Impacts of stormwater outlets on microplastic distribution within water, sediment and biota along the Cape Peninsula of Cape Town.

By

Rushdi Ariefdien

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Supervisors: Dr Conrad Sparks and Dr. Maya Pfaff

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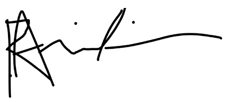
DECLARATION

I, Rushdi Ariefdien, declare that the contents of this dissertation represent my own unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed  Date 22/01/2024

Abstract

Microplastics (MPs) are contaminants that can be found in coastal ecosystems. The exact sources of MPs brought into coastal waters are relatively unknown, however, runoff from stormwater outlets is said to be one of the main general inland sources that contribute to MPs in coastal ecosystems. Stormwater runoff in many coastal cities is poorly managed and contributes approximately 80% of plastics found in coastal ecosystems. This study aims to identify if stormwater outlets are indeed a source of introducing MPs into coastal environments via runoff and whether MPs introduced into these locations are causing a risk within the environment and biota. The study compared impacted stormwater sites at Camps Bay, Mouille Point and Three Anchor Bay (Cape Town, South Africa) with a referenced control site. It was found the stormwater impact sites were indeed a source to contribute a higher abundance of MPs. The study found that the total abundance of MPs in samples during summer (dry season) within mussels – *Mytilus galloprovincialis,* sea urchins – *Parechinus angulosus*, whelks – *Burnupena sp*. (per grams of soft tissue wet weight), water (pet litre) and sediment (per kilogram) had a significantly higher concentration of MPs with a total abundance of 4.96 ± 0.39 (standard error) particles per unit, while winter (wet season) had an abundance of 3.95 ± 0.78 particles per unit. It should, however, be noted that water and sediment were found to have a significantly higher concentration during winter, while biota (mussels, sea urchins, whelks) were significantly higher during summer. Using four risk indices Contamination factor (CF), Pollution load index (PLI), Pollution risk index (PRI), Polymer risk index (H) and a condition index, MPs around stormwater outlets were assessed to gain an understanding of the risk MPs are having on the environment and biota. Risk assessments done on water, sediment and biota found that all sites were at a high risk for CF and moderate for PLI. The H and PRI calculations found that only Camps Bay was at a high and very high risk due to the types and amounts of polymers found at this location. The condition of mussels was also found to be negatively influenced by stormwater outlets as their condition decreased with the increase of MPs. To conclude, stormwater outlets are indeed a source of transporting MPs into the coastal environment and pose risks to the health of organisms like mussels.

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ABBREVIATIONS AND ACRONYMS

Contamination Factor	CF
Dry Weight	DW
Fourier-transform infrared spectroscopy	FTIR
Potassium hydroxide	KOH
Microplastics	MPs
Polybutylene terephthalate	PBT
Pollution Load Index	PLI
Pollution Risk Index	PRI
Polymer Risk Index	H
Polyethylene Terephthalate	PET
Polypropylene	PP
Polystyrene	PS
Polyvinyl Acetate	PVA
Polyvinyl Chloride	PVC
Polyvinylidene Fluoride	PVDF
Soft Tissue Wet Weight	STWW
Wastewater Treatment Plant	WWTP
Waste Water Treatment Work	WWTW

Chapter 1 – General Introduction

1.1 Introduction

Since the 1960s, plastic production has grown rapidly on a global scale and has affected various ecosystems (Geyer et al., 2017). Large coastal cities all around the world distribute approximately 80% of plastics from land base sources via drainage systems (Jambeck et al., 2015). Drainage systems such as stormwater outlets are one of the main distributors of plastic pollutants to coastal environments, and this has become a major concern globally (Weideman et al., 2020; Jannö, 2016; Jönsson, 2016).

