte Canyon Gate and the Red Butte Garden, there are less impervious surfaces surrounding the creek, despite increasing anthropogenic presence outside of the RNA. Outside of the Red Butte Canyon, moving down the catchment past the University of Utah campus and along East 1300 South, impervious surface area subsequently increases and compounds. This increase in the impervious surface area surrounding the creek is another potential factor in the spike of Cl^- and TN concentrations at Miller Park (Leopold, 1968; Walsh et al., 2005).

An additional interesting pattern that is revealed in the comparison of microplastics to TSS and DOC is the large decrease in particles at Miller Park (Fig. 4.1, 4.2c & 4.2d). As Miller Park is the most urbanized lotic site within the Red Butte Creek catchment, it would be expected to have high concentrations of microplastic particles. However, as discussed above, Miller Park had the lowest concentration of microplastics, in addition to the lowest levels of DOC and second-lowest levels of TSS. These findings illustrate that something is happening at Miller Park that impacts the transport of particles in the water column, which is consistent with microplastic concentrations at the site. This is possibly due to 1) the unique fluvial geomorphology altering the hydrology of the site; 2) ground water discharge diluting particle loads; 3) entrainment in Miller Park structures (e.g., bridges, instream channel boulders); and/or 4) the regular flushing out of particles during storm events.

Flood volume and flood peak are known to increase with trends of urbanization (Leopold, 1968). These changes in volume and peak can alter stream morphology to compensate for amplified discharge in the event of flooding caused by increased impervious surfaces in urban areas (Leopold, 1968). As a result, hydrography becomes flashier due to the magnitude of discharge during these events (Walsh et al., 2005). Additionally, the scouring of floods can alter the fluvial geomorphology in these areas, which can create small reservoirs that provide temporary storage for water and its contents, including forms of pollution (Leopold, 1968). As discussed above, the anomaly of Miller Park is possibly due to the hydrology at the site and the pool that surrounds the area where the water enters the deep, narrow gully. It is possible that the scouring of floods at Miller Park and the high velocity of water rushing through the culvert has resulted in 1) a stagnant pool that also acts to concentrate and trap suspended particles; and 2) the regular flushing out or particles during storm events (Lechner, 2020; Leopold, 1968). This altering of the stream flow at Miller Park is another possibility for what is driving the hydrology and cycling of particles at this site, leading to decreased suspended particles in the flowing part of the stream (Leopold, 1968).

Overall, these findings are indicative of urban stream syndrome with elevated concentrations of contaminants and the inconsistent response of suspended solids (Walsh et al., 2005). Microplastics were correlated with all water quality variables considered; however, our results suggest that the source of these pollutants appears to be a factor in the strength of the correlation. As TN and Cl^- comes from polluted groundwater, they are less coupled with microplastic loads. Conversely, microplastics are more correlated with TSS and DOC, which are measurements of particles in the water column. Therefore, our findings suggest that microplastic distribution is more related to particles in the water column, rather than strictly a predictor of chemical water quality due to the different sources of water and other influences on pollution.

4.2 Scale of Microplastic Pollution in Red Butte Creek

To put this research into context, microplastic concentrations per-day was qualitatively explored using average daily discharge at some of the lotic sites within the catchment. While average microplastic particles per liter vary from site to site, so does discharge, impacting total daily microplastic loads at each site. At all of these sites, the daily microplastic particle load reaches millions within the Red Butte Creek catchment, and even billions within the Jordan River (Fig. 5, Table 6). The Red Butte Canyon RNA had the lowest load of microplastics per day followed by Miller Park. Although Miller Park had the lowest concentration of microplastics per liter, it had the second lowest load of microplastic particles per day, as discharge was higher at the site (Table 6). One potential explanation for this phenomenon is groundwater upwelling, possibly acting as a factor in diluting the microplastic concentrations but not reducing the load. This demonstrates that it is not necessarily simply particles per liter that determine the scale of pollution within a specific area, but also the volume of water flowing through the site.

These calculations provide a snapshot in time, yielding a general picture and scale of what microplastic pollution looks like on one day in October of 2020. When thinking about particles per liter, it is difficult to extrapolate to the scale of the catchment, and what those particle counts mean in terms of impacts to the water body. However, these estimates of microplastics per day are quite alarming, especially when considering that these data capture just one day of microplastic loads in one stream in Utah. As more plastics are discharged into the environment, environmental effects will continue to increase in response (Geyer et al., 2017). This study highlights the fact that microplastics are ubiquitous in the environment, even in relative undeveloped streams, and truly an issue we need to address.

4.3 Future Research and Questions

This study included a chance for human error in sampling and identifying inorganic particles from the water samples. However, every effort was made to reduce contamination of the samples from the collection through to drying as well as identifying particles. Future research on microplastic pollution in Utah should include a more robust sampling method that follows the NOAA manual for microplastic analysis in the marine environment (Masura et al., 2015). This method involves wet peroxide oxidations (WPO) to eliminate organic matter in the samples, followed by density separation to collect the particles, a microscope examination for identification, and gravimetric analysis to determine the mass of microplastics in the sample (Masura et al., 2015).

