Comparison of Microplastics in Puget Sound via the Puyallup River From 2017-2018 Using University of Washington (UW) Tacoma Datasets

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Abstract

Plastic material is the most prominent constituent of pollution in the marine environment and it has a myriad of adverse consequences. This research investigates the contribution of microplastics to Puget Sound, Washington, via the Puyallup River from 2017 to 2018. Datasets from UW Tacoma were analyzed to determine spatial and temporal variation of microplastic abundance across nine sampling stations. The stations were located around the Puyallup River's nearby wastewater treatment plants (WWTPs) as these plants act as possible sources of pollution. A majority of the data indicated that microplastic abundance increased from 2017 to 2018 ($P = 0.0287$). Additionally, the data demonstrated a positive correlation between average microplastic abundance per city and total population both years (2017 $R^2 = 0.8749$, 2018 $R^2 = 0.6195$). Although spatial results were variable, abundance increased in the Puyallup River between the two sites closest to Puget Sound. 2018 data had a larger microplastic type distribution than 2017 with 63 percent fiber and 37 percent fragment, while 2017 only had fibers. Puyallup River results were compared to a study conducted on the Snohomish River in 2017. Mean river microplastic abundance between the two sites showed no difference in 2017 ($P = 0.0549$) and a significant difference in 2018 ($P = 0.0008$). Regulations on anthropogenic related pollution are necessary as microplastics continue to accumulate in the ocean. Further research with larger datasets and over longer timescales is crucial for resolving variability in the data and determining the impact plastic pollution has on marine communities.

Plain Language Summary

Pollution of plastic material is a widespread problem in the ocean. This study compared the transportation of microplastics to Puget Sound from the Puyallup River between 2017 and 2018.

Microplastics are small pieces of plastic that either broke down from larger plastics or are manufactured for use in human products such as soaps. These plastics are easily transferred to the ocean by river since they are generally lightweight. Datasets from UW Tacoma were examined to determine how the abundance of microplastics varied across the Puyallup River and between the two years. Nine total stations were sampled in this study. Sampling stations were chosen based on the location of local wastewater treatment plants (WWTPs) since wastewater is known to be a possible contributor of pollution. Generally, the data showed that more microplastics were found in 2018 than 2017 across the same stations. The data also showed a higher average number of microplastics was related to more people in the area. Abundance of microplastic varied across the river stations. Two different types of microplastic were found in the 2018 samples whereas 2017 had just one type. The data from the Puyallup River was compared to data collected on the Snohomish River in 2017 which showed a difference in abundance for 2018 only. It is necessary for policies to be put in place for reducing plastic pollution related to human activity. Additional research is essential for gaining a better understanding of the prevalence of microplastic types and their impacts.

Introduction

The pollution of our oceans is a pressing problem for the health and prosperity of marine environments. Prior to the enactment of the Marine Protection, Research and Sanctuaries Act in 1972, the United States had no regulations on the disposal of waste products into the ocean (https://www.epa.gov/ocean-dumping/learn-about-ocean-dumping, 3/3/2021). A majority of the global marine litter is plastic material (Derraik 2002). Microplastics are either manufactured or created by the breakdown of larger plastic materials. Manufactured microplastics such as microbeads are classified as primary, whereas larger plastics that experience degradation are called secondary (Thompson et al. 2004; Arthur et al. 2009). Although there is no absolute lower boundary for size, a microplastic is generally defined as being in the range of 333 microns to 5 millimeters (Arthur et al. 2009). Plastic in the environment is unsafe since toxic chemicals such as bisphenol A (BPA) can be leached into the water and taken up by marine organisms (Vandenberg et al. 2007). Microplastic pollution has lasting effects on marine communities because some materials do not disintegrate easily and can even remain in the sediments. This results in long residence times and persistence at sea (Lebreton et al. 2017). Microplastics impact marine communities via contamination of their habitats and accidental ingestion. The consumption of plastic material is harmful as it can be toxic, pose as a choking threat, or cause death (Barnes et al. 2009). Pollution of fisheries can result in economic losses. Consumption of microplastics propagates through the food web affecting invertebrates and vertebrates alike (Wright et al. 2013). Ultimately, plastic pollution transported to the ocean can have adverse consequences on humans via food sources. Plastic particles enter the human diet by the ingestion of contaminated fish and seafood (Davison and Asch 2011). BPA from plastic can cause various health conditions in humans such as cancer, infertility, and deformities (Vandenberg et al. 2007).

It was calculated that in 2010 coastal countries alone input 4.8 to 12.7 million metric tons of plastic waste into the ocean, and without mitigation strategies, by 2025 that value is expected to increase by an order of magnitude (Jambeck et al. 2015). Anthropogenic factors have played a significant role in amplifying this problem. Population density has been found to be positively correlated to the amount of microplastics in the environment (Mbedzi et al. 2020). This is especially relevant for heavily populated cities on coastlines or by rivers since these locations have direct contact with water. Previous work has identified that rivers are significant contributors for transporting microplastics into the ocean (Xiong et al. 2019). It is estimated that rivers worldwide contribute 1.15 to 2.41 million tons of plastic pollution to the ocean annually (Figure 1, Lebreton et al. 2017).

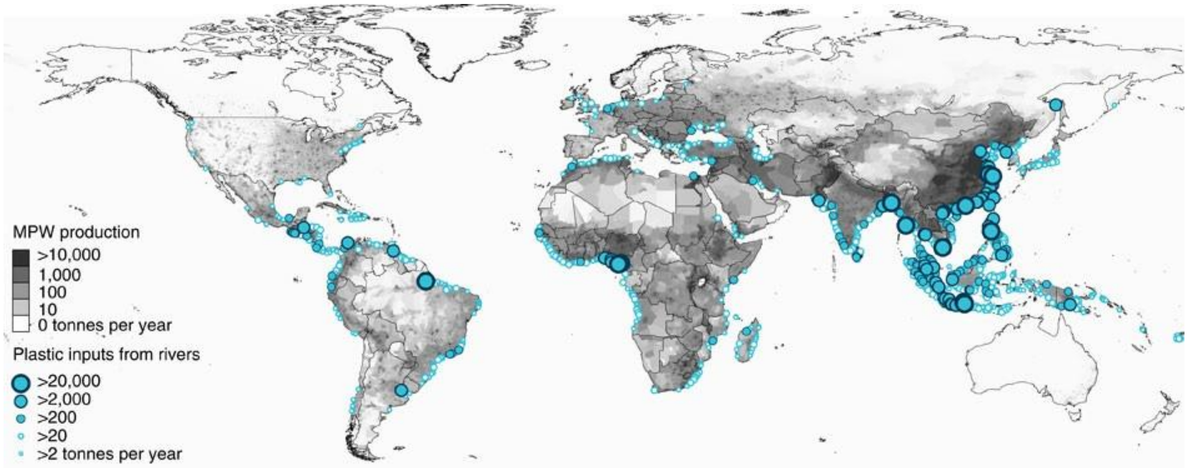


Figure 1. Global river contributions calculated from mismanaged plastic waste (MPW) production by country, population density, and average runoff per month (Lebreton et al. 2017). MPW production is shown in grayscale. Blue circles show river plastic input.

The Puget Sound estuary system is an important location for this research topic due to the several rivers which can be potential sources of microplastic pollution. This study compared the spatial and temporal change in microplastic concentration in Puget Sound due to the Puyallup River inflow. In most regions of Puget Sound, the deep, saline water flows southward into the estuary while less saline surface water has a net transport northward out of the estuary (Cannon

1983). Since the Puyallup River is a source of fresh water, microplastics are expected to disperse toward the north after entering Commencement Bay. Vashon Island experiences clockwise circulation where water flows north through Colvos Passage and south through East Passage (Cannon 1983). An ebb tide results in northward transport of surface waters (Figure 2), while a flood tide shows the opposing southward transport.