The Cape Peninsula of Cape Town is affected by various stormwater drainage systems. Very little information exists of these drainage systems and catchment areas. The exact catchment area of these stormwater outlets is not mapped out and it's abstruse to distinguish the type of areas that are impacting the catchment areas in terms of industrial, residential or more pristine. Nevertheless, runoff from these structures goes unscreened or treated into coastal waters in the intertidal and subtidal zones (Weideman et al., 2020). Runoff introduces an array of pollutants and waste into the coastal environment. Waste products of high concern are microplastics (MPs), which are particles smaller than 5 mm that occurs in various shapes such as fragments, fibres, films or spheres (Depledge et al., 2013; Nel and Froneman, 2015; Nel et al., 2017). The MPs particles can then be defined based on polymer types, which all have different hazardous scores (Lithner, 2012).

The source of MPs in coastal areas is hard to determine, but most are derived from land-based sources and enter the coastal region via rivers or drainage systems. Previous studies have indicated that rivers and stormwater outlets are sources of MPs into the coastal environment (Jannö, 2016; Jönsson, 2016; Preston-Whyte et al., 2021; de Villiers, 2018). According to Jannö (2016) and Jönsson, (2016), MPs concentrations increase in the rainy season due to high precipitation and runoff entering the coastal region.

The abundance and distribution of MPs is unknown around stormwater outlets in Cape Town, and it is imperative to obtain more information to understand the potential impact of MPs in the coastal region. Water, sediment and invertebrates are adequate monitoring media to identify the abundance of MPs at a specific location. By obtaining the abundance of MPs in biotic and abiotic samples, risk indices can be used to ascertain the impact of MPs in the environment. Risk indices are not only limited to the abundance of MPs, but also indicate the hazardous risk based on the type of polymers. Lithner et al. (2011) have distinguished a hazardous score for each polymer type, allowing to calculate the risk to the environment or fauna is in by using the polymers found at impacted locations. Regarding the intake of MPs in fauna, very little is known about how they react. Therefore, condition indices are also crucial information that can tell us the impact that stormwater sites are having on fauna.

There is a lack of comprehensive literature on the current research hotspots, circulation process and future development trend of MPs in aquatic ecosystems (Gao et al., 2022). When it comes to MPs research, very little is known due to the limited amount of published literature (Gao et al., 2022). Many countries, including South Africa, have identified MPs as a global concern and research and monitoring of MPs has taken place (Browne, 2011; Mvovo, 2021). Therefore, this dissertation investigates whether stormwater outlets are a source of introducing MPs into the coastline and to identify the potential hazard of MPs in the coastal environment of Cape Town.

The distribution and abundance of MPs around stormwater outlets is covered in chapter three. The aim of this study is to provide insight into whether stormwater outlets are bringing a higher abundance of MPs into coastal waters. By using a reference control site, we can compare the abundance of MPs found at impacted sites adjacent to stormwater outlets and control sites that are roughly 200 metres away from them. The chapter will cover MPs found at an impact (impacted by stormwater outlet) and a respective control site within the intertidal and subtidal zones at Camps Bay, Mouille Point and Three Anchor Bay. The results on this chapter will be on fauna from three different feeding groups, being mussels, sea urchins and whelks, and abiotic samples being water and sediment. The results will illustrate whether the impacted stormwater systems are indeed a source of introducing high amounts of MPs into the coastal region. FTIR analysis will be presented in this chapter to identify the types of polymers found at sampled sites.

Chapter four will be based on environmental risk indices and condition indices. To further the study, risk assessment calculations were done to give us an understanding of how polluted impacted stormwater sites are by using the contamination factor (CF) and pollution load index calculations (PLI). By using FTIR analysis we can distinguish the type of polymers that these stormwater outlets are inserting into coastal marine waters. By using the polymer hazard scores we can determine how hazardous impacted sites are by calculating the polymer risk index (H) and the pollution risk index (PRI). Additionally, this chapter will cover the condition index calculation done on biota, to establish whether stormwater outlets are having a negative effect on the health status and physiological activity of invertebrates. Risk indices will be calculated to understand the level of impact MPs are having on fauna and the environment.