In terms of future questions, there is much to still be explored in the context of the Red Butte Creek and how microplastic pollution impacts freshwater ecosystems in Utah. Due to the small sample size of this study, a more comprehensive and robust sampling and analysis of the creek exploring variability throughout the year would likely provide more insight into the observed patterns and how the different variables interact. More sampling around lentic waterbodies would help to provide a more concrete picture of what is happening at each site and the consequences for microplastic concentrations in the lotic sites below. More specifically, Miller Park would be a good candidate to comprehensively sample to determine how hydrology impacts microplastic distribution due to having both lotic and lentic waters in the small vicinity. Additionally, sediment analysis could be used to determine particle deposition rates, providing another piece of the puzzle about microplastics in terms of hydrology and scale of pollution.

Other significant questions to be explored include how microplastics impact microbial respiration and activity by using dehydrogenase activity analysis or calculating biological oxygen demand, in addition to quantifying bioaccumulation and biomagnification in these water systems (Hill et al., 2012; Peng et al., 2017). As discussed above, the Jordan River is highly polluted and an impaired river as it is a major collection point for pollution throughout the Wasatch, and runs through the dense urbanization of the Salt Lake Valley. A study could be designed to determine which inputs of storm drains, water reclamation facilities, tributaries, and/or canals might be the biggest sources of microplastics. Therefore, the Jordan River would be a good candidate for a comprehensive study on microplastics in relation to water quality, microbial respiration, and biomagnification.

4.2 Solutions

Microplastic pollution needs to be acknowledged and addressed on a global scale using sustainable solutions, as plastic and microplastic pollution is a transboundary issue and a universal threat to our environment, ecosystems, and species (Brahney et al., 2020; Peng et al., 2017). In freshwater ecosystems, suggested sustainable solutions to address microplastic pollution include altering the type of plastic released into the environment (Wong et al., 2020), for example, by replacing conventional single-use plastics with bioplastics that are more easily biodegradable in the natural environment (Wong et al., 2020). However, although some bioplastics are made of biomass and renewable sources of carbon, others are made of petrochemicals that have a high carbon footprint, and therefore, are not a suitable or truly sustainable solution (Wong et al., 2020). The problem that arises with the other bioplastics made of more sustainable sources is that the cost of material and manufacturing is high, making them harder to adopt (Wong et al., 2020).

Other modes of intervention include addressing the efficiency of wastewater treatment plants in removing microplastics from treated water. Although wastewater treatment plants can already remove 95% of microplastics, due to the high volume of water treated at these facilities, a large number of microplastics evade capture and end up in the environment (Wong et al., 2020). Advance treatment technologies exist that can increase the removal of microplastics from treated wastewater up to 99.9% (Wong et al., 2020). However, this technology is expensive and requires increased maintenance to keep the system running, consequently decreasing installment due to the economic and efficiency costs (Wong et al., 2020).

As plastic pollution is widely dispersed around the world, it is simply not possible or enough to remove plastic debris as it is already ubiquitous in the environment (Brahney et al., 2020; Geyer et al., 2017; Peng et al., 2017). Plastics need to be addressed at the source for effective remediation using policy and legislation. One place for legislation is in the implementation and enforcement of these sustainable solutions. As these solutions often come with a higher price tag, adoption of these technologies is often forgone without the use of incentives or legal requirements. Additionally, legislation can be used to create plastic bans that prohibit the use of specified single-use plastic products, promoting more sustainable lifestyles by encouraging reusable items and the reduction of personal waste of items such as plastic bags and water bottles. However, our plastic problem is far larger than just consumer choice. Legislation needs to address plastics on a commercial scale, requiring vendors and manufactures to make the required changes to decrease the use of plastic, rather than placing responsibility on the consumer. With the use of legislation in conjunction with sustainable solutions and encouraging people to decrease their consumption and to buy less stuff, we can curb our society's addiction to plastics and plastic pollution to begin to address this issue.

Conclusion

In conclusion, microplastics were found at every site along the Red Butte Creek, Salt Lake City, Utah, which displays symptoms of the urban stream syndrome, both in terms of microplastics and water quality variables. However, our results suggest that microplastic pollution abundance and distribution is caused by more than just increasing urbanization, and that microplastics can be present even in pristine landscapes such as the Red Butte Canyon RNA. Additionally, water quality indicators are not uniform in comparison to degrees of urbanization, as they are influenced by water sources, landscapes, and complex mechanisms that drive pollution concentrations throughout catchments.

This study was only a snapshot in quantifying microplastics pollution along Red Butte Creek, as this study is based on a small number of water samples at one point in time from the Red Butte Creek. Therefore, this study was unable to determine the full scope of microplastic pollution in Red Butte Creek. However, it was able to provide some insight on the scope of particle pollution on one day in the month of October in 2020. These findings highlight the importance of microplastic research in freshwater ecosystems and the scale of this issue.

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