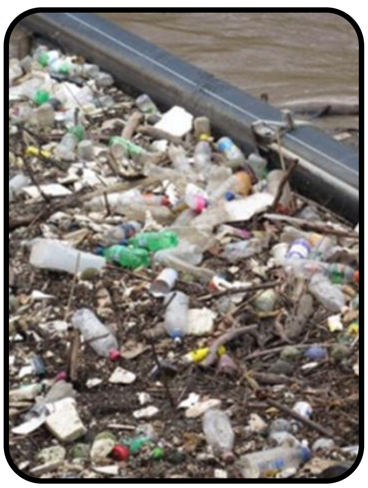
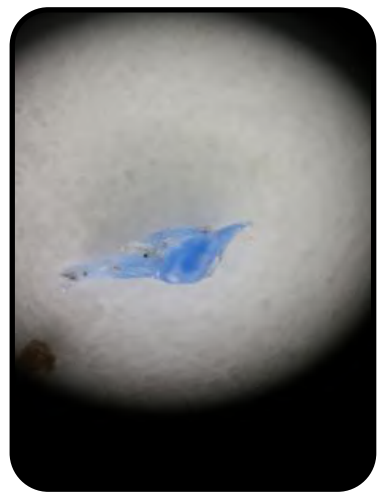
Microplastics in the Maribyrnong and Yarra Rivers, Melbourne, Australia





Report by Port Phillip EcoCentre, May 2018

Funded by the Victorian Government's Port Phillip Bay Fund

The Port Phillip EcoCentre acknowledges the Wurundjeri people as the traditional custodians of the rivers studied in this research.

Executive summary

The potential for plastic pollution to harm aquatic life is recognised by scientists as a global problem. Microplastics are classified as pieces of plastic smaller than 5 mm in diameter, which are mostly parts of broken up larger plastic products. Given the consequences of microplastic on marine ecosystems and human health, an Australia Senate Inquiry into the threats of marine plastic was conducted in 2015-2016. It recommended active support for research into the threats posed by microplastic pollution, including research to identify the extent of microplastic pollution.

These recommendations gave added weight to the findings of Port Phillip EcoCentre's 'Pilot study to identify the extent of microplastics in the Maribyrnong and Yarra Rivers and Port Phillip Bay' (July 2014), conducted in collaboration with the Yarra Riverkeeper Association. Monthly trawls commenced as the 'Turn off the Tap' project, funded by the Victorian Government. The final samples of this study spiked in microplastic litter. Subsequently, round 1 of the Port Phillip Bay Fund funded the 'Clean Bay Blueprint' project (2017-2020) to prepare Port Phillip Bay's first catchment-to-coast microplastic litter profile, including continued monthly microplastic trawls in the Yarra and Maribyrnong Rivers. The continuation of the trawls under the 'Clean Bay Blueprint' project provides an opportunity to collect additional data and analyse trawl samples in order to determine if the riverine microplastic increase observed in early 2017 was relatively short-term or is ongoing. This report shares initial findings which will inform and refine investigations over the next two years.

This study highlights the pervasiveness of plastics in our urban water catchments and reflects their ubiquitous use, mobility, and extreme persistence. The trawls removed a total of 6,335 litter items from the surface waters of the Yarra and 3,532 litter items from the surface waters of the Maribyrnong River. **In total, over 828 million litter items flow into Port Phillip Bay annually from the two rivers' surface waters. Over 612 million (74%) of these items are microplastics.** In both rivers, microplastics formed the bulk of litter and accounted for 77% and 67% of the total litter count in the Yarra and Maribyrnong, respectively. In both rivers, most of the litter caught consisted of hard plastic remnants of broken up plastic items. Of the other researched litter items polystyrene, nurdles and plastic bottle caps were most problematic in the Yarra, while in the Maribyrnong, plastic straws and soft plastics were more prevalent.

Although large variations in monthly collections were noted through the entire study period, it was found **the Yarra River carries significantly more litter than the Maribyrnong and that its litter loads are increasing.** Particularly, the more recent increases in polystyrene and hard plastic remnants seem to be responsible for this. Seasonally, the Yarra carries more litter in autumn and winter, whereas litter loads in the Maribyrnong is higher in summer. It is as yet unclear what the causes of the differences in litter items and seasonal variations are, but this will be investigated.

In view of the negative effects plastic pollution has on wildlife in Port Phillip Bay, and the potential threat to human health in the longer term, five recommendations have been formulated based on the findings in this report:

1) *Improve the life-cycle stewardship of plastic*

Improve on the current linear, single use and 'throw away' models of plastic life-cycle by demanding responsible manufacturing, handling, and recycling via circular economy models and principles.

2) *Implement bans on the use of unnecessary plastic from a higher level perspective*

Rather than implementing a product-by-product ban, potentially leaving bans open to exploitation, concentrate on designing a higher framework that use sustainable designs and materials as criteria for all products.

3) *Stimulate innovation and alternatives to plastic products*

Actively fund and subsidise industry and start-up initiatives that move away from manufacturing plastics or try to replace them with truly sustainable alternatives.

4) *Cultivate effective partnerships and taking shared responsibility*

As plastic pollution is everybody's problem, the government, industry and community need to concentrate on forging working partnerships that result in effective collaboration.

5) *Increase education and 'plastic literacy' of all plastic users*

A multi-pronged approach in plastic awareness education is needed in the community to achieve necessary behaviour change.

Under the Port Phillip Bay Fund, Clean Bay Blueprint will continue its riverine research and combine the findings with street and beach data to compile Victoria's first whole-of-catchment litter baseline and source reduction recommendations by 2020.

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Introduction

In 2014, the Victorian Government funded the Port Phillip EcoCentre to conduct Australia's first ever pilot study to identify the extent of microplastic pollution in the Yarra and Maribyrnong Rivers[1]. The five month study sought to measure baseline levels of microplastics entering Port Phillip Bay from either river and to document common streams of microplastic pollution. The pilot study provided a solid framework for future research and identified plastic resin pellets ('nurdles'), polystyrene beads and fragments of assorted user plastics as common microplastic items (Blake and Charko, 2014). From January 2015 to June 2017 the 'Turn off the Tap' project continued to track common streams of microplastic pollution and to identify fluctuations in microplastic loads across seasons. In July 2017, the Victorian Government awarded the EcoCentre another 3 years of funding under the Port Phillip Bay Fund to continue this vital research under the project name 'Clean Bay Blueprint'. The results from January 2015 to October 2017 are presented in this report.

Plastic pollution types

Most plastic pollution in Port Phillip Bay originates from land-based sources and enters the oceans through storm water drains, waste water treatment plants and river runoff. Wide use of single-use plastics, improper waste management practices, inadequate waste water treatment, and littering have led to tonnes of marine plastic pollution entering the ocean on a daily basis. In 2015, Jambeck et al (2015) estimated that around eight million metric tonnes of our plastic waste enter the oceans from land each year, with much of this litter entering the oceans via rivers (Mani et al., 2015, Jambeck et al., 2015).

Much of the litter that enters our oceans consists of extremely small pieces of plastic debris resulting from the disposal and breakup of consumer products and industrial waste. These small plastic pieces range in size from a few microns to five millimeters in diameter and are collectively known as microplastics (Thompson et al., 2004). Two main types of hard microplastics are found most often in waterways and oceans: nurdles and fragments (Barnes et

[1] The Litter Hotspots Program supported a catchment wide partnership building approach to reducing litter in all waterways entering Port Phillip Bay. From 2013 to 2017 there were three funding rounds with funding of $1.47 million to support both single-year small grants projects and a number of larger multi-year projects.

al., 2009). Nurdles are the pre-fabrication material for a wide range of industrial and consumer plastic products and they enter the aquatic environment mainly through accidental spillage at processing plants, but can also be lost during transport (Cole et al., 2011). They are spherical or cylindrical in shape, are usually clear or white in colour but it is not uncommon to find black, red, yellow and blue pieces (Cole et al., 2011). Hard plastic fragments on the other hand are known as secondary microplastics, and are derived from the breakup of larger plastic items (Cole et al., 2011). They are irregular in shape and vary greatly in color due to their primary design. Once in the ocean, microplastics persist for thousands of years, and have been observed in marine systems worldwide (Cole et al., 2011, Barnes et al., 2009).

Hard plastic fragments, polystyrene and film dominate microplastic pollution in many urbanised catchments around the globe. These items were the most abundant litter types collected in trawls in the New York-New Jersey Harbour estuary, USA, one of the most urbanized estuaries on earth. Similarly, fragments, polystyrene and plastic foil dominated microplastic loads along the length of the Rhine River in Europe (Mani et al., 2015). This is not surprising given that worldwide, the packaging industry, the primary material source of microplastics in this study, is the third largest after food and energy (Moore and Phillips, 2011). In 2014 alone, 311 million tonnes of plastic were produced globally (Gourmelon, 2015) and production is growing exponentially. Because of plastics' durability and extremely mobility (it floats, flies, sinks), it eventually enters our waterways either by accident or intentionally (Moore and Phillips, 2011).

The large litter items frequently captured in this study including straws, lolly wrappers, and plastic bottle caps eventually deteriorate through physical, biological and chemical processes (Andrady, 2011) into tiny fragments that enter Port Phillip Bay at an alarming rate.