Chapter 2 – Literature Review

2.1 Introduction

The human population is currently on the rise, with coastal areas commonly being urbanised and surface water flow constantly being altered, which causes physical, chemical and biological impacts on the marine environment (Walsh, 2000). Coastal communities all around the world have managed runoff by using drainage structures. These drainage structures known as stormwater outlets evidently discharge effluent into coastal marine environments. The discharge from these outlets introduces anthropogenic materials such as MPs into the intertidal and subtidal zones (Jambeck et al., 2015). Due to population rise, runoff entering the marine environment has become a great threat to ecological environments and human health. The City of Cape Town is a large coastal city with 4.5 million inhabitants (World Population Review, 2020), covering 307 km of coastline that is highly ecologically diverse and productive (https://www.capetown.travel/wp-content/uploads/2022/02/CT-Coastal-Map-2021-Web.pdf).

South Africa is ranked 11th in the world for worst contribution of plastics (Jambeck et al., 2015). Studies from Jambeck et al. (2015) estimated a 4.8 – 12.7 million tonnes of plastic waste are released into coastal ecosystems annually and it is estimated that South Africa contributes 0.09 – 0.25 million tons of plastics from land-based sources, with Cape Town being responsible for 40% of plastics entering the coastline from coastal cities (Collins and Hermes, 2019). Coastal ecosystems are therefore prone to be impacted by stormwater systems. Plastic litter causes several impacts around the marine environment which is, unattractive, causes health hazard for humans and wildlife (Armitage and Rooseboom, 2000). MPs have the ability to carry pathogens and is extremely costly to conduct clean ups (Armitage and Rooseboom, 2000). One of the key reasons that plastics are consistently introduced into our coastal areas is due to poor waste management and poor drainage structures (Jambeck et al., 2015).

MPs have been identified as a threat to the environment since the 1970s, however, only recently have they been recognised as a global problem in the water environment (Yin et al., 2021). Due to their stable chemical profile, MPs, which are ubiquitous in the oceans, can exist in marine environments for centuries. Marine MPs derive predominantly from primary and secondary sources. The plastic particles that are added to personal care and cosmetic products are primary MPs. A lot of these plastics found in the environment are MPs. Research in this field from 2013 to 2020 has grown exponentially, and research topics in environmental science, public environment science ecology and toxicology have increased (Yin et al., 2021). Most studies have mainly focused on the abundance and distribution of MPs, but hardly any of them focus on the risk MPs pose on the environment and the functionality of ecosystems. It's imperative to understand the source, abundance and characteristics of MPs to get a better understanding of the threat to the environment and to inform waste management in order to produce a better functional plan to reduce MPs from entering coastal environments.

2.2 Characteristics and impacts of microplastics

MPs can be defined as any synthetic solid particle or polymeric matrix that ranges between 1 µm and 5 mm and are potentially hard to see with the naked eye (Frias and Nash, 2019; Depledge et al., 2013; Nel and Froneman, 2015; Nel et al., 2017). MPs can be divided into four categories: size, colour, shape and polymer type (Mvovo, 2021). Various studies have indicated that the main types of colours found were white transparent, blue and black (Hennicke et al., 2021, Sevillano-Gonzalez et al., 2022, Feng et al., 2020, Nel and Froneman 2015), although these colours could often be mistaken under the microscope (Mvovo, 2021). MPs either originate directly in micro forms, called primary MPs, or are abrasions from larger MPs, known as secondary MPs (Depledge et al., 2013, Nel and Froneman, 2015). Primary MPs are produced in the form of a pellet or nurdle (Nel and Froneman, 2015). The most common source of MPs found in the marine environment are secondary MPs (Nel and Froneman, 2015). Secondary MPs can be found as fibres, fragments, spheres or film. The majority of the shapes of the MPs found in China were predominantly fibres (Li et al., 2018b), with most of the MPs ranging from 0.5mm – 1.0mm in size (Zhang et al., 2017; Wang et al., 2019b).