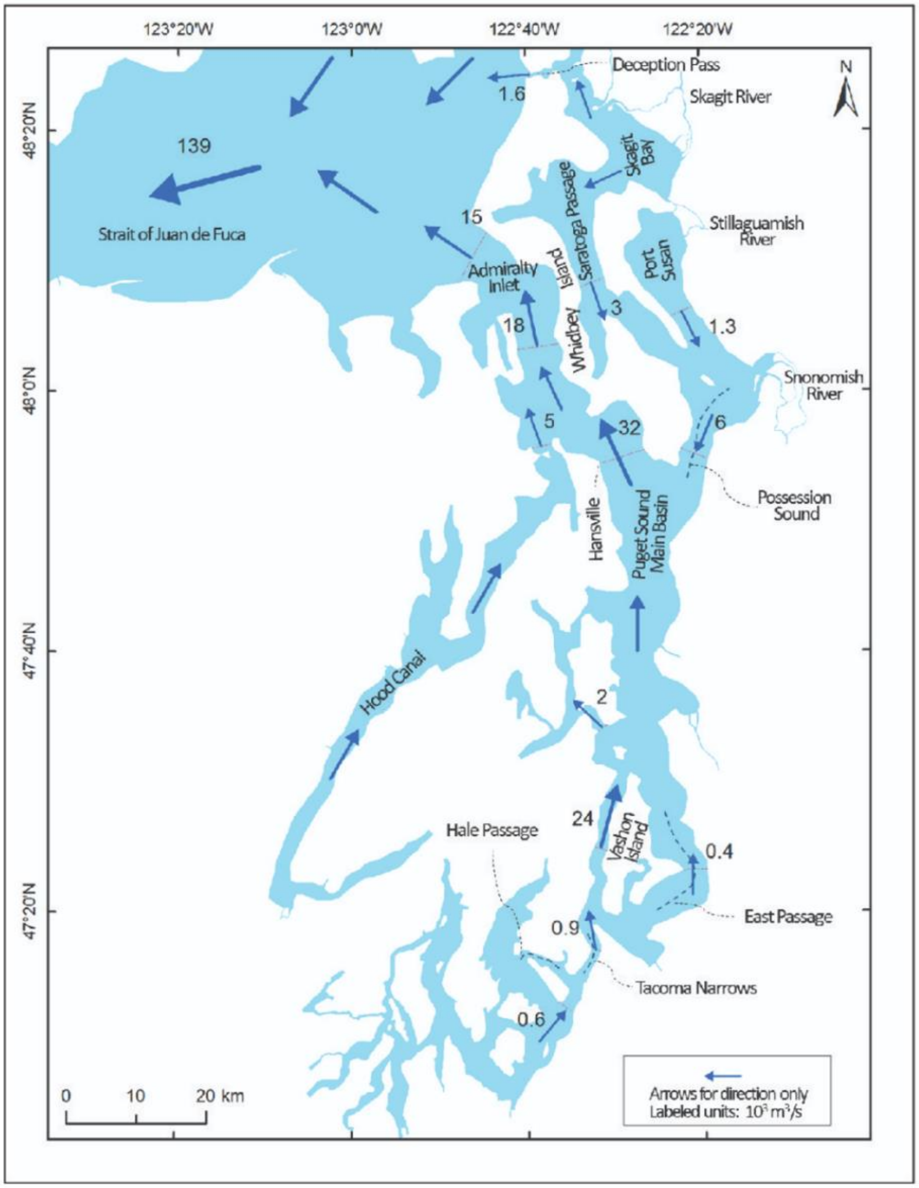


Figure 2. Tidally averaged outflow of surface waters in Puget Sound during 2006 (https://www.pnnl.gov/projects/salish-sea-model/circulation-maps, 11/11/2020). This represents an ebb tide. Flow direction is indicated by arrows and flow magnitude is shown in units of 10^3 m^3/s.

However, since East Passage is wider than Colvos Passage, it has slower current speeds (Cokelet et al. 1990). The faster, near constant northern currents channeling water through Colvos Passage from the Tacoma Narrows will pull water from Commencement Bay to maintain mass balance (Ebbesmeyer et al. 1984). Therefore, particles that enter Commencement Bay from Puyallup will likely get swept into Colvos Passage. Once at the northernmost point of Vashon Island particles can either circulate southward through East Passage or flow seaward (Cannon 1983).

The possibility of microplastic pollution exposure is heightened by the population density of nearby cities and waterway use. Some local cities around the Puyallup River have relatively high populations (Figure 3, https://data.wa.gov/Demographics/heat-map-population-density/exfi-4bxp, 11/11/2020). The Port of Tacoma and surrounding area is crucial for coastal transportation and shipping (https://wsdot.wa.gov/ferries, 11/11/2020; https://www.historylink.org/File/20998, 11/11/2020). There are several major fishing areas and fisheries around Commencement Bay which could be impacted by microplastic pollutants (https://wdfw.wa.gov/fishing/commercial, 11/11/2020). Along the Puyallup River there are multiple WWTPs which are sources for microplastics in river watersheds (Kay et al. 2018). River sample stations are focused around five local WWTPs (Figure 3). Since microplastics are known to accumulate over time in marine environments (Thompson et al. 2004) this study tests the hypothesis that an increase in microplastic abundance will be observed due to continuous river flow from 2017 to 2018. Research of microplastics in Puget Sound can be used as a platform for other estuary systems around the world. Microplastic research is important for influencing environmental policy regarding mismanaged plastic waste and the production of microplastics.