Plastic pollution and its effects on wildlife

Marine plastic pollution has become an increasingly urgent threat to wildlife in waterways and oceans. Worldwide, at least 690 species have encountered plastic pollution, many of which are listed as threatened species (Gall and Thompson, 2015). Ingestion of plastic, including microplastics, can lead to injury (e.g. blocked digestive tracts, and organ rupture) and death (Lavers et al., 2014). Furthermore, plastics, the most abundant of plastic pollution items, *adsorb* (attract as an exterior film) organic micro-pollutants or persistent organic pollutants (POPs), which include polychlorinated biphenyls (PCBs), Dichlorodiphenyldichloroethylene (DDE) and nonylphenol (Teuten et al., 2009). The ingestion of these toxic chemicals is known to affect the physiology and behaviour of organisms, which ultimately affects population stability, as shown by reproductive dysfunctions caused by PCBs in orca and dolphin populations in Europe (Jepson, 2016). Furthermore, these chemicals bioaccumulate and biomagnify up the food chain. This increasing concentration of toxic chemicals in the tissues of organisms at successively higher levels in a food chain has been linked to disease and death in several top predators (Gall and Thompson, 2015).

The potential for marine plastic pollution to cause harm has resulted in it being recognised as a global problem and is listed as one of the greatest threats to marine biodiversity (Gall and Thompson, 2015, Depledge et al., 2013). In December 2017, 193 countries signed a United Nations resolution to eliminate plastic pollution from the world's oceans. Increased efforts to identify the extent of marine plastic pollution, particularly microplastics, and to evaluate the effects of microplastic pollution on marine fauna have commenced in oceans around the globe (Gall and Thompson, 2015). However, relatively few marine and freshwater systems have been investigated in Australia. This is of grave concern considering coastal and estuarine systems around Australia are some of the most diverse ecosystems in the world. Locally, Port Phillip Bay and surrounding waters are supporting an increasing recreational angler community and are home to an estimated 10,000 species, with several of those species unique to the Bay (yarraandbay.vic.gov.au). Studies that quantify the effect and extent of microplastics in these biodiverse waters are necessary to inform policy frameworks that reduce marine plastic pollution.

Study method

Study site

Between January 2015 and October 2017, a total of 60 monthly trawls were conducted in the Maribyrnong and Yarra Rivers. The Yarra River flows 242 km from the Yarra Valley through to the city of Melbourne, emerging at Port Philip Bay. More than one-third of Victoria's population lives in the Yarra catchment, which spans about 4000 square kilometers (Barua et al., 2013). The catchment includes 40 rivers and creeks including the Maribyrnong River which runs for 160 kilometers from its source on the slopes of Mount Macedon. The sites were selected on the basis of being close to the lower reaches of each river and therefore indicative of the total pollution load of each respective catchment. The Maribyrnong trawls commenced at the 'Water Canon' jetty extending from the west bank of Coode Island, 300 m upstream from the Yarra. The Yarra trawls commenced at Bolte Bridge, 2.5 km upstream of the Maribyrnong mouth. The black dots on the maps in figure 1 illustrate the approximate location of where trawls are conducted relative to the respective river catchment, while the satellite image in figure 2 shows the approximate locations of the trawl transects. The length of each trawl varied slightly due to the state of the tide and prevailing wind conditions at the time. As river boating involves changing course to safely navigate around other watercraft that may be encountered, the course of the trawls in each river was not rigidly defined, yet trawl speed was kept constant at all times.

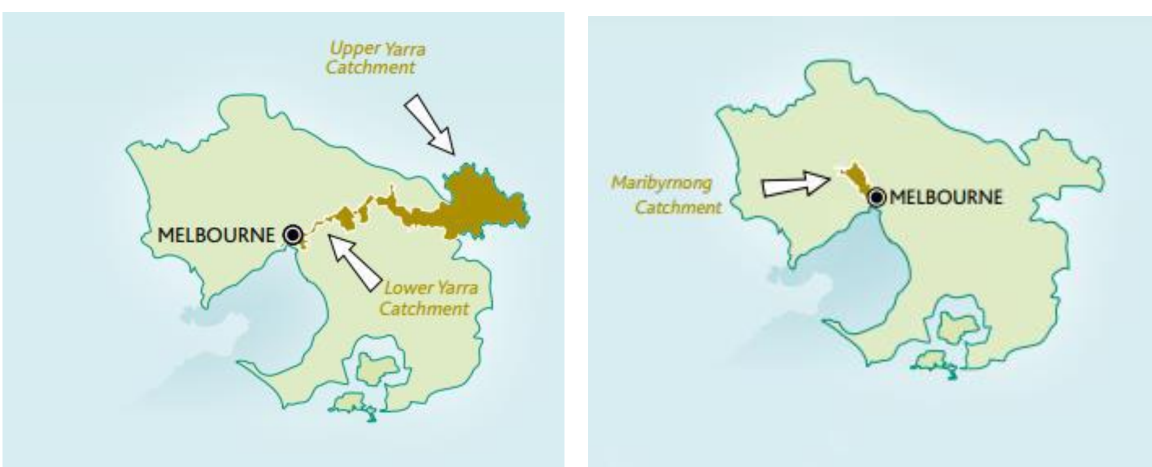


Figure 1: Black dots illustrate the approximate trawl locations within the Maribyrnong and Yarra catchments. Images courtesy of Melbourne Water

Figure 2: Approximate trawl location transects in the Maribyrnong and Yarra Rivers.

River trawls

A manta net designed to collect floating debris off the water's surface was deployed from the side of the boat and positioned outside of the wake zone. In each river, all trawls commenced at the same place, traveling upstream for 30 minutes, with the boat motor operated at a constant 1,000 rpm to maintain an appropriate and constant speed to operate the net consistently (Fig. 3A).

The 'mouth' of the manta net measures 600 mm x 200 mm, and the net is 3 m long with a 30 x 10 cm² collection net (codend) made of a 0.33 mm mesh size (Fig.3B). After 30 minutes, the net was retrieved onto the boat, the codend removed and placed in a container to be dried and sorted. The manta net is of the same specifications used by The 5 Gyres Institute to measure microplastics in international studies and in a recent review of methods that measure microplastic in aquatic environments, Mai et al. (2018) confirmed that this collection method is recommended for large-scale surface water sampling.

Figure 3: A. Manta net deployed on side of Yarra Riverkeeper vessel. B. Codend used to capture microplastic samples.

Sample analysis method

Dried trawl samples were analysed by separating litter items from the organic matter with the naked eye, using tweezers. Litter items were then sorted by litter type and the diameter measured with a ruler where applicable. Litter categories included: hard plastic pieces <2 mm, hard plastic pieces 2 mm-5 mm, hard plastic pieces 6-10 mm, hard plastic pieces > 10 mm, nurdles, polystyrene beads <4 mm, polystyrene beads ≥4 mm, plastic bottle caps, plastic straws, soft plastics (film), lolly wrappers, cellophane pieces, cigarette butts and 'other' items, which included twine, rubber and sponges.

As per internationally accepted guidelines, plastic pieces smaller than 5 mm in diameter are referred to as microplastics (Thompson et al., 2004). The categories, hard plastic pieces <2 mm, hard plastic pieces 2 mm-5 mm, nurdles and polystyrene beads <4 mm were grouped into the microplastic category. The soft plastics/film and cellophane categories were excluded from the microplastics category as the diameter of each soft plastic item was not noted, a shortfall of this study. However, it is worth noting that 585 and 598 soft plastic items (including cellophane) were collected from the Yarra and Maribyrnong Rivers respectively, over the duration of this study. These soft plastics inevitably break up into microplastics and are therefore a key contributor to microplastic loads entering Port Phillip Bay. Plastic items not visible to the naked eye, including microfibres, were excluded from this study due to logistical, technical and funding constraints.

Figure 4: A. Litter caught in Yarra River boom traps breaks up into millions of microplastics. Photo courtesy of Heidi Taylor. B. Microplastics collected in the Yarra River as part of the Trawl program. C. Image of <1mm microplastic item sourced in the Yarra River

Trawl results and data analysis

The results of the sample analysis show substantial concentrations of plastic litter present in the Yarra and Maribyrnong Rivers. A total of 6,335 litter items were captured and analysed from the Yarra and 3,532 litter items from the Maribyrnong between January 2015 and October 2017. An average of 204 litter items were collected from the Yarra monthly, while an average of 122 litter items were collected from the Maribyrnong monthly.

Monthly, trawl samples weighed an average of approximately 22 g, most of which was comprised of organic plant matter. On average, litter comprised 3.26 g or 15% of the total sample, highlighting the pervasiveness of litter in our waterways.

Because the Yarra's width in the trawl location is more than 160 times wider than the net, and the Maribyrnong's width in the trawl location is 120 times wider, the actual volume of litter in both rivers is astounding. For the Yarra, the rough calculation:

$$\mathbf{204}\ \boldsymbol{litter\ items}\ \ \boldsymbol{x}\ \mathbf{48}\ \boldsymbol{half\ hour\ sessions/day}\ \ \boldsymbol{x}\ \mathbf{365}\ \boldsymbol{days}\ \boldsymbol{x}\ \mathbf{160}\ \boldsymbol{times\ net\ width}$$

yields 571,852,800 litter items entering the Bay from the Yarra annually.