MPs found in the marine environment either have a low or high density. A lower density allows plastic particles to float on the sea surface, while highly dense particles sink (Mvovo, 2021). MPs come in various polymer types: polystyrene (PS), polyvinyl acetate (PVA), Polyethylene terephthalate (PET), Nylon and Polyvinyl chloride (PVC) (Collins and Hermes, 2019). Three of the top polymers found in Africa's MPs research are polyester (PET), polypropylene (PP) and polystyrene (PS) (Mvovo, 2021). MPs fibres that are commonly found in the ocean due to washing of laundry and domestic drainage (Almorth, et al., 2017) are mainly nylon, PET and PP (Gago et al., 2018). Lithner et al. (2011) rank these polymers on a hazardous score, meaning that each polymer is ranked based on the hazardous substance from which they are made.

MPs are a hazard since they take extremely long to degrade and their surface area absorbs organic pollutants, heavy metals, pathogenic microorganisms and plastics additives that are released during the cracking process (Klingelhofer et al., 2020, Chen et al., 2019). MPs have been noted to cause detrimental impacts towards biota and humans due to their movement up trophic levels. The inability to degrade poses a major threat to all water ecosystems as well as human well-beings (Gall and Thompson, 2015; Mvovo, 202). MPs are vectors for transferring chemicals as they absorb various organic pollutants, heavy metals, and endocrine-distributing compounds (Prarat and Hongsawat, 2022). A study done by Selvam et al. (2021) found that six different elements of metals have been identified in commercial fish, showing a significant relationship between MPs and metals.

MPs are a high risk to gametes, embryos and offspring as they cause profound toxicity (Yin et al., 2021). MPs can interfere with plasma membrane fluid and inhibit the binding of gametes or cover the surface of embryos, causing hypoxia, affecting nutrient absorption and causing abnormal growth and metabolic disorders in offspring (Yin et al., 2021). It has been noted that smaller MPs have a higher bioavailability, and the retention times are much long in organisms meaning more toxic to biota (Jeong et al., 2016).

Ingested MPs cause various physical damage to internal organs and tend to accumulate toxins in the bloodstream (Li et al., 2020b). Some of the main effects of MPs ingestion are starvation, gut damage, reduced digestive efficiency and a reduction in energy storage (Watts et al., 2015). MPs can also destroy the ratio of probiotics and pathogenic bacteria, reduce the secretion of mucus in the intestines and lead to the destruction of the intestinal barrier, and cause a lipid deposition (Li et al., 2020a). MPs usually enter the oesophagus, stomach, and intestines via the mouth of organisms, causing a toxic effect to the digestive tract (Yin et al., 2021). A study done by Brennecke et al. (2015) detected MPs in gills, stomach and hepatopancreas of crabs. Usually, after MPs are digested and pass through the intestinal barrier, they can enter other internal tissues of the organism (Dawson et al., 2018).

MP are evidently vectors for transporting toxic chemical compounds, thus, when ingested by biota they bio-magnify through the food-web (GESAMP, 2015). The adsorption of chemicals accumulated on MPs can cause several lethal and sub-lethal effects (Wang et al., 2018). A study done by Gray and Weinstein (2017) state that MPs fibres accumulated faster and caused a greater degree of acute toxicity than MP fragments and beads. Another study by Qiao et al. (2019) records that those MPs fibres had a prominent impact on biota compared to other forms of MPs, causing notable physical damage, decrease in weight and increase in stress. Yin et al. (2021) also state that MPs are mainly found in water bodies and are mostly harmful to marine life.