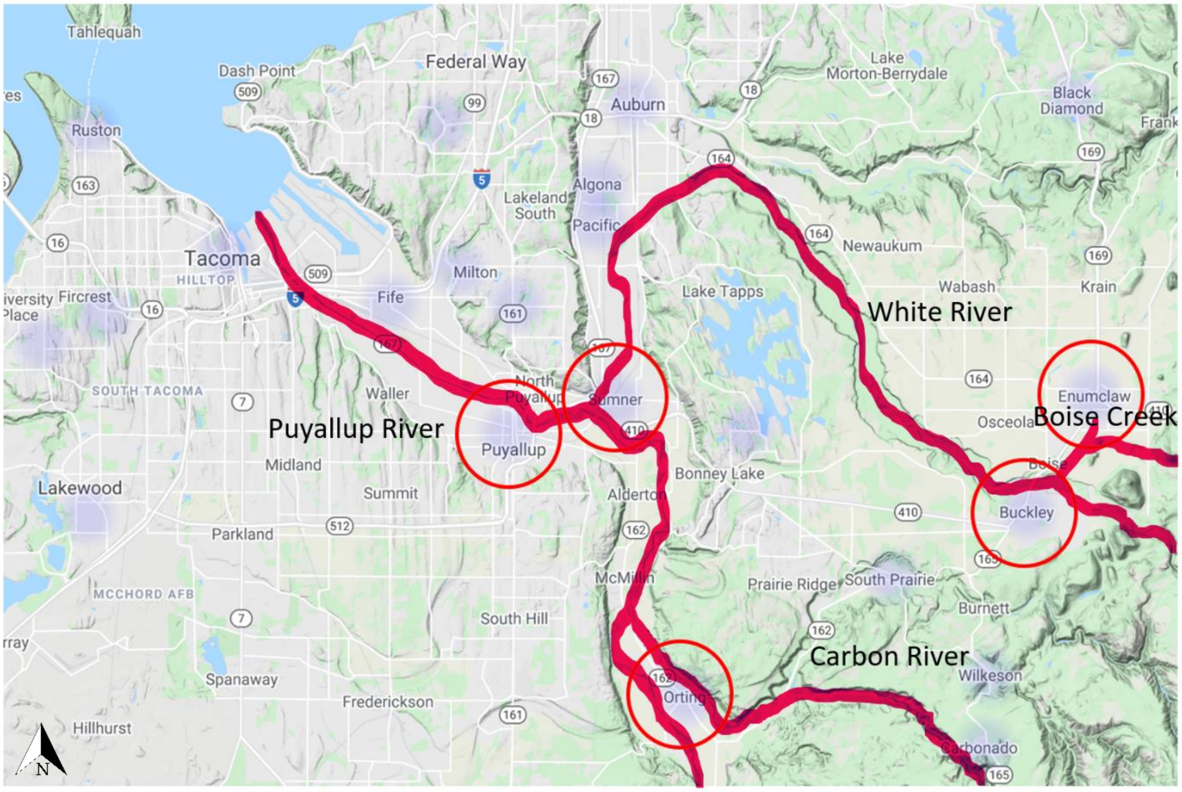


Figure 3. Population density heat map for local cities around the Puyallup River (https://data.wa.gov/Demographics/heat-map-population-density/exfi-4bxp, 11/11/2020). Areas with a darker purple hue indicate higher population density. Circled in red are the five cities with WWTPs where samples were collected. Red lines highlight the rivers.

Methods

The goal of this study is to determine the Puyallup River's contribution of microplastic to Puget Sound. The source of the data used for this study is two datasets from UW Tacoma (in Excel format) for 2017 and 2018, one containing river data and another with Puget Sound basin data. Since the Puyallup River discharges into Commencement Bay, this location will serve as the basin samples.

Sample collection-

UW Tacoma research groups collected the data. Samples were taken at nine sites upstream and downstream of the Puyallup River and in Commencement Bay (Figure 4, Table 1). Seven are river sites focused around WWTPs at Enumclaw, Buckley, Orting, Sumner, and Puyallup (Figure 3, Table 1). The remaining two sites are the basin samples, defined as north or south of river input (Table 1). River samples for 2017 were collected in February and 2018 were collected in November. Basin samples for both years were taken between April and May. River sites were located along Boise Creek, White River, and Carbon River, which all feed into the Puyallup River. Sampling methods were modeled from previous literature by National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program (Masura et al. 2015).

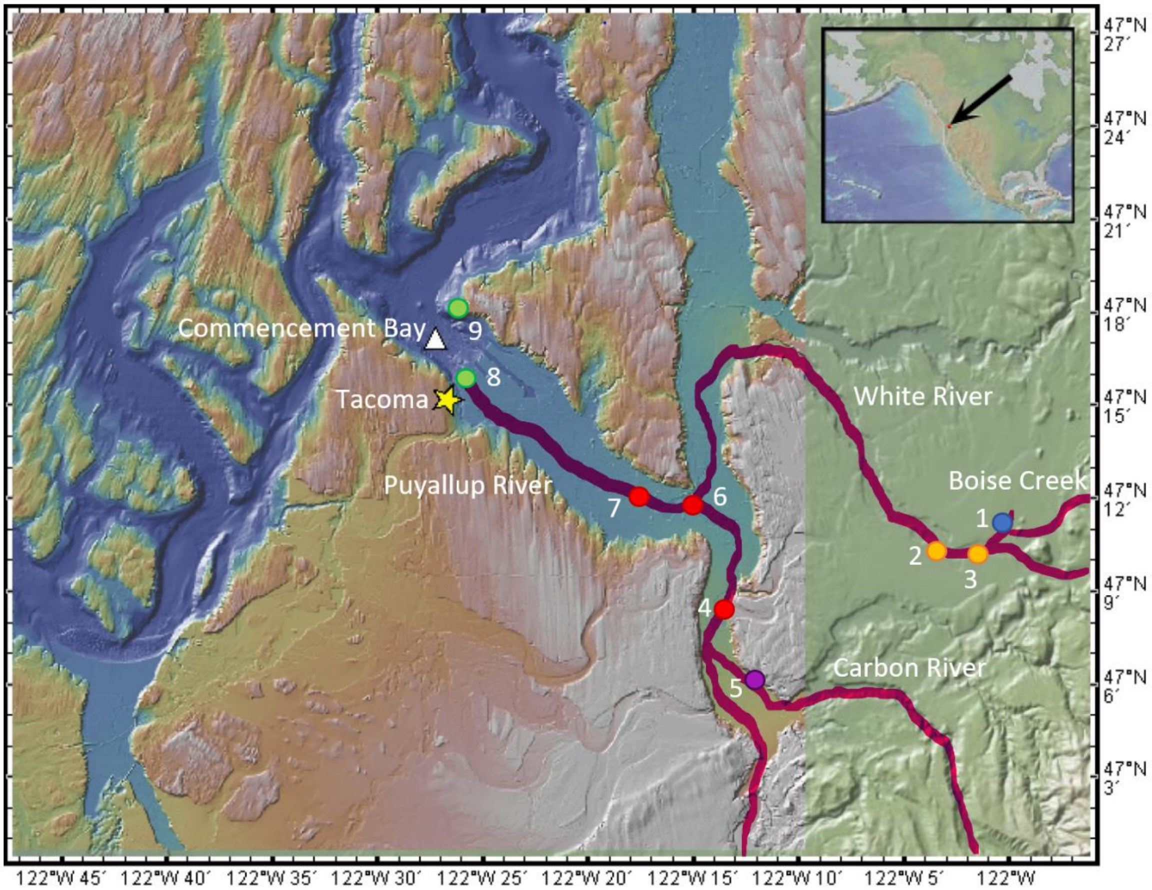
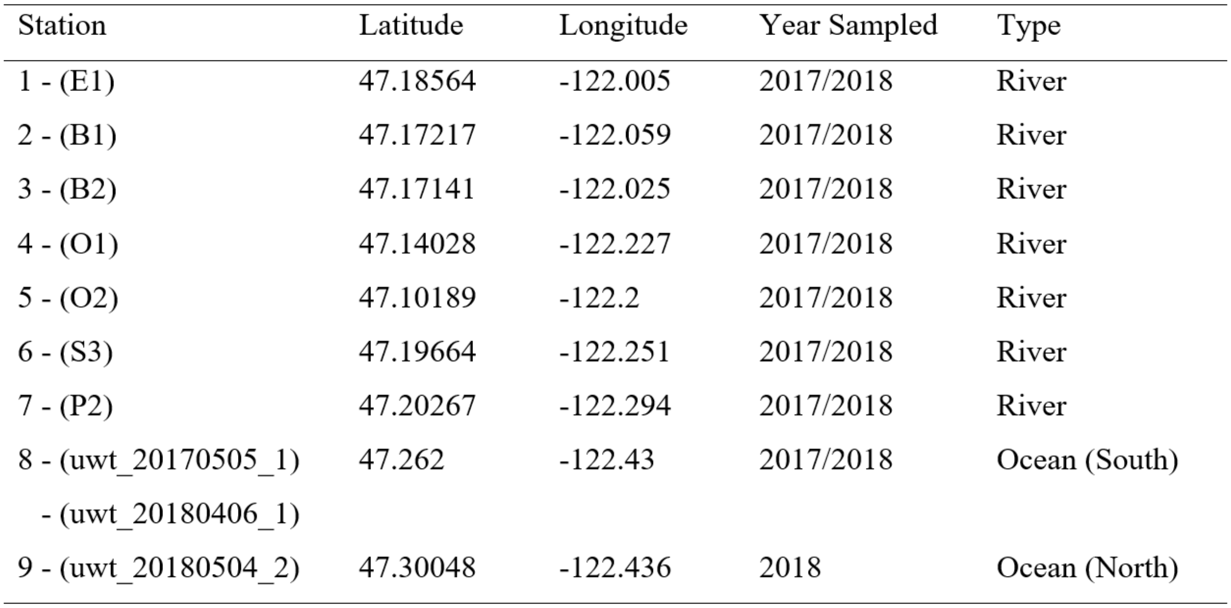


Figure 4. Map of sampled stations. Red circles indicate Puyallup River, the blue circle is for Boise Creek, orange circles represent White River, and the purple circle is for the Carbon River. The green circles indicate basin sampling sites, located in Commencement Bay. Red lines highlight the rivers.