For the Maribyrnong, this calculation is:

$$\mathbf{122}\ \boldsymbol{litter\ items}\ \ \boldsymbol{x}\ \mathbf{48}\ \boldsymbol{half\ hour\ sessions/day}\ \ \boldsymbol{x}\ \mathbf{365}\ \boldsymbol{days}\ \boldsymbol{x}\ \mathbf{120}\ \boldsymbol{times\ net\ width}$$

yielding 256,492,800 litter items entering the Bay from the Maribyrnong annually.

These calculations suggest that an average total of **828,345,600** litter items flow into Port Phillip Bay annually from surfaces of the Yarra and Maribyrnong Rivers combined.

It should be noted that since these litter items are caught by surface trawls, this number is likely to be an underestimation.

Comparing litter in the rivers

Hard plastic remnants, polystyrene and soft plastics as a whole were the most common items found in both the Yarra and Maribyrnong (Figs. 5 & 6).

Hard plastic remnants made up the bulk of the captured litter items, comprising of 65% of the total capture for the Yarra and 62% of the total items captured in the Maribyrnong. Polystyrene was the second most captured item, with 22% of all items in the Yarra and 13% of items in the Maribyrnong being polystyrene. Lastly, soft plastics (consisting of cellophane, lolly wrappers and unidentifiable soft plastics) made up 9% of total items captured in the Yarra and 17% in the Maribyrnong.

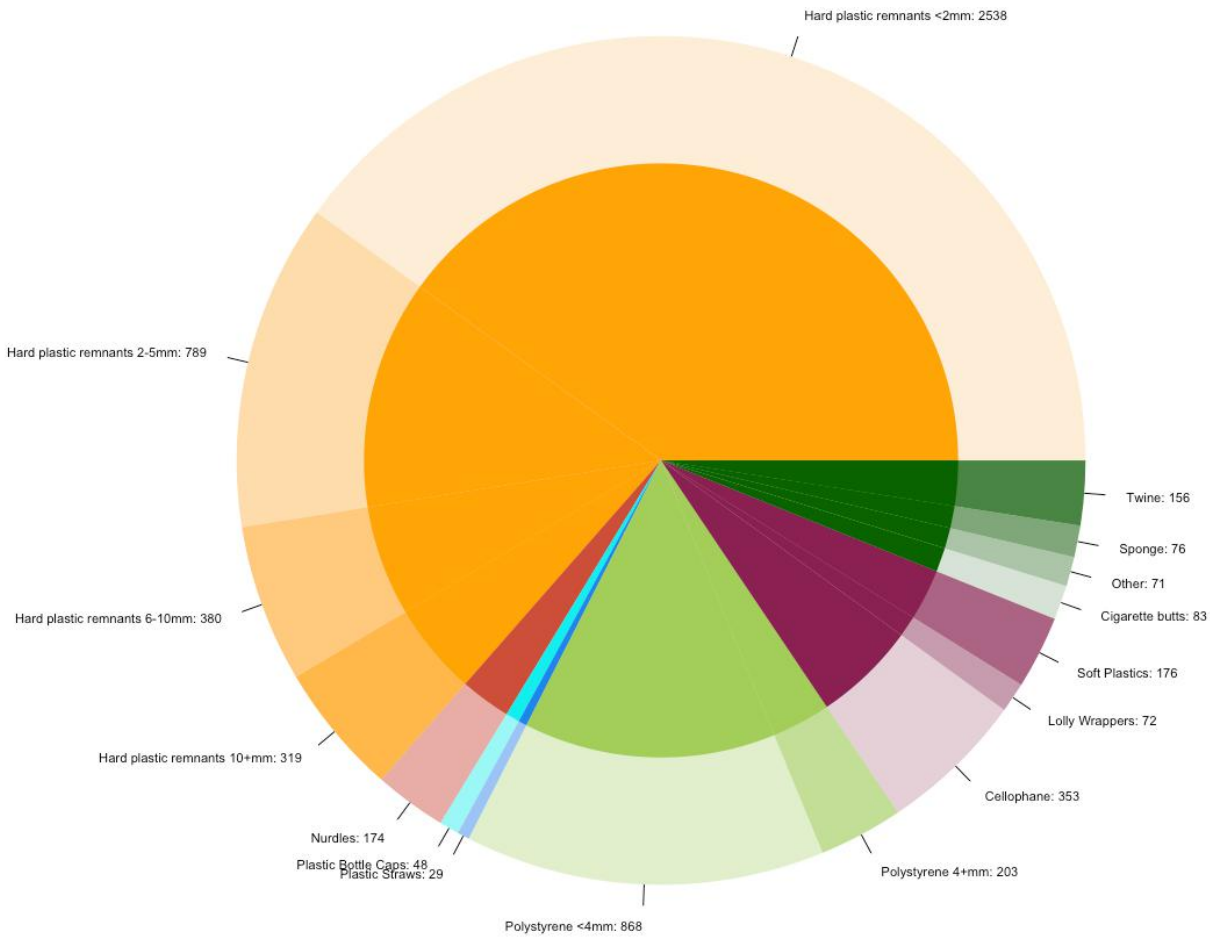


Figure 5: Litter composition in trawl samples obtained from the Yarra River.

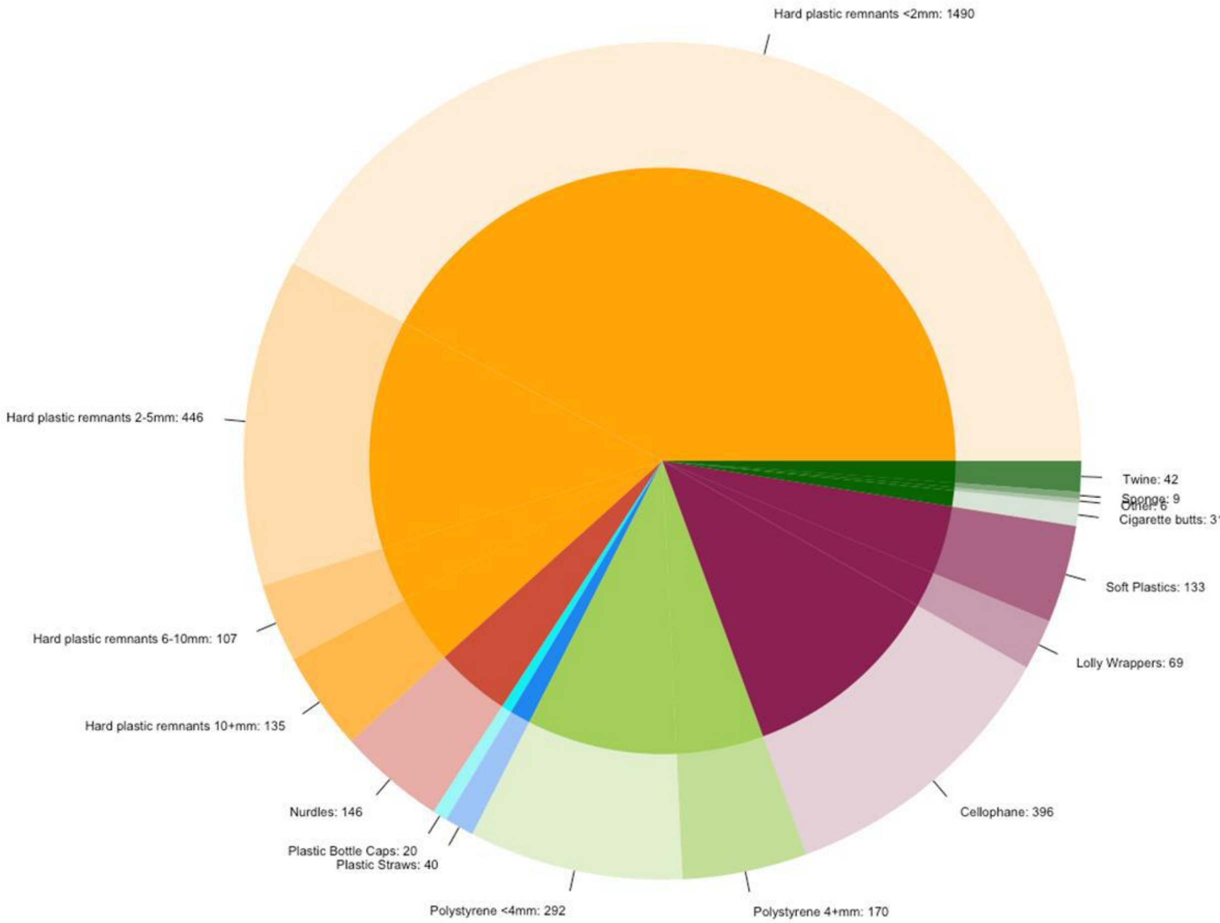


Figure 6: Litter composition in trawl samples obtained from the Maribyrnong River.