MPs can stay in the marine environment for hundreds of years since they degrade slowly (HELCOM, 2010; Lassen et al., 2015; Depledge et al., 2013). MPs are capable of disturbing food webs by mimicking food particles, adsorbing hazardous bioaccumulative substances and causing famine in filter feeders (HELCOM, 2010). Plastic debris in sandy terrains tends to change the volume of water flushed through sediment, fluxes of organic matter and biological activity (Lamprecht, 2013). Plastics insulate heat and can reduce the subsurface temperature of sediment, thus affecting breeding periods in specific organisms (Lamprecht, 2013) and making them a high concern to marine ecosystems.

2.3 Spatial distribution of microplastics

MPs have been found in seawater and sediments and, because of their small size, they are also easily ingested by a wide range of marine animals (Gall et al., 2015; Galloway et al., 2017, Depledge et al., 2013; Nel and Froneman, 2015; Nel et al., 2017). As a result, microplastic pollution is posing a threat to marine ecosystems (Lei et al., 2017). Anthropogenic activities such as leisure activities, surface runoff, wastewater treatment plant effluents, aquaculture and fisheries, dumping of domestic and industrial waste, and even air pollutants can all contribute to MPs from both primary and secondary sources entering and impacting seawater, causing these areas to have a higher concentration of MPs (Talvitie et al., 2017; Simon et al., 2018; Wright et al., 2020).

The distribution of MPs in ecosystems come in various patterns and sources, which are not well researched in developing countries (Mvovo, 2021). There is various published literature globally on the distribution of MPs within water, sediment and various invertebrate species. Studies by Sparks (2020), Nel and Froneman (2015), Sparks and Awe (2022) and de Villiers (2018) have all assessed the distribution of MPs in either water, sediment or invertebrates along South Africa's coastline.

2.3.1 Microplastics in water

A study by Jiang et al. (2022) revealed that MPs abundance found in the seawater of four key seas of China ranged from 0.13 – 545 items/m^3, which is on par with those recorded in other nations, sometimes ranging even lower. A South African study done by Nel and Froneman (2015), found an average of 257.9 ± 53.36 to 1215 ± 276.7 MPs particles/m^2 in water.

Nel and Froneman (2015) found mainly fibres and fragments and made no direct linkage to the population increase, which suggested that the source of MPs was not mainly from inland sources but were brought in by water circulation. Jiang et al. (2022) found a higher MP abundance during the wet season compared to the dry season, suggesting that stronger plastic waste recycling strategies should be implemented in preparation for the wet season. Due to higher energy events that most likely occur during the winter period, it is assumed that MPs are resuspended from sediment, causing more MP particles to be found in surface water (Bom et al., 2022).

The composition of MPs varies across regions considerably. Studies based in China found that 56% of the total MPs sampled from Jiaozhou Bay were PET (Zheng et al., 2019), and 51% of the total MPs sampled from the Bohai Sea were PE (Zhang et al., 2017). A subsequent study, however, found that 91.8% of fibres in worldwide oceanic surface waters came from plants and animals and were in fact not plastic. This implies that prior studies may have overestimated the amount of MPs in marine ecosystems (Suaria et al., 2020). As a result, a more precise methodology for identifying microfibres should be devised (Jiang et al., 2020).

2.3.2 Microplastics in sediment

MPs research on sandy beaches is well documented (Pinheiro et al., 2019). The strandline of these environments is constantly analysed for MPs that the previous tidal cycle has deposited (Pinheiro et al., 2019). Although sediment is one of the top-studied fields regarding MPs research, concentration in sediment is often represented in two units: items/kg and items/m², which makes comparing MP levels across research challenging. Different sampling and floating procedures, on the other hand, may have an impact on the results of MPs in the sediments, which should be considered when comparing the data.