Table 1. The nine sites sampled in 2017 and 2018 for this research project. Seven of the sites are Puyallup River samples. The other two are Puget Sound basin samples.



Station	Latitude	Longitude	Year Sampled	Type
1 - (E1)	47.18564	-122.005	2017/2018	River
2 - (B1)	47.17217	-122.059	2017/2018	River
3 - (B2)	47.17141	-122.025	2017/2018	River
4 - (O1)	47.14028	-122.227	2017/2018	River
5 - (O2)	47.10189	-122.2	2017/2018	River
6 - (S3)	47.19664	-122.251	2017/2018	River
7 - (P2)	47.20267	-122.294	2017/2018	River
8 - (uwt_20170505_1) - (uwt_20180406_1)	47.262	-122.43	2017/2018	Ocean (South)
9 - (uwt_20180504_2)	47.30048	-122.436	2018	Ocean (North)

Ship sampling-

Manta net tows were taken at each of the basin sample locations for 5-10 minutes at 2-4 knots depending on how much debris was in the water. The manta net used had a mesh size of 330 microns and had a flow meter attached to calculate water volume sampled. The wash net was held up and any collected plastic material was washed into a cod-end.

River sampling-

A 1-Liter stainless steel bucket was lowered by hand to collect water samples at each station. The bucket was triple rinsed with deionized (DI) water and then with river water. Sample jars were also triple rinsed with river water. Passive collectors were set up at each site for the duration of sampling to account for microplastics in the environment. The passive collector was a 0.7-micron glass fiber filter laid inside a petri dish, exposed to air. Twenty-one total samples were collected as three samples were taken at each of the seven river sites.

Sample Analysis-

Analysis methods of the microplastics data were based on previous literature defined by the NOAA Marine Debris Program (Masura et al. 2015). Samples were processed and examined in the UW Tacoma Limnology and Oceanography Lab. For all stations, the plastics were placed in labeled sample jars. Passive collectors (blanks) were set-up in the lab under the hood and on the counter by the microscope station to ensure lab contaminants were accounted for.

Analysis for ship samples-

Material was filtered through 5.6 mm and/or 0.3 mm sieves to categorize collected samples by size. Those samples were dried, and the mass was recorded. The plastics were then exposed to wet peroxide oxidation (WPO) to eliminate organic substances. Density separation of this mixture was done to separate plastic material from the rest of the sample by isolating and collecting the lighter, floating debris. Once that material dried it was weighed. Microplastic particles were collected in a vial with forceps under a microscope at 40X magnification. Each microplastic was counted as it was transferred to the vial. The material in the vial was weighed. The distance the manta net was towed in meters was calculated by the difference in flow meter readings (Equation 1). Volume of seawater in cubic meters was calculated by multiplying the distance derived from Equation 1 by the area of the net (Equation 2). Plastic concentrations were calculated by dividing the total count per sample by the volume of water filtered (Equation 3).

Analysis for river samples-

The filtration system was triple rinsed with DI water to avoid contamination. Samples and blanks were filtered through a vacuum flask. A 0.7-micron glass fiber filter was used in this process. The vacuum filter collection cup was triple rinsed with DI water between samples. The filter was examined with a microscope at 40x magnification to record and count the fibers found in the sample. Fiber count and the standard volume of the sample bucket (1 Liter) was used to directly calculate microplastic concentration via Equation 3.

Equation 1: $Distance\ (m)\ =\ \frac{Difference\ in\ flow\ meter\ readings \times 26873}{999999}$

Equation 2: $Volume\ (m^3)\ =\ area\ of\ net\ (m^2) \times distance\ (m)$

Equation 3: $Abundance\ (m^{-3}\ or\ L^{-1})\ =\ \frac{Total\ count\ per\ sample}{volume\ (m^3\ or\ L)}$

Data Analysis-

To analyze this data Excel was used to determine microplastic abundance per station. This process was modeled after a previous microplastics study conducted in the Northeastern Pacific Ocean (Figure 5, Desforges et al. 2014). River microplastic data were compared between 2017 and 2018 and a t-test was used to determine statistical significance. Upstream and downstream locations were examined for spatial comparison. The northern versus southern basin stations were compared to determine the dispersal direction of microplastics in 2018. Correlation between river microplastics and inland population density was examined with a liner regression. Population data used in this research was gathered from the 2010 Census (https://data.wa.gov/Demographics/WAOFM-Census-Population-and-Housing-2000-and-2010/tx5i-i2ja/data, 11/11/2020). The distribution of microplastic type was contrasted between 2017 and 2018. Results from this study were compared to a microplastics project conducted on the Snohomish River in 2017 (Hofmans 2017). Microplastic abundance per station and microplastic type distribution were compared between the two locations. A t-test was utilized to compare both years of data from the Puyallup River to the Snohomish River data to determine statistical significance.