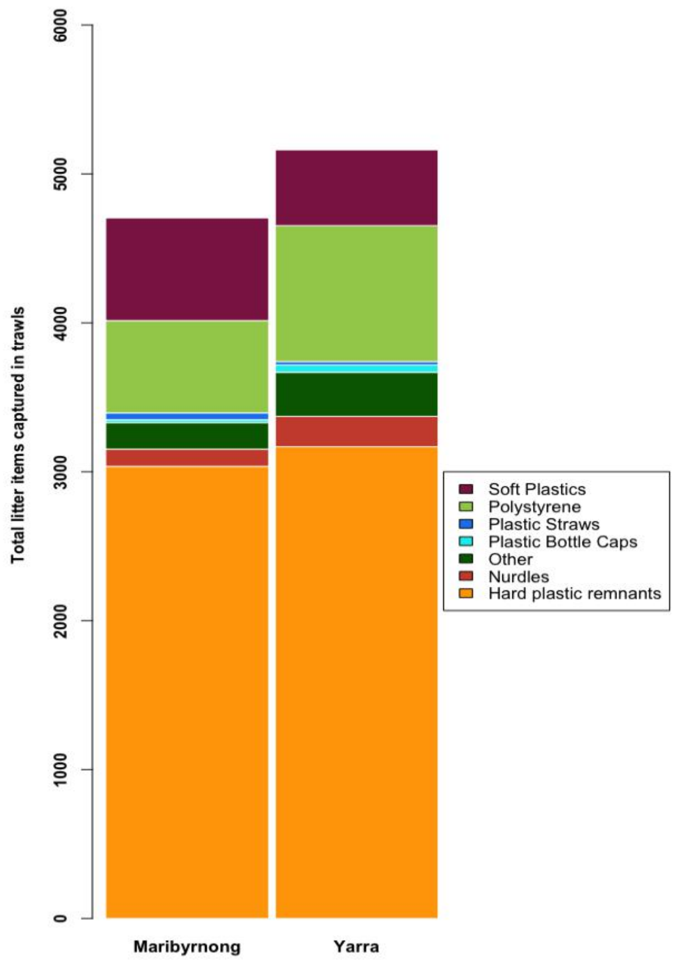


Figure 7: Comparison of number of litter items in Maribyrnong and Yarra Rivers.

When comparing the total litter counts between rivers, a significant difference between the Maribyrnong and Yarra Rivers was found (chi-squared = 21.2, df = 1, $P < 0.001$), with plastic litter overall more likely to be found in the Yarra than the Maribyrnong (Fig. 7).

There is also an overall significant effect of the rivers on distribution of plastics by item category (chi-squared = 139.7, df = 6, $P < 0.001$).

There was no significant difference in numbers of expected **hard plastic remnants** between the Maribyrnong and Yarra ($P > 0.05$).

Polystyrene, nurdles, plastic bottle caps and 'other' numbers are significantly below expected ($P < 0.05$) in the Maribyrnong, and significantly above expected in the Yarra ($P < 0.05$), meaning these items are more likely found in the Yarra than in the Maribyrnong, compared to the litter baseline calculated from the total data.

Plastic straws and soft plastics are significantly above expected in the Maribyrnong ($P < 0.05$) and significantly below expected in the Yarra ($P < 0.05$), indicating that straws are significantly more likely to be found in the Maribyrnong than in the Yarra. A more detailed representation of this data can be found in Appendix A.

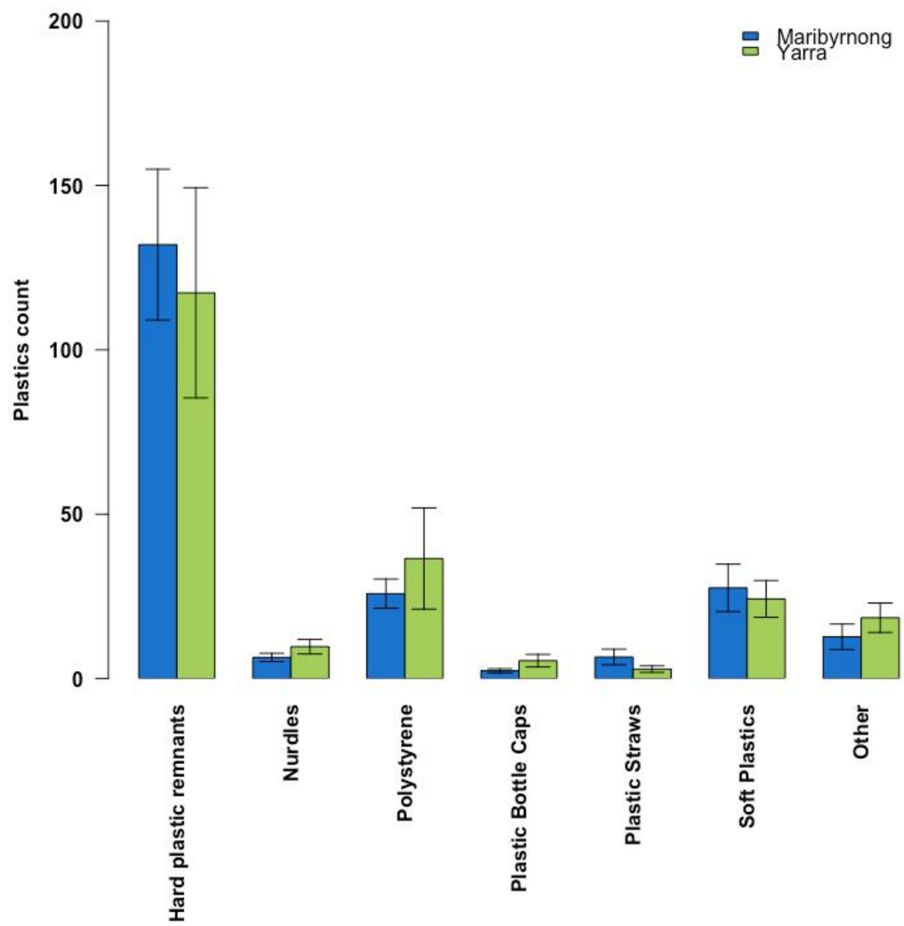


Figure 8: Comparison of mean monthly number (±SE) of litter items captured by the manta net in the Maribyrnong and Yarra Rivers between January 2015 and October 2017. Note that values shown are means, but statistical tests were conducted on frequency of counts using chi-squared analyses (i.e. the standard errors shouldn't be used to infer anything about statistical significances. They are rough indicators of variation around a mean only).

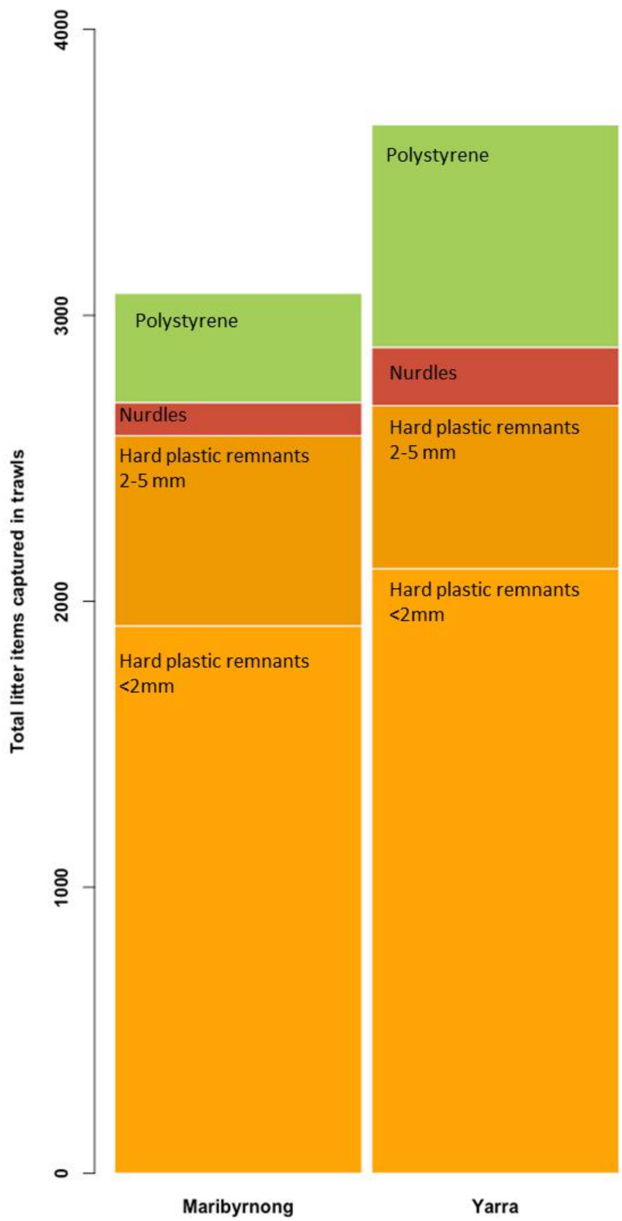


Figure 9: Total number of microplastics captured during river trawls.

In both rivers, microplastics formed the bulk of litter and accounted for 77% (4,889 pieces) of the total load in the Yarra and 67% (2,374 pieces) of the Maribyrnong load (Fig. 9). Hard plastic remnants <2 mm in length dominated the microplastics category and accounted for 57% and 63% of microplastics in the Yarra and Maribyrnong, respectively.

Of the earlier mentioned total litter entering the Bay, microplastics make up 74%, which means 612,178,842 microplastics flow *from the surface* of the two rivers into the Bay every year.

Seasonal differences in litter

There are significant effects of the seasons and the rivers themselves on the total count of litter (chi-squared = 463.0, df = 3, $P < 0.001$).