MP abundance in sediments could be affected by a variety of environmental conditions. Typhoons, for example, increased the number of MPs in Sanggou Bay by around 40% and substantially modified the compositions of MP shapes, sizes, and colours, according to Wang et al. (2019a). Another study done by Li et al. (2019) found that the accumulation of MPs is a result of sediment settling due to water flow. Li et al. (2019) found that the abundance of MPs in the gulf (1780 – 2130 items/kg) sediments were higher than that of estuarine sediments in the Maowei Sea (520 – 940 items/kg), which had a significantly different distribution pattern of MPs in water bodies. Estuaries do, however, serve as a transition area among inland and marine ecosystems, making it easier for MPs to migrate and accumulate (Hu et al., 2018). Furthermore, the concentration of microbes and plankton may enhance the density of floating MPs, causing them to settle faster (Näkki et al., 2019). Another key element in MP sinking was organic debris, which could envelop MPs and create aggregations with high densities (Turner et al., 2015; Porter et al., 2018). In the South African region, de Villiers (2018) found an average of 101 ± 147 MPs fibres per/dm^3 along sandy beaches in the Cape Peninsula, noting that the increase of MPs abundance around river sites was noticeable during peak winter season and suggested that rivers act as conduits to transport MP fibres towards the coastal area.

In most beach and bay sediments, PS, PP and PE were the most common polymer types of MPs. It has been recorded that PET accounts for a large sum of the total MP (51.35%) polymers found in sediment (Zheng et al., 2019). The possible implications of MP contamination on the marine benthic ecosystem deserve consideration because sediment has become a significant sink for MPs. It is suggested that most MPs also ends up being trapped in sediments (Bour et al., 2018).

2.3.3 Microplastics in biota

The detection of MPs in marine fishes, mollusks, zooplankton, mammals and birds emphasises the likelihood of MP pollution to occur in marine ecosystems (Jiang et al., 2022). Non-selective filter feeders like the *Mytilus galloprovincialis*, which are mussels that filter and digest most of the particles in the water column according to their size. These bivalves directly absorb MPs from their surrounding areas and the mean averages can be linked to the abundance of MPs in the surrounding environment (Jiang et al., 2022). As a result, they are susceptible to ingesting microplastics (Moore et al., 2001), which can cause detrimental impacts to their physiological state and growth (Andral et al., 2004).

Grazers such as the Parechinus angulosus sea urchins are non-selective feeders too; they are primary herbivores and graze on the sea floor and benthic surfaces (Sevillano-Gonzalez et al., 2022). Their feeding activity is limited to algal biomass and serves as food for many predators, allowing MPs to transfer up trophic levels (Sevillano-Gonzalez et al., 2022), which can be visible in various predator invertebrates such as snails (Ekaratne and Goonewardena, 1994). Previous studies have provided evidence that MP particles are able to be transferred up the food web and accumulate in top predators (Nelms et al., 2018; Zhang et al., 2019). Scavnegers/Predators like the *Burnupena spp*. which are snails that pray on the *Mytilus galloprovincialis* are vulnerable to MPs contamination due to transfer of MPs p trophic levels.

A lot of experimental exposure studies with MPs have taken place within invertebrates, specifically mussels. However, due to the unrealistic high particle concentrations that are constantly used in laboratory experiments, short exposure periods and lack of controls have raised a concern about exposure studies and how well they represent the natural environment (Barkhau et al., 2022; Li et al., 2022). Nonetheless various exposure studies with high concentrations of inorganic particles have reported an increased pseudofeces production and decreased clearance and filtration rates of filter feeders (Penning et al., 2013; Madon et al., 1998). Studies have also found a decline in assimilation efficiencies, metabolic rates and oxygen consumption (Madon et al., 1998). However, an uncertainty still lies in exposure studies whether effects are caused by specific properties of synthetic materials such as the presence of additives/toxins or simply by the presence of suspended solids at high concentrations within organisms (Barkhau et al., 2022). The reduction of feeding activity of mussels and other invertebrates has been recorded in several other studies, which are directly linked to MPs particles and not by high load of inorganic particles (Wright et al., 2013).