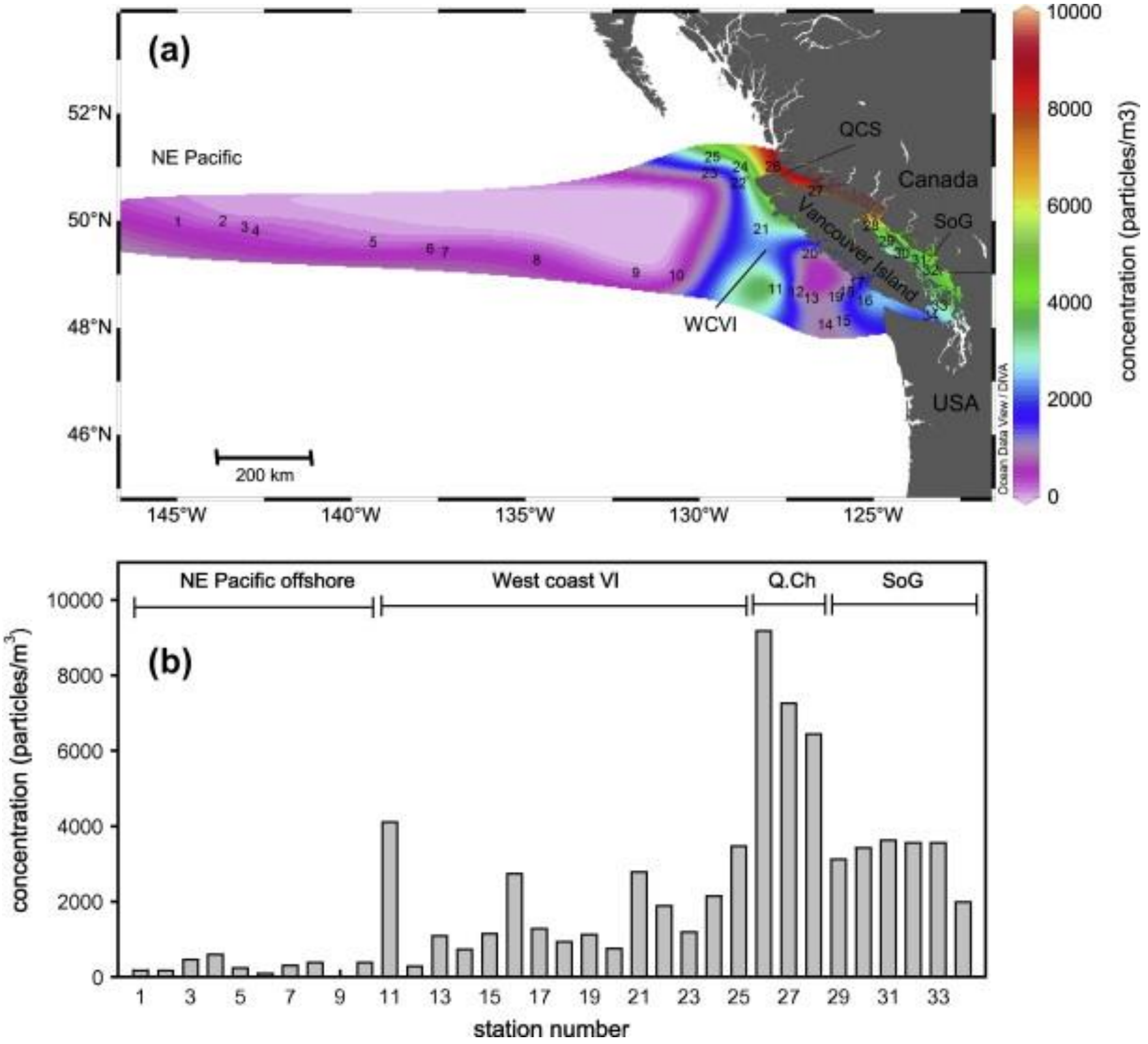


Figure 5. Spatial distribution of microplastics in Northeastern Pacific Ocean subsurface waters (Desforges et al. 2014).

Results

River microplastics data were analyzed as the full dataset as well as for a subset of the data (Figure 6). This was conducted in this manner because stations 1 and 2 show exceptionally higher abundance values for 2017 as opposed to the remainder of the dataset (Figure 6A). With the entire river dataset, stations 1-7, statistical testing showed no significant difference between the 2017 and 2018 mean river abundance values (P = 0.4978, Figure 6A). The subset of the data, stations 3-7, showed a significant increase between the 2017 and 2018 mean river abundance values (P = 0.0287, Figure 6B). Both years showed variable results for abundance between upstream and downstream sites, however, microplastic abundance did increase in the Puyallup River (post convergence of sampled rivers) shown at station 6 to 7 (Figure 6). For the basin data, in 2018, no plastics were found at station 9 (north) while station 8 (south) had 76 fragments and 77 fibers. Station 8 (south) had five fibers in 2017.

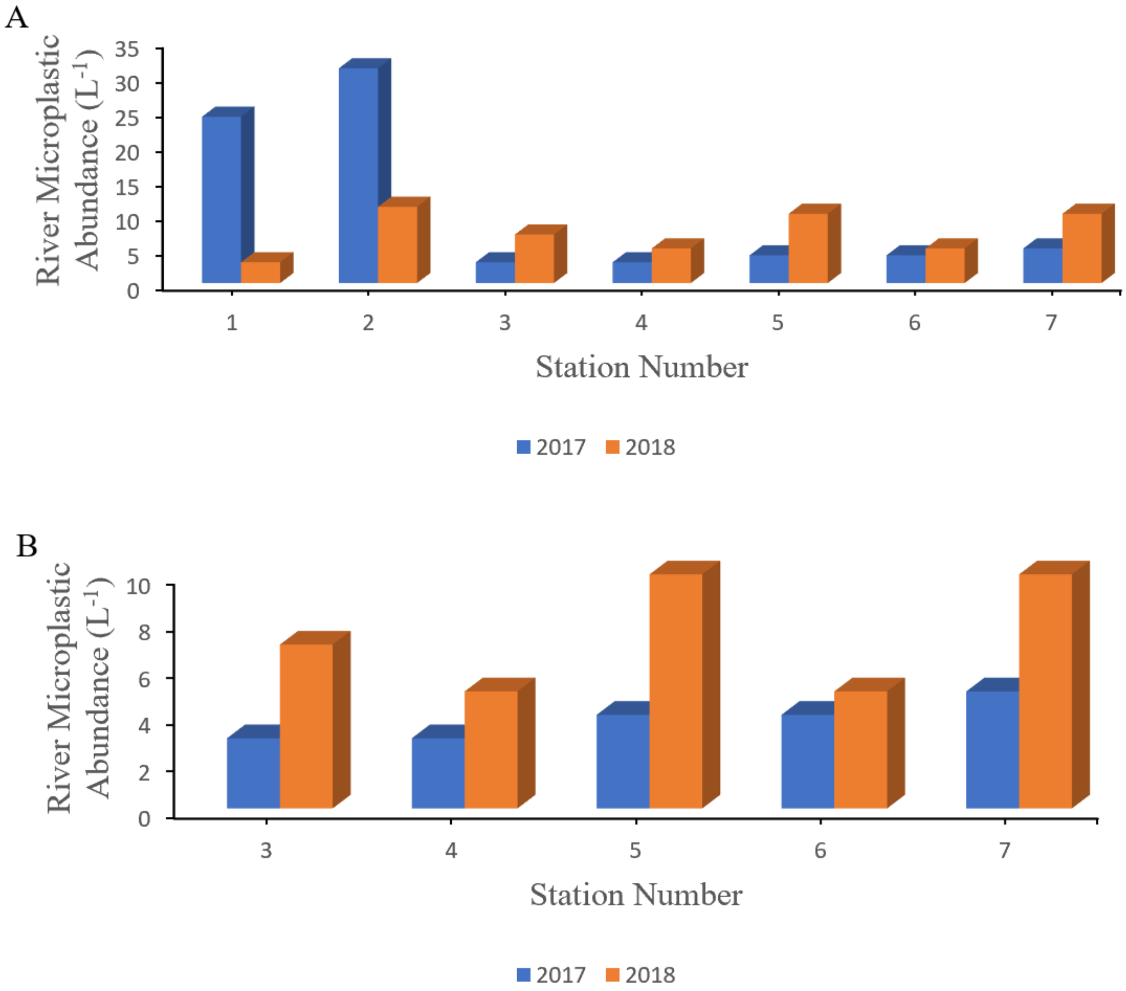


Figure 6. Microplastic abundance across all river stations, 1-7 (A) and a subset of the data including stations 3-7 (B). Blue represents 2017 data and orange represents 2018 data.

Correlation between river microplastics and population density were analyzed for the full dataset and the same subset (Figure 7). Considering the entire dataset, stations 1-7, 2017 showed a weak negative correlation between average microplastic abundance per city and total population ($R^2 = 0.0965$) while 2018 had a weak positive correlation ($R^2 = 0.1993$) (Figure 7A). The subset of the data, stations 3-7, showed a positive correlation between average microplastic abundance per city and total population for both years (Figure 7B). In 2017 this was a strong correlation ($R^2 = 0.8749$) and in 2018 the correlation was moderate ($R^2 = 0.6195$) (Figure 7B). Therefore, Buckley, Orting, Sumner, and Puyallup had a positive correlation for stations 3-7.