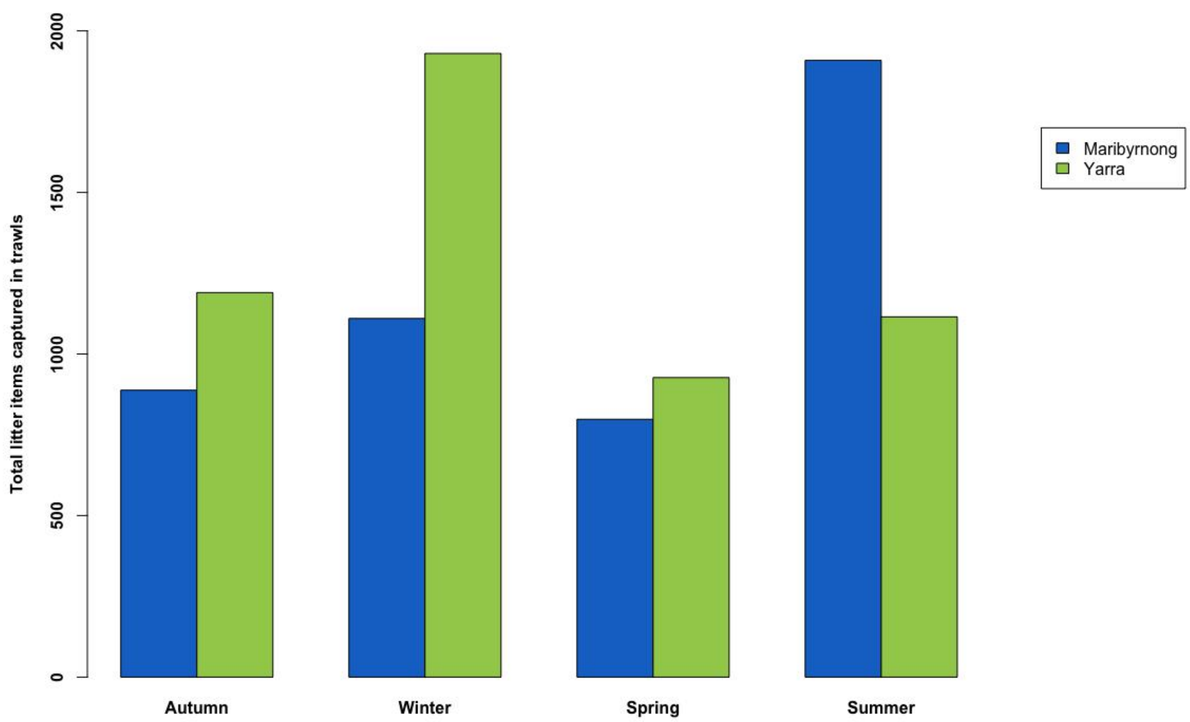
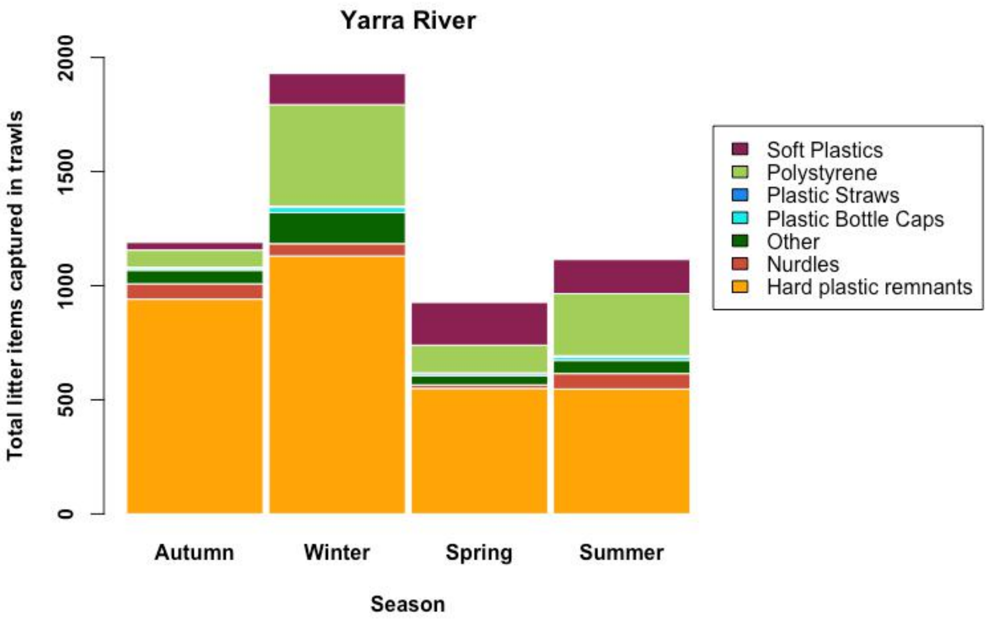


Figure 10: Seasonal variation in the number of captured litter items in the Maribyrnong and Yarra Rivers between January 2015 and October 2017.

In autumn and winter, plastic litter is more likely to be found in the Yarra than the Maribyrnong ($P < 0.05$ for both seasons). In summer however**,** plastic litter is more likely to be found in the Maribyrnong than in the Yarra ($P < 0.01$). The two rivers show no difference in their litter loads during spring ($P > 0.05$) (Fig. 10).

River height did not influence total litter capture. Similarly, BOM rainfall data from the Warrandyte and Melbourne Airport weather stations for the Yarra and Maribyrnong respectively, did not indicate an influence.

Figure 11 shows more detailed litter item distributions over the seasons for the separate rivers. Hard plastic remnants remain the largest category of items throughout all seasons in both rivers, followed by polystyrene and soft plastics, respectively.



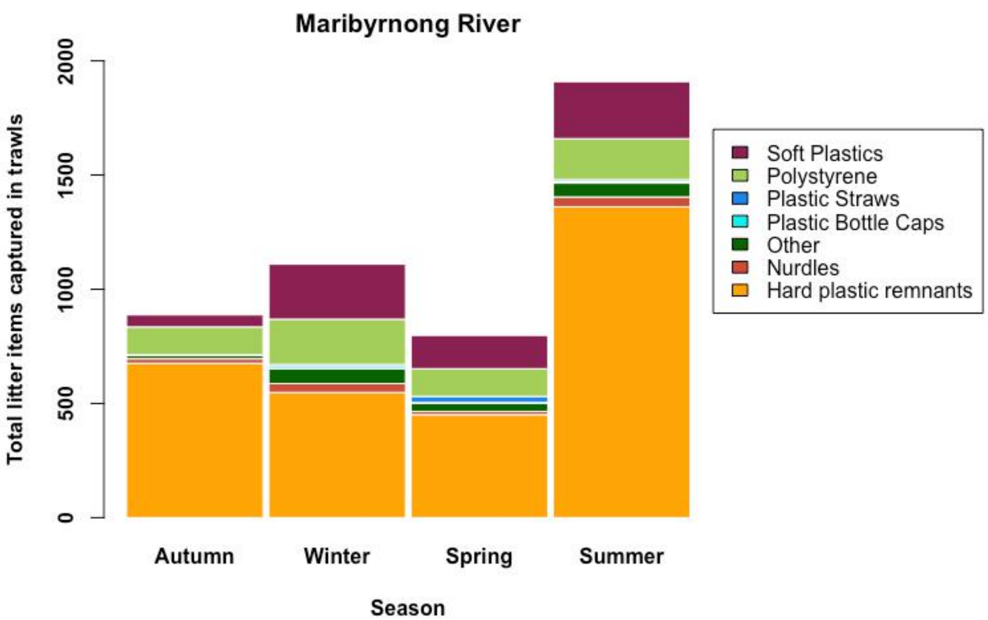
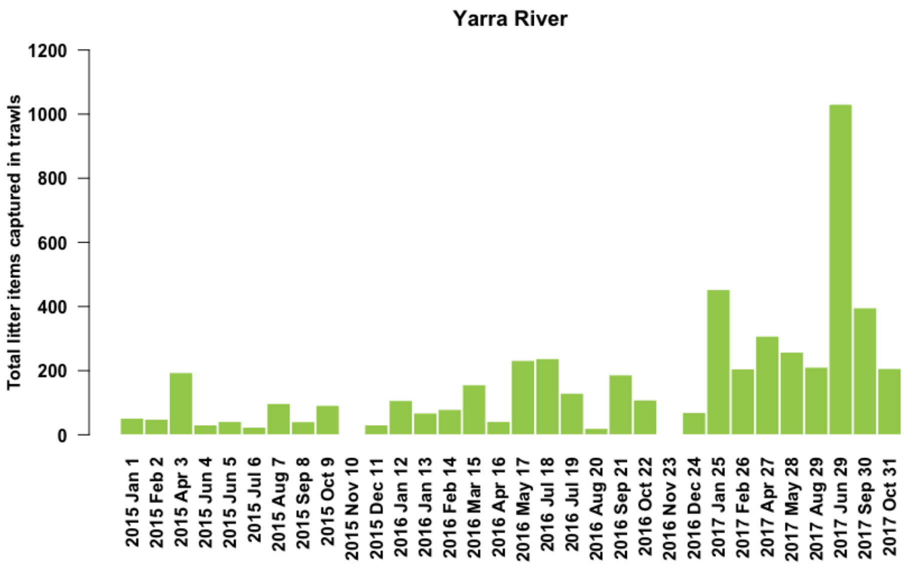


Figure 11: Seasonal variation in the total number of captured litter items in the Maribyrnong and Yarra Rivers between January 2015 and October 2017.