MPs have the ability to remain within an invertebrate's digestive tract and haemolymph for between 12 and 48 days after exposure (Browne et al., 2008). However, residence time of fibres is unclear since there are very little laboratory studies (Watts et al., 2014). The abundance of MPs can also vary between different feeding groups. It is assumed that non-selective filter feeders would have higher numbers of MPs particles compared to grazers and carnivores like sea urchins and whelks. So, it is important to consider the organism's feeding mode that can be linked to the amount and the type of MPs particles that is ingested, and not necessarily on the type of habitat or trophic group (de Borros et al., 2020; Piarulli et al., 2020). Organisms such as like sea urchins are also able to shred and convert plastic particles into finer fragments, making them available to other organisms such as detritovores – as they do with algae (Yorke et al., 2019).

Within rocky shores there is some information regarding verification of MPs within filter feeders such as mussels, but there is very little literature that is available on other common rocky shore invertebrates such as snails (Doyle et al., 2019). In this study, whelks (*Burnepena sp*.) will be used to identify the distribution of MPs around stormwater outlets. They are known to be predators of mussels (Hunt and Scheibling, 1998) and it is likely that MPs will be transferred from mussels to whelks due to predator-prey relations (Zheng et al., 2019). It is mentioned by Alava (2020) that MPs can move up the food web through predator and prey relations and we expect to observe a lower abundance of MP particles in predators, according to the theory of trophic level dilution.

Due to MPs accumulation in biota, this study has selected three different feeding group: namely filter feeders (mussels - *Mytilus galloprovincialis*), grazers (sea urchins - *Parechinus angulosus*) and carnivores (whelks - *Burnupena spp*). Each of these organisms are commonly found within the intertidal and the subtidal zones. Very little MPs research that include verification using FTIR has been done on sea urchins (Hennicke et al., 2021) and snails (Doyle et al., 2019) compared to that of mussels.

2.4 Description of biota

Mytilus galloprovincialis, which is part of the phylum Mollusca and class Bivalvia are mussels that can be found on wave exposed rocky shores and dominate mid-low intertidal zone (Branch et al., 2022). The *Mytilus galloprovincialis* is a species of mussels that was introduced into South Africa from Europe and are extremely fast growing (Branch et al., 2022). They are often smooth, black or blue in colour and grow up to 60 – 140 mm in size (Branch et al., 2022).

Parechinus angulosus sea urchins which falls under the phylum Echinodermata and class Echinoidea are grazers that are abundantly found on rocky shore and in kelp forest along the Eastern and Western Cape of South Africa (Branch et al., 2022). These urchins are densely covered by shortish pointed spines that vary in length and grow up to 60 mm. They vary in colour but are commonly found in purple, green, red or pale (Bracnh et al., 2022)

The *Burnupena spp*. is part of the phylum Mollusca and class Gastropoda of which six different genera can be found in South Africa. The *Burnupena spp*. used in this study being the *Burnupena cincta, Burnupena lagenaria* and *Burnupena papyracea* are found to be scavengers and predators. Burnupena sp. often scavenge on dead or pray on injured animals (Branch et al., 2022). They can be found in both the intertidal and subtidal and grow up to 35 – 50 mm in size. Each Burnupena has distinct characteristics. The *B. cincta* has coarse spiral ridges with the aperture being around 1.5 times longer than the spire and can be found in a dull brown with a touch of green algae (Branch et al., 2022). The *B. lagenaria* is shorter than the *B. cincta* with the spire less than half the length of the aperture and can be found with a violet-brown or yellow aperture. The *B. papyracea* is dull brown but is often covered with purple bryozoan, which is toxic and protects the whelk against predators (Branch et al., 2022).