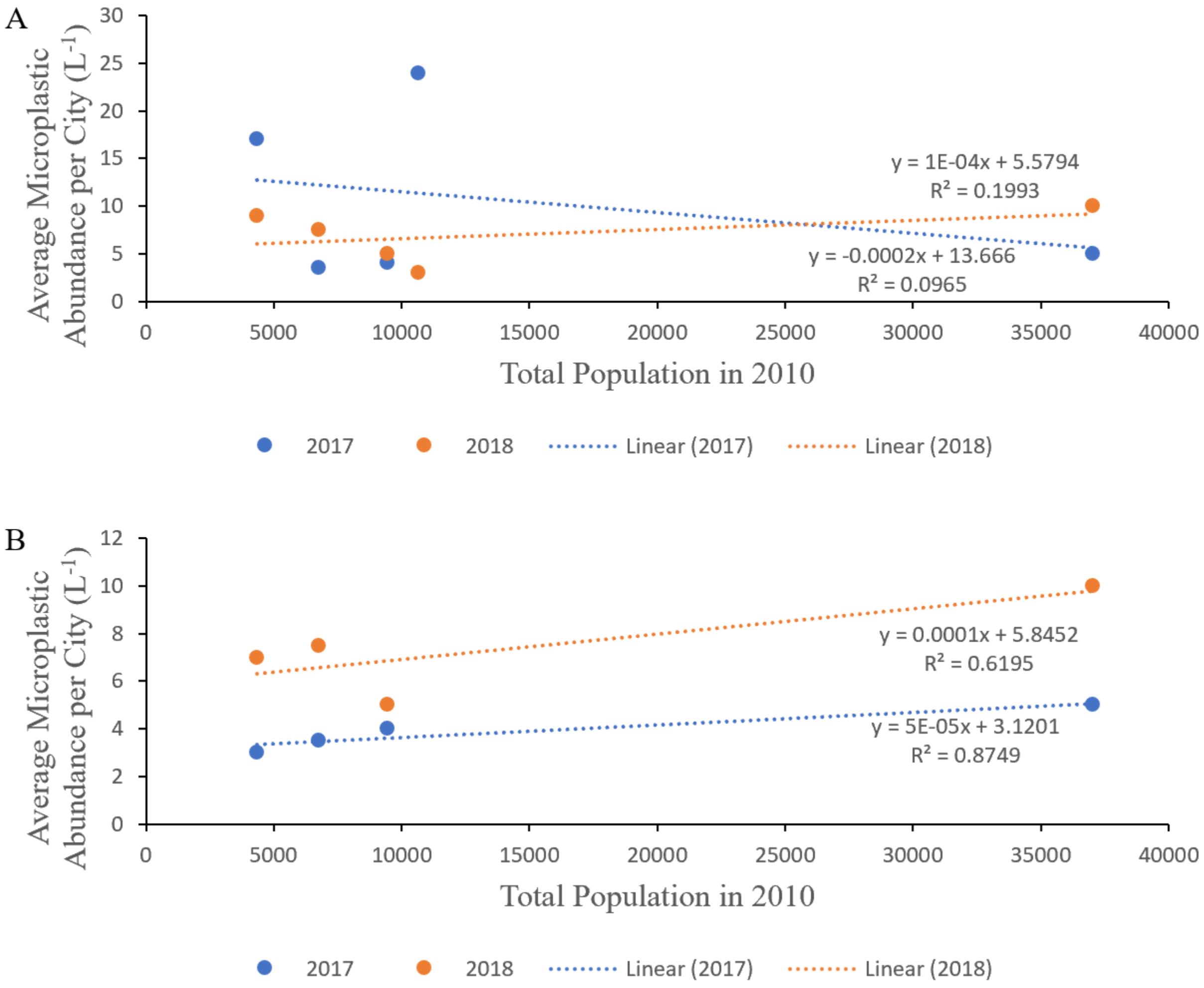


Figure 7. Correlation of river microplastic abundance and population density across all river stations, 1-7 (A) and for a subset of the data, stations 3-7 (B). Blue is 2017 data and orange is 2018 data.

Microplastic type distribution was examined for the combination of both ocean basin and river data (Figure 8). For 2017, only fibers were identified in the samples (Figure 8A). 2018 samples contained two different types of microplastics, fiber and fragment (Figure 8B). All of the fragments were found in the Puget Sound basin at station 8 (south). Therefore, 2018 had more types of microplastic than 2017, with 63 percent fiber and 37 percent fragment (Figure 8B).

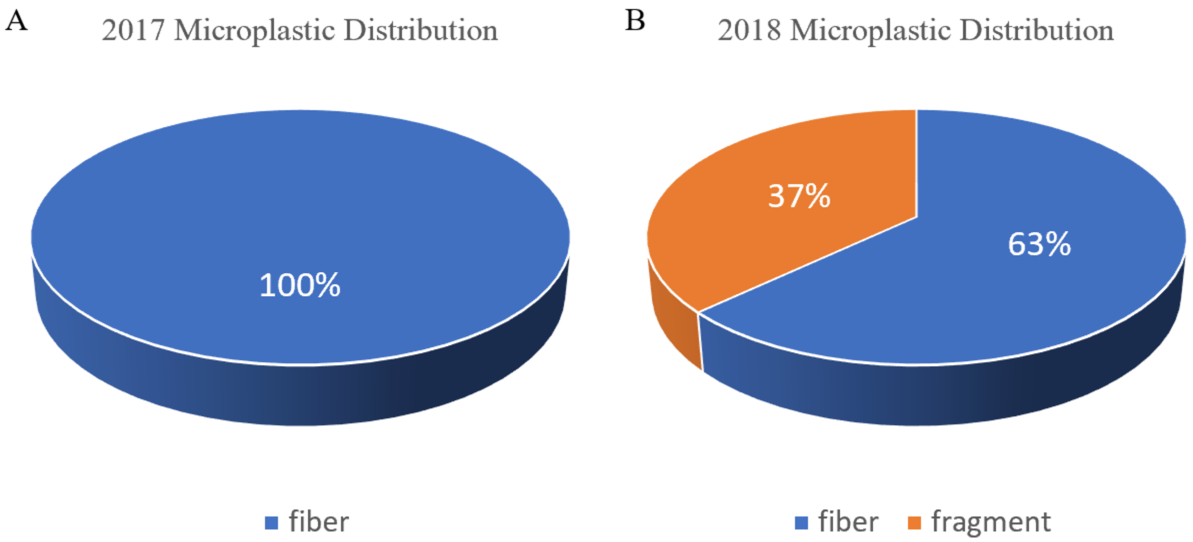


Figure 8. Distribution of microplastic type from both river and ocean data from 2017 (A) and 2018 (B). Blue represents fibers and orange represents plastic fragments.

Puyallup River results for average abundance of river microplastics and microplastic type distribution were compared to data collected from the Snohomish River (Figure 9). A t-test that analyzed the 2017 Puyallup River data against the Snohomish River data showed no significant difference between mean river abundance values (P = 0.0549, Figure 9A). However, a comparison between the 2018 Puyallup River data and the Snohomish River data showed a highly significant statistical difference between mean river abundance values (P = 0.0008, Figure 9A). In 2018, on average, the Puyallup River microplastic abundance was higher than that of the

Snohomish River. Additionally, five different types of microplastics were observed in the Snohomish River samples which included fiber, fragment, foam, film, and bead (Figure 9B). The large microplastic type distribution detected is a stark contrast to the Puyallup River data which found only one type for 2017 and two types for 2018 (Figure 8).