Changes in litter over time

Between January 2015 and October 2017, the number of litter items in the Yarra has increased significantly (Kendall's tau correlation test: z = 5.1, P < 0.001, tau = 0.168). However, there has been no overall change in the number of litter items captured in the Maribyrnong (Kendall's tau correlation test: z = 0.51, p-value = 0.610, tau = 0.174) (Fig. 12). Appendix B offers a more detailed graphic representation of these data.



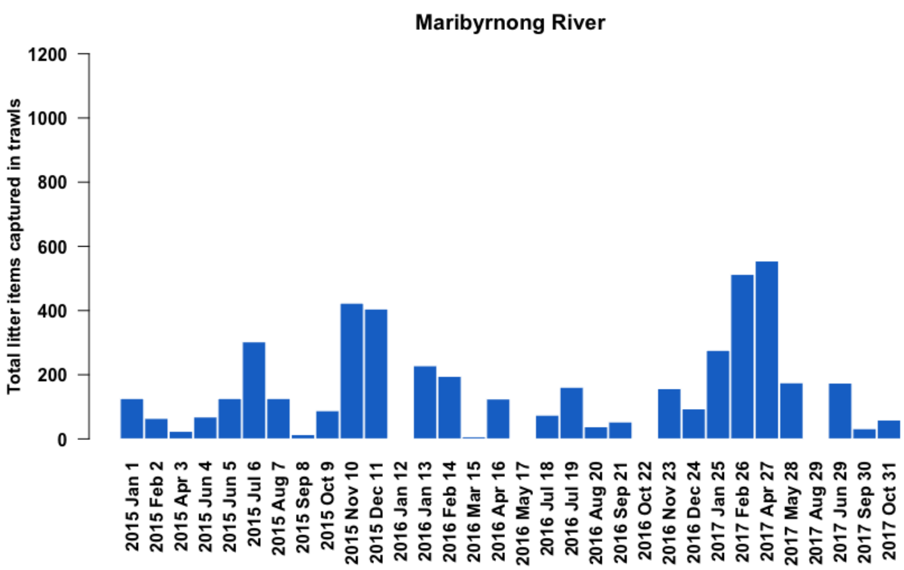


Figure 12: Total number of captured litter items in the Maribyrnong and Yarra Rivers presented by trawl between January 2015 and October 2017. The labels indicate year, month and trawl number. A total of 31 paired trawls were conducted during this time.

These results warranted a closer examination of litter changes in the Yarra over time: Nurdles, plastic bottle caps, straws, soft plastics and ‘other’ in the Yarra are not increasing over time (all $P > 0.05$). However, hard plastic remnants ($z = 4.6$, $P < 0.001$, $tau = 0.284$) and polystyrene ($z = 2.9$, $P = 0.004$, $tau = 0.261$) are significantly increasing.

Figure 13A shows the increase of hard plastic remnants in the Yarra between January 2015 and October 2017. Noteworthy is a very high count in the August 2017 sample (423 items of hard plastic remnants <2mm). Figure 13B shows the increase of polystyrene over time, which is partly driven by two high counts of polystyrene items. The highest count of polystyrene (336 items) was also found in the August 2017 sample.

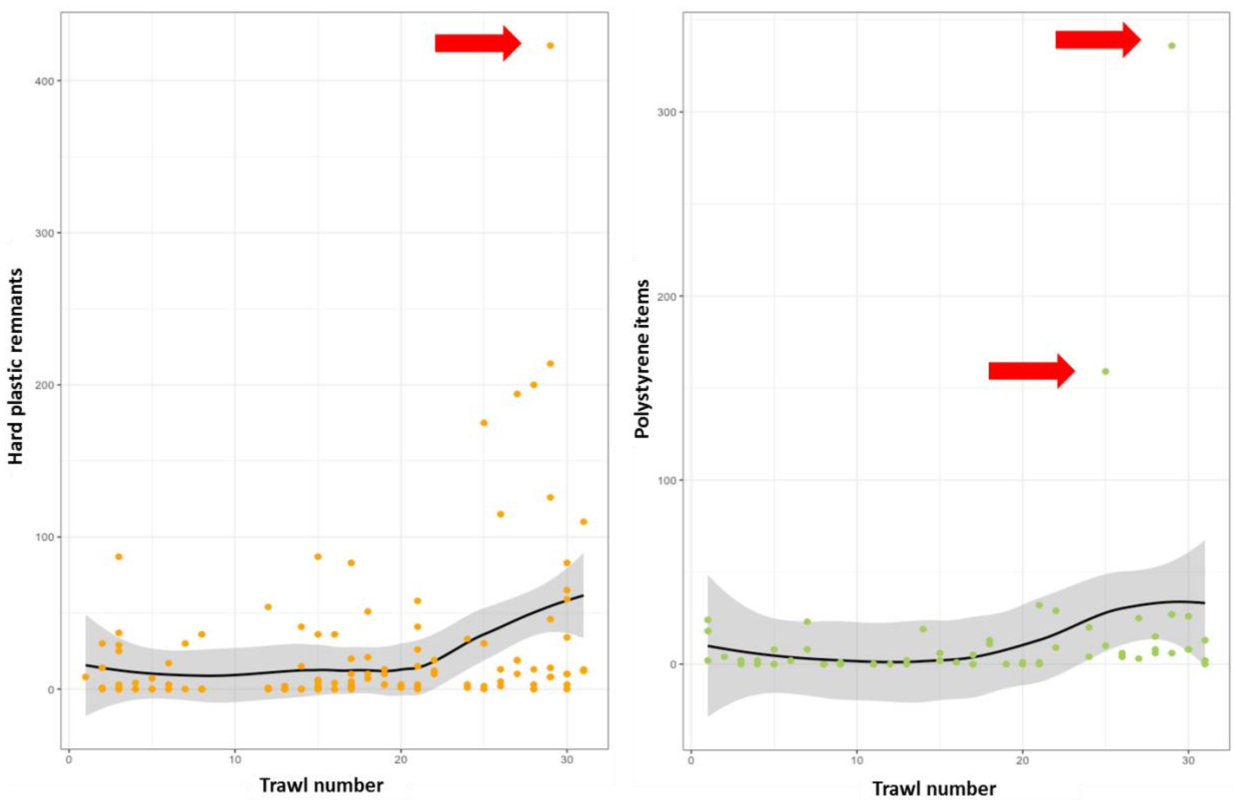


Figure 13: A. Number of hard plastic remnants in the Yarra River, between January 2015 and October 2017; B. Number of polystyrene pieces in the Yarra River, between January 2015 and October 2017.

Closer examination of these high data points revealed that both hard plastic remnants ($t = -85.3$, $df = 129$, p-value < 001) and the two polystyrene spikes (Jan 2017, $t = -24.8$, $df = 62$, p-value < 0.001; and Aug 2017, $t = -55.2$, $df = 62$, p-value < 0.001) were significantly above background counts.

Discussion

Litter quantification and composition in the Yarra and Maribyrnong Rivers

Clean Bay Blueprint and the preceding projects are the first studies to investigate microplastic loads in the Yarra and Maribyrnong Rivers and provide the first estimation of microplastic loads entering Port Phillip Bay on an annual basis. Each of the 60 trawl samples analysed between January 2015 and October 2017 contained plastic pollution, mostly consisting of microplastics. Nearly a billion pieces of plastic flow into Port Phillip Bay annually, of which well over half a billion are microplastics smaller than 5 mm in diameter. These results are expected to be underestimations of the litter volume entering the Bay, as it does not take into account the depth of the river and the fact that high-density particles with additives or other attachments and larger items such as plastic bags will sink below the level of trawled surface area (Mai et al. 2018). As the mesh size of the net was 330 nm and sorting and counting of microplastics was done with the naked eye, particles smaller than what could be caught in the net, or observed and confirmed as plastics during sorting (including microfibres and nanoparticles), were not included. It must therefore be emphasised that total plastic pollution numbers in the rivers are likely to be much higher than the numbers in this report and preventative and mitigating actions to reduce plastic pollution are urgently required.

Sample analyses revealed that hard plastic remnants, polystyrene beads and cellophane were the most common items captured. Despite the manta net's selectivity to small, buoyant items, the sample results largely align with local beach clean-up litter audits. Litter audits along the Westgate Park foreshore, and along St Kilda beaches between years 2015 and 2017, revealed foam packaging (polystyrene) and plastic film remnants (bits of plastic bags, wrap, cellophane etc.) are the second and third most dominant litter category, after cigarette butts (amdi.tangaroablue.org). As cigarette butts sink after a relatively short period in water, their numbers in the Yarra and Maribyrnong River trawls does not align with beach clean-up data. It is also worth noting that beach clean-up efforts are typically geared toward the collection of large litter items and small plastic remnants and microplastics are rarely recorded in litter audits (amdi.tangaroablue.org). This may explain the mismatch between trawl and beach clean-up litter findings. Nevertheless, trawl findings provide a fairly good representation of the broader marine plastic pollution issue, providing information about the composition and relative abundance of dominant buoyant litter items entering Port Phillip Bay.

When comparing the types of litter in the rivers, it was found that the Yarra has higher counts of polystyrene, nurdles, plastic bottle caps and ‘other’ items than the Maribyrnong, whereas straws and soft plastics are more problematic in the Maribyrnong. The extensive manufacturing, retail and hospitality precincts along the banks of the Yarra may be partly responsible for poor polystyrene management and disposal. Further investigation is required to account for this difference.

An alarming result of this study is that litter has been increasing in the Yarra and that the Yarra surpassed the Maribyrnong in terms of expected plastic pollution loads in 2016. These changes are driven by increases in hard plastic remnants and polystyrene rather than the other categories of litter, meaning these are the two litter categories that should be addressed immediately. As metropolitan Melbourne’s population is set to grow from 4.7 million to 7.9 million by 2051 (DELWP, 2017) and as the majority of people use plastic, it is expected that these plastic pollution increases will continue until effective measures are taken.

When examining the seasonal effects on the rivers, the Maribyrnong has its largest surface litter output in summer, while for the Yarra litter numbers are highest during autumn and winter. As rainfall and river height do not seem to have an effect on these results and both rivers behave so differently, it is likely that a combination of other factors drives this phenomenon. One reason for this difference could be related to differences in the industrial usage and population density along the rivers (Yonkos et al., 2014). Factors could also include sports events that draw large numbers of people to the vicinity of the rivers (Zbyszewski and Corcoran, 2011), such as football season for the Yarra and horse racing events at Flemington Race Course and increased riverine park use in summer for the Maribyrnong. Both rivers could be influenced by seasonal factors such as local council’s street sweeping schedules, management schedules maintained by Melbourne Water and in the case of the Yarra, the frequency of emptying the floating litter traps by Parks Victoria.

The latter could potentially play a role in the observed spikes in polystyrene and hard plastic remnants in the August 2017 Yarra sample; in 2013 a similar occurrence was observed during a trawl, in which the litter counts in the Yarra sample were unusually high. This event was traced back to the trawl coinciding with the emptying of the upstream litter traps that same day (N. Blake 2018, *pers. comm.*), in which small plastic pieces are lost into the environment due to the design of the litter traps and manner of emptying them.

Implications for marine life in the Yarra estuary and Port Phillip Bay

Port Phillip Bay is a relatively closed system, due to the distance between the Bellarine and Mornington Peninsulas being only just under 3.5 km. Due to the prevailing winds, it is likely the bay is a sink for a major portion of the plastics that enter it from the rivers. To date, very few studies have assessed microplastic ingestion/interaction rates for species in Port Phillip Bay. However, worldwide freshwater and marine species at all trophic levels, possessing varied feeding strategies, ingest microplastics (Eerkes-Medrano et al., 2015). In lab based studies, ingestion has been associated with: the retention and accumulation of microplastics in organisms including mussels (Browne et al., 2008), lobsters (Murray and Cowie, 2011) and scallops (Brillant and MacDonald, 2000); injury and subsequent disrupted feeding/swimming activity in lugworms (Browne et al., 2013), stress, immune response, altered metabolic function and toxicity in lugworms (Browne et al., 2013), fish and mussels (Rochman et al., 2013), and tumor formation in fish (Rochman et al., 2013), to name a few.

This study found that microplastics form the bulk of items entering the Bay from the surface waters of the rivers. Smaller sizes of plastic can potentially be ingested by a larger range of species. Because of the Bay's potential for high microplastic concentration and because these waters are so biodiverse, high rates of plastic ingestion are likely. Faunal ingestion rates and impacts of marine microplastics at the individual, population, and community levels need to be assessed to prevent biodiversity loss in the Bay and to better understand the human health implications of consuming seafood from the Bay.

Especially in the light of the State Government's $46 million Target One Million plan, aiming to grow recreational fishing in Victoria to 1 million anglers by 2020, and investments in aquaculture in the Bay, the potential effects of eating seafood from the Bay on public health should not be ignored.

Further study on microplastics

The estimations in this study showed that the Yarra and Maribyrnong can transport over 2 million plastic pieces - of which more than 1.6 million are microplastics - into Port Phillip Bay daily and that this may be an underestimation. Ling et al (2017) noted that plastic filaments, including highly pervasive clothing microfiber pollution, between 0.038 mm and 0.250 mm formed the dominant categories of microplastic in coastal and estuarine sediments around Australia, including Port Phillip Bay (Ling et al., 2017). However, we know little about the downstream movement and deposition of microplastics in rivers. It is unclear what portion of riverine microplastics travel downstream and what portion is deposited to the sediment. Some microplastics are likely transported long distances, as several studies report high concentrations of microplastic in estuaries, with rivers implicated as major microplastic sources to these coastal zones (Yonkos et al., 2014, Lima et al., 2014, Sadri and Thompson, 2014). An example of this was revealed during a community clean up event organized by the Yarra Riverkeeper Association in April 2018, where a vacuum suction device deployed by Ocean Crusaders removed over 4.7 million polystyrene balls and pieces from the Yarra River and its banks (A. Kelly 2018, *pers. comm.*).

Some microplastics are deposited into sediments. In the North Shore Channel for example, microplastic concentrations in sediments were up to 15,000 times higher than surface water samples (Hoellein et al., 2017). Consequently, in order to accurately identify the magnitude of microplastic pollution in Port Phillip Bay it is necessary to better understand microplastic depositional patterns and take into account factors such as hydrology (i.e., storms), geomorphology (i.e., depositional zones), and locations within river networks to name a few.

Recommendations

There is now irrefutable evidence that plastics and microplastics have an unacceptable impact on the environment. Many governments have now accepted the recommendation from the science community that society should not wait until there is more quantified evidence of the degree of damage before acting to reduce marine plastic pollution impacts (Lavers and Bond, 2017, Gall and Thompson, 2015). In their report 'Marine Plastic Debris and Microplastics' the United Nations stated that there is a moral argument that we should not allow the ocean to become further polluted with plastic waste, and that marine littering should be considered a 'common concern of humankind' (UNEP, 2016).

The high quantities of litter and microplastics in the Yarra and Maribyrnong Rivers highlight the large contribution of these rivers to marine plastic pollution mass in Port Phillip Bay. It is important to note that the numbers of microplastics mentioned in this report are underestimations of microplastic loads in the rivers. In light of these results, the emphasis needs to be on the importance of immediate measures to manage plastic pollution at all stages of its 'life-cycle', but particularly at the early stages where plastic sources are known and can be more easily contained.

The results of this study generated several recommendations.

1) *Improve the life-cycle stewardship of plastic*

As the bulk of the litter samples in this study contained mostly hard plastic remnants, broken up from larger plastic items, it is essential to improve on plastic waste management practices of the items that result in these microplastics. This includes large-scale infrastructure like a container deposit scheme, tackling items such as bottle caps and plastic bottles, before they make their way into the rivers and break up into microplastics.

Recently, China announced it will not be importing any more recycling from Australia. This has presented the government with a rare opportunity to redesign new waste management and recycling systems with a circular economy structure. Necessity is a great driver of innovation and as such some Victorian plastics manufacturers have already invested in machinery that can process used recyclables (including moderately contaminated plastics) back into nurdles and then into the next life stage of plastic products for sale to the public; all within their own, local manufacturing business (F. Charko 2018, *pers. comm.*). Reshaping the lifecycle of plastic and keeping the processes in-house and local could change the way we value plastic as a resource, and reduce the use of new fossil fuels for the manufacturing process.

In addition to ecological benefits, early-stage interventions would reduce the opportunity cost of volunteers spending time manually removing litter from the environment, which is costly (Australian Conservation Foundation, 2011) and relatively ineffective, as it is treating the symptom rather than addressing the cause. One example of a low-cost early intervention is the placement and management of storm water drain pollutant pit traps in key places draining into the river systems.

On an industry level, nurdles can be vastly reduced in the environment by implementing a stewardship best practice product handling manual such as Operation Clean Sweep (opcleansweep.org.au) and making this mandatory for all users and manufacturers of nurdles in Victoria.

2) *Implement bans on the use of unnecessary plastic from a higher level perspective*

Internationally, countries like Britain and Scotland are implementing an increasing number of bans on problematic litter items such as straws and plastic bags. At the time of writing, the Victorian State Government has joined most other Australian States by announcing the implementation of a ban on plastic bags, sparking the largest number of public consultation submissions ever received by the Department of Environment, Land, Water and Planning (DELWP 2018, *pers. comm.*). An overwhelming majority (over 90%) of the thousands of respondents were in favour of the ban.

Although banning items such as straws and ubiquitous packaging of fruit and vegetables in supermarkets is a start towards preventing these items from getting into the environment, we recommend future bans are implemented on a higher level materials-based approach, rather than by individual end product, to avoid perverse incentives (such as offering thicker plastic bags for a price). This means that rather than product-by-product bans, the government needs to implement higher level regulations that require materials and designs to fulfill a set of sustainability criteria at all stages of their life cycle. Products that do not fulfill these criteria could then be amended or phased out by an agreed date.

3) Stimulate innovation and alternatives to plastic products

Reducing the amount of plastic used by the growing Victorian population is most likely the key to reducing the trend of increasing plastic pollution in the Yarra. The government can play an important role in the transition away from plastic, seeking opportunities to work closely with industry, and stimulate new products designed to replace plastics by investing in innovative ideas and promising start-ups. Similarly, existing plastic manufacturers should be stimulated and supported (e.g. with subsidies or tax breaks) to make the change to alternative forms of packaging and move away from producing plastics. Packaging products like polystyrene, which were particularly problematic in the Yarra and on the increase, need to be replaced by truly environmentally friendly alternatives.