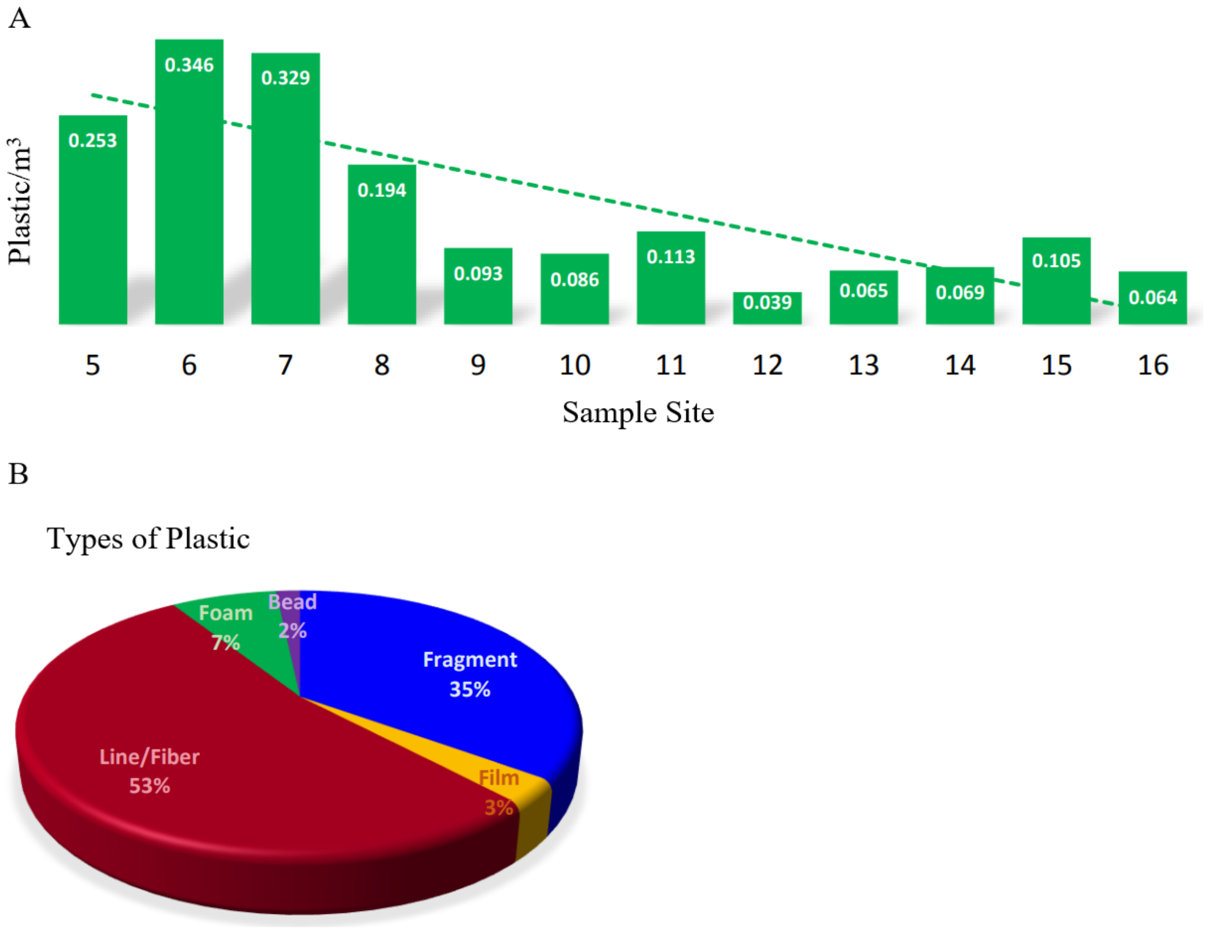


Figure 9. Snohomish River microplastics data collected in 2017. Microplastic abundance per station (A) and microplastic type distribution of samples (B). Dashed green line in (A) is the linear trendline. For (B) red indicates line/fiber, blue is fragment, yellow shows film, green is foam, and purple represents bead. Adapted from Hofmans 2017.

Discussion

Examination of the full dataset of river microplastics across the stations yielded variable spatial and temporal results (Figure 6A). Temporal variability is possibly due to sampling error or environmental conditions that could have impacted results at the downstream stations near Boise Creek in 2017. Heavy rainfall or flooding in the area may have resuspended microplastics into the water column which were collected as a consequence. Possible differing environmental conditions in 2017 may have had more influence on the Boise Creek microplastic data as opposed to other rivers since the creek is narrower. Spatial variation between upstream and downstream sites could be a result of the small dataset available for this study. Additionally, not all of the WWTPs had both an upstream and a downstream site with data for 2017 and 2018 which further reduced the dataset usable for annual comparison.

Furthermore, 2017 and 2018 were collected in different months of the year which could have played a role in creating variable results if seasonal differences are relevant to this research. Due to this, the only spatial trend observed is that microplastic abundance increased as the rivers converged into the Puyallup River (Figure 6). Since the Puyallup River directly connects a network of inland waterways to Commencement Bay, it is expected from previous literature that it would aid in transporting microplastics to the ocean (Xiong et al. 2019). The increase in abundance identified is likely due to the accumulation of microplastics from upstream rivers plus additional microplastic pollution from the city of Puyallup.

A majority of the dataset that was analyzed, stations 3-7, showed a strong temporal trend for microplastic abundance increasing between 2017 and 2018 (Figure 6B). Stations 3-7 had higher abundance in 2018 than in 2017 which was consistent with this project’s hypothesis (Figure 6B). This evidence provides support to the hypothesis being investigated and aligns with previous literature as an accumulation of microplastic is observed over time (Thompson et al. 2004). Based on these results, there are strong implications for an urgent need to enhance plastic pollution regulations. Unregulated mismanaged plastic waste will continue to afflict marine ecosystems, coastal economies, and human health (Davison and Asch 2011).

A comparison between southern and northern basin stations in Puget Sound for 2018 resulted in the evident congestion of microplastics toward the south. The northern station had higher dispersion of microplastics which is expected from Puget Sound circulation patterns (Cannon 1983). Based on circulation around Vashon Island, microplastics are likely dispersed north and therefore a smaller abundance would be found at a northern station as the pollution is more spread out (Cannon 1983). However, this data is only taken from one observation so more research would need to be conducted for reliability. Additionally, this data is likely to have variable results based on seasonal mixing patterns and tidal cycles in Puget Sound. Samples collected at separate times will be associated with different points of the tidal cycle which would impact flow direction. Seasonal mixing patterns influence results as winter storm waves can mix microplastics to a depth in which they cannot be collected with traditional methods. Seasonal waterway use is also important as there is strong evidence that more vehicles and people increase microplastic abundance (Mbedzi et al. 2020).

Correlation between river microplastic abundance and population density exhibited variable results when analyzing the full dataset (Figure 7A). The variability seen in these results is likely due to the abundance anomalies found at the downstream stations near Boise Creek. To support that theory, an examination of the data subset, stations 3-7, yielded an apparent strong and moderate positive correlation between abundance and population density in 2017 and 2018, respectively (Figure 7B). Implications from this result show that anthropogenic factors have a substantial influence on microplastic pollution of local waterways, as observed in previous literature (Mbedzi et al. 2020).

Microplastic type distribution across the basin and river samples was larger in 2018 than in 2017 (Figure 8). This could be a result of new sources of microplastics that were introduced to the environment. Pollution waste from local WWTPs or other anthropogenic factors may have played a role in exposure of new types of plastic. The ubiquity of fibers in samples collected near WWTPs that service residential areas can be sourced from textiles (Kay et al. 2018). The presence of secondary plastics such as fragments exhibits that degradation of larger materials is an important source of microplastics (Kay et al. 2018). Random chance variations in mismanaged plastic waste will have a substantial impact on results during a short timescale study. It is crucial that future research in the field is applied for long timescales and in various regions in order to resolve the data variability.