4) Cultivate effective partnerships and taking shared responsibility

The problem of plastic pollution is everybody's. It is as much the responsibility of the community and government, as it is the industry's. To reduce plastic pollution in the environment, it is critical that conversations and true working partnerships are forged and maintained with a long-term vision of collaboration and tangible outcomes. An example of what this could look like is the Californian Blue Business Council, run by a community organisation and consisting of businesses that recognise their ecological and economic dependence on clean water and work as a network to implement business models that prioritise healthy waterways (bluebizcouncil.org).

On a community level, the Victorian Government is pro-actively investing in research and community partnerships to trace the chemical and geographic origins of plastic pollution, including hard plastic fragments. At the time of writing of this report, the second round of successful Port Phillip Bay Fund applications was announced. One of the projects to be funded is The Plastics Lab, to be based at RMIT University, which is a laboratory that will assist the community with the chemical analysis of microplastics and improve the identification of source products. In addition, Scouts Victoria was successful in their application to conduct Baykeeper

Street to Sea litter audits in various areas of the catchments, allowing for a closer look at sources of plastic pollution in Port Phillip Bay.

5. Increase education and 'plastic literacy' of all plastic users

As part of cultivating shared responsibility of plastic use and disposal, education of plastic product users on responsible plastic use and disposal is essential. The State Government has rightly decided to invest in education by funding education-based projects through the Port Phillip Bay Fund, but social change requires engaging a critical mass of the entire plastic-using population, which is effectively every Victorian. We recommend a multi-pronged approach, including via formal education of all levels (including in design and engineering), mainstream media and community organisations.

Future focus of Clean Bay Blueprint

The monthly river trawls of the Clean Bay Blueprint project will continue until May 2020 and are expected to yield a total dataset of nearly 5.5 years' worth of information on microplastic pollution. The results can be used as both a baseline for plastic pollution loading of the Maribyrnong and Yarra Rivers, but also have the potential to be a measure of the effectiveness of any large scale anti-litter measures and programs that may be delivered by others in the next three years.

From April 2018 to February 2019, a pilot program of 10 additional manta net trawls will be conducted in the Bay, between Port Phillip Heads and Pope's Eye. The intention is to investigate what plastic pollution comes into the bay with the incoming tide and southerly winds from the Bass Strait, to paint a more complete picture of litter influx into the bay from the ocean.

Acknowledgments

We thank the Victorian Government for financial support of the Litter Hotspots and Clean Bay Blueprint projects and all EcoCentre research volunteers for their field and sample analysis assistance. We acknowledge Christopher Johnstone for his work on the data analysis, and Professor Mark Osborn for reviewing and commenting on the draft report. We acknowledge Andrew Kelly, the Yarra Riverkeeper, for his invaluable river expertise and Parks Victoria for access to the Burnley Wharf. Research was conducted under research permits issued by the Victorian Government's Fisheries Act 1995 (RP1234).

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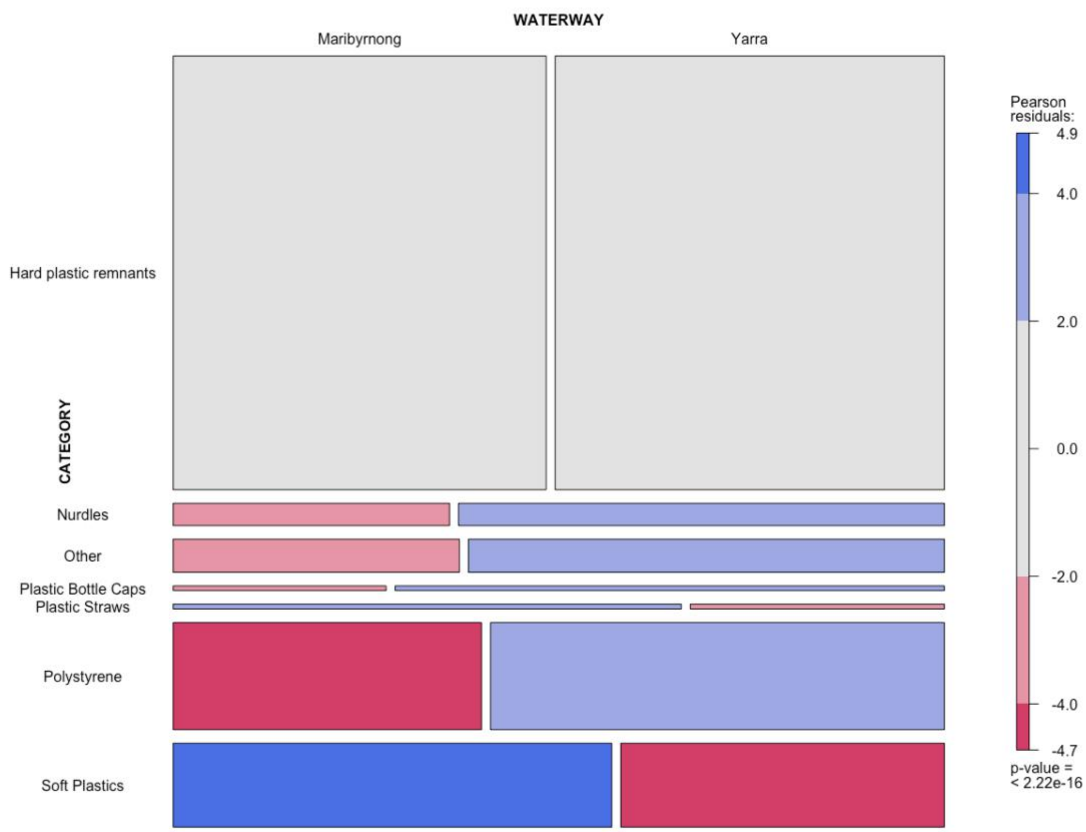
Appendices

Appendix A

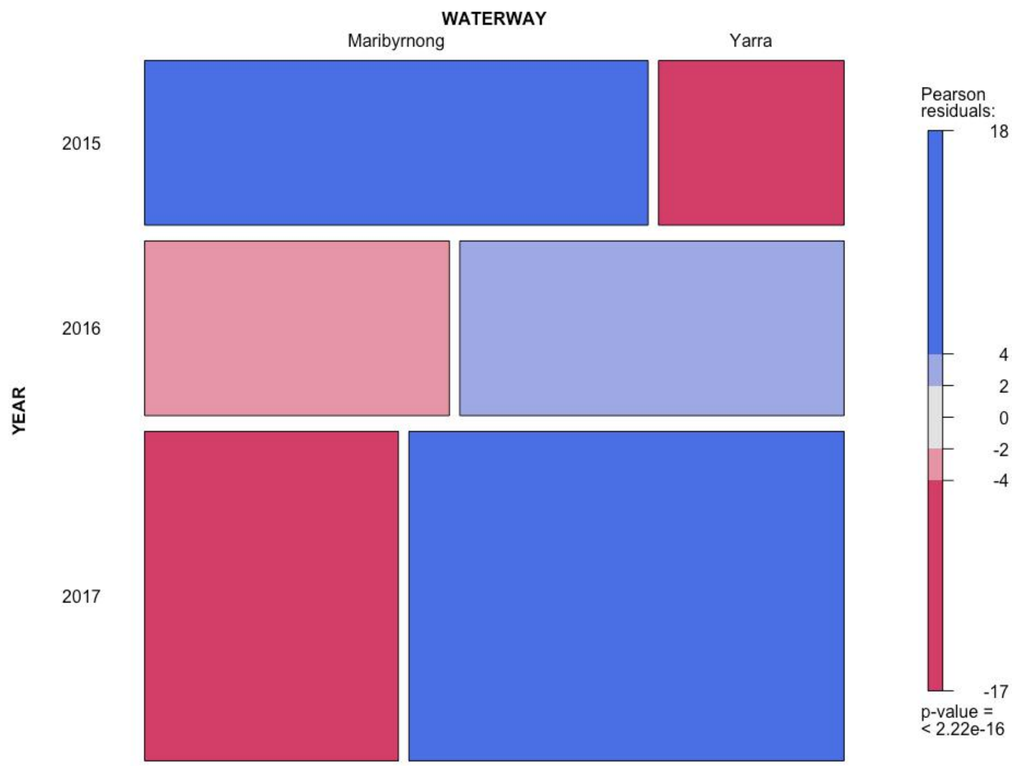
Mosaic plot 1 (which can be viewed similarly to figure 7, but upside down) shows the item counts in the different litter categories and compares them to the expected levels of litter in the Maribyrnong and Yarra Rivers. Red indicates a significantly lower than expected number of the item category; blue indicates a significantly higher than expected number. The brighter the colours, the more the data differs from expected levels. Grey indicates there is no difference in expected litter between the two rivers. The heights of the blocks represent the portion of item counts for a particular river. Widths of the blocks indicate the portion of total counts in a particular item category.



Mosaic Plot 1: Comparison between the expectations of finding the different items in the Maribyrnong and Yarra Rivers.

Appendix B

Between January 2015 and October 2017, the number of litter items in the Yarra has increased significantly (Kendall's tau correlation test: z = 5.1, P < 0.001, tau = 0.168). However, there has been no overall change in the number of litter items captured in the Maribyrnong (Kendall's tau correlation test: z = 0.51, p-value = 0.610, tau = 0.174). When the same significant results are visualized by year (mosaic plot 2), it shows that litter counts have been increasing in the Yarra compared to the Maribyrnong, and have been since 2016, with blue blocks indicating a higher than expected litter load and red a lower than expected litter load.



Mosaic plot 2: Comparison of litter in the Maribyrnong and Yarra Rivers over time.