Puyallup River microplastic abundance was found to be statistically higher than the abundance observed at the Snohomish River for 2018 but showed no difference for 2017. Various factors such as fluid mechanics or regional differences in climate would impact the dispersion and transportation of microplastics in these two rivers. For instance, the Puyallup River has an average discharge of 106 m^3/s, while the Snohomish River average is 269 m^3/s (https://snoflo.org, 11/2/2020). The slower flow rate of the Puyallup River may result in longer suspension as well as reduced dispersal and transportation of microplastics to Puget Sound. Local variables such as precipitation rate or river mixing may also increase the likelihood for these two rivers to display different microplastic abundances. Another contributor to data variability is that the Snohomish River samples were collected with a manta net while the Puyallup River was sampled with the 1-Liter bucket method. Inconsistent sampling methods lead to variations in the data as manta nets generally filter more water than just 1 Liter. Future research in the field should employ similar collection methods to minimize disparity between results. The Snohomish River data also had a larger microplastic type distribution than Puyallup did both years (Figure 8 and 9B). There is a possible relationship between these differences observed and unique sources of pollution to their respective local environments. Relative proximity of these sources to the waterway will impact the ease of microplastic transportation to the marine environment.

Conclusion

Microplastic research is essential as plastic material is the most prevalent pollutant in the ocean (Derraik 2002). This toxic contamination has devasting impacts on marine communities, ecosystems, habitats, and food webs (Barnes et al. 2009). Propagation of these microplastics through the food web via ingestion of contaminants poses health risks to humans (Davison and Asch 2011). Since rivers are known transporters of microplastics (Xiong et al. 2019), and anthropogenic factors are positively correlated to microplastic abundance (Mbedzi et al. 2020), Puget Sound was an ideal location of study for this project. Puget Sound supports many local industries and recreational activities that may contribute to pollution. This research examined the Puyallup River’s contribution of microplastic to Puget Sound from 2017 to 2018 to investigate possible accumulation of microplastics. The samples were collected around WWTPs as they serve as locations of possible contamination (Kay et al. 2018). A majority of the dataset showed that microplastic abundance increased from 2017 to 2018 (Figure 6B) and is positively correlated to inland population density (Figure 7B). These results show the significance of plastic accumulation in the ocean over time and that humans are playing an extensive role in marine pollution.

Suggestions for future research relate to resolving the variability of microplastics data. Longer sampling timescales are necessary to discern trends of microplastic abundance over time. Applying this research to other coastal and open ocean regions would be beneficial in determining how widespread the impact of plastic contamination is. It is also essential to maintain consistent sampling methods between experiments and locations so that results are comparable. It may also be helpful to choose sampling locations that make standard sampling methods feasible. For example, rivers should be evaluated to ensure that that they are deep or wide enough to fit a manta net used for sampling. Additional research is crucial for evaluating long-term ecological impacts marine communities are facing with continued pollution. Regulations on mismanaged plastic waste is imperative to ensure the health of the environment.

Acknowledgments

I would like to thank the University of Washington, Tacoma, for the providing the datasets that allowed for the investigation of this thesis. I would like to thank the University of Washington, Seattle, School of Oceanography, for the opportunity to board the R/V Carson to collect microplastics samples in the surrounding waters of Tacoma. Special thanks to the Captain and crew that made gathering this valuable data possible. I would like to thank my mentor, Kathy Newell for her unending support and guidance throughout the process of formulating my thesis. I would like to thank Julie Masura for providing me the necessary data and background knowledge to be successful in this project. I am thankful for the Ocean 443-444-445 professors, Kathy Newell, Rick Keil, Mark Warner, Ginger Armbrust, and William Wilcock who all helped enhance the meaning of this process over the past two quarters. Finally, I would like to thank my Ocean 443-444-445 classmates and my family for their encouragement and support.

References

Arthur, C., J. Baker, and H. Bamford. 2009. Proceedings of the international research workshop on the occurrence, effects, and fate of microplastic marine debris. NOAA Tech. Memo. NOS-OR&R-3.

Barnes, D. K. A., F. Galgani, R. C. Thompson, and M. Barlaz. 2009. Accumulation and fragmentation of plastic debris in global environments. Phil. Trans. of the Royal Society B. **364(1526):** 1985-1998. doi: 10.1098/rstb.2008.0205

Cannon, G. A. 1983. An overview of circulation in the Puget Sound estuarine system. NOAA Tech. Memo. ERL PMEL-48.

Cokelet, E. D., R. J. Stewart, and C. C. Ebbesmeyer. 1990. The annual mean transport in Puget Sound. NOAA Tech. Memo. ERL PMEL-92.

Davison, P., and R. G. Asch. 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Mar. Ecol. Prog. Ser. **432:**173-180. doi: 10.3354/meps09142

Derraik, J. G. B. 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. **44(9):** 842-852. doi: 10.1016/S0025-326X(02)00220-5

Desforges, J. -P. W., M. Galbraith, N. Dangerfield, and P. S. Ross. 2014. Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar. Pollut. Bull. **79(1-2):** 94-99. doi: 10.1016/j.marpolbul.2013.12.035

Ebbesmeyer, C. C., C. A. Coomes, J. M. Cox, J. M. Helseth, L. R. Hinchey, G. A. Cannon, and C. A. Barnes. 1984. Synthesis of current measurements in Puget Sound, Washington - Volume 3: circulation in Puget Sound: an interpretation based on historical records of currents. NOAA Tech. Memo. NOS OMS 5.

Hofmans, G. 2017. The quantification of microplastics along a primary Puget Sound river: a study from headwaters to estuary.

Jambeck, J. R., R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, and K. L. Law. 2015. Plastic waste inputs from land into ocean. Science. **347(6223):** 768-771. doi: 10.1126/science.1260352

Kay, P., R. Hiscoe, I. Moberley, L. Bajic, and N. McKenna. 2018. Wastewater treatment plants as a source of microplastics in river catchments. Environ. Sci. and Pollut. Res. **25:** 20264-20267. doi: 10.1007/s11356-018-2070-7

Lebreton, L. C. M., J. V. D. Zwet, J. -W. Damsteeg, B. Slat, A. Andrady, and J. Reisser. 2017. River plastic emissions to the world’s oceans. Nat. Commun. **8:** 1-10. doi: 10.1038/ncomms15611

Masura, J., J. Baker, G. Foster, and C. Arthur. 2015. Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. NOAA Tech. Memo. NOS-OR&R-48.

Mbedzi, R., R. N. Cuthbert, R. J. Wasserman, F. M. Murungweni, and T. Dalu. 2020. Spatiotemporal variation in microplastic contamination along a subtropical reservoir shoreline. Environ. Sci. and Pollut. Res. **27:** 23880-23887. doi: 10.1007/s11356-020-08640-4

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, and A. E. Russell. 2004. Lost at sea: where is all the plastic? Science. **304(5672):** 838.

Vandenberg, L. N., R. Hauser, M. Marcus, N. Olea, and W. V. Welshons. 2007. Human exposure to bisphenol A (BPA). Repro. Toxic. **24(2):** 139-177. doi: 10.1016/j.reprotox.2007.07.010

Wright, S. L., R. C. Thompson, and T. S. Galloway. 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. **178:** 483-492. doi: 10.1016/j.envpol.2013.02.031

Xiong, X., C. Wu, J. J. Elser, Z. Mei, and Y. Hao. 2019. Occurrence and fate of microplastic debris in middle and lower reaches of the Yangtze River – From inland to the sea. Sci. of the Total Environ. **659:** 66-73. doi: 10.1016/j.scitotenv.2018.12.313