2.5 Poor waste management

MPs are an emerging contaminant with an extensive distribution in the environment and can cause adverse ecological impacts. It is estimated that around 2 million tonnes of MPs fibres are mismanaged each year and released into the ocean, with 700 000 MPs fibres potentially originating from a single garment through domestic laundry (Mishra et al., 2019). Synthetic fibre production has increased remarkably from 16 to 42 million tonnes in the past decade, making up 64,2% of the global consumptions of fibres (World Apparel fiber consumption survey, 2017). This, adds to the increase of mismanaged MP fibres from synthetically made garments (Miller et al., 2017). Additionally, synthetic fibres tend to have a high combustion rate and low melting point compared to more natural fibres, causing environmental and safety concerns (Mishra et al., 2019). According to Browne et al., (2011) MP fibres account for approximately 85% of coastal anthropogenic debris (Browne et al., 2011). MPs have several different paths in which they are transferred and/or transported to the aquatic environment by domestic waste, industrial waste or stormwater runoff (Li et al., 2018c; Ziajahromi et al., 2017).

A solution that supposedly reduces the input of MPs into the environment are wastewater treatment plants (WWTPs) (Hidayaturrahman and Lee, 2019). They are however considered as one of the sources of introducing MPs into the aquatic environment since they continuously discharge large quantities of treated water into the aquatic environment (Gies et al., 2018). MPs in treated water from WWTPs are not completely disposed of despite being treated at various levels (Hidayaturrahman and Lee, 2019). A study by Talvitie et al. (2017) states that WWTPs have developed technologies to improve the quality of water by treating final effluent to remove MPs. Regarding the alarming increase in MPs, WWTPs should apply some sort of technology to remove MPs from treated water that is released back into the aquatic environment (Hidayaturrahman and Lee, 2019). Hidayaturrahman and Lee (2019) found that MPs removal technology at WWTPs can remove 99.2% of MPs from effluent, depending on the type of technology. Some of these methods can consume high amounts of energy, such as the membrane bioreactor that removes pollutants through crossflow filtration.

Although MPs removal technologies can remove MPs from effluent, there is still a considerable number of mismanaged MPs that are discharged back into the aquatic environment. It is significantly important to implement and improve technologies to assist in the removal of MPs from sources like stormwater outlets, rivers and WWTPs (Mishra et al., 2019). Additional solutions by which MPs fibres can be reduced are by utilising products such as the Cora Ball and the Guppyfriend bag, which are used in washing machines, that filter out MPs fibres that would have been released into domestic drainage (Mishra et al., 2019).

2.5 Stormwater outlets

Stormwater drainage systems in coastal communities are used to prevent flooding and act as a conduit, gathering and altering the natural flow of terrestrial surface water (Cox and Foster, 2013). Stormwater systems are seen as a significant pathway for MPs to enter the marine environment (Coalition Clean Baltic, 2017; Weideman et al., 2020). These drainage systems collect large quantities of pollutants and waste from their catchment footprint and introduce them into the marine environment (Weideman et al., 2020). In South Africa, runoff that is introduced into the marine environment is rarely screened and treated before entering coastal waters (Weideman et al., 2020). Previous studies conducted in South Africa in the 1990s and 2000s also state that stormwater systems are significant for introducing litter into the marine environment (Arnold and Ryan, 1999; Armitage, 2007).

Like most coastal communities, the City of Cape Town discharges runoff through stormwater outlets into shallow coastal waters where photosynthetic organisms dominate (Cox and Foster, 2013). Other common pollutants that are found in stormwater runoff are heavy metals such as cadmium, copper, zinc and metal, oils, and organic pollutants (Coalition Clean Baltic, 2017). A waste product that has attracted a lot of concern in the marine environment is MPs. Studies have shown that stormwater runoff has a high input of MPs, depending on the season and due to runoff being untreated (Jannö, 2016; Jönsson, 2016). A previous study by Preston-Whyte et al. (2021) recorded high volumes of MPs close to stormwater outlets in South Africa. Other studies have also indicated that the main way in which MPs and other forms of litter was transported was by means of stormwater drainage systems via runoff (de Villiers, 2018; Weideman et al., 2020). Evidently, MP pollution directly linked to water waste disposals in stormwater (Browne et al., 2011) with microfibres being the most abundant MP type (de Villiers, 2018; Mvovo, 2021; Nel and Froneman, 2015). Browne et al. (2011) found that fibres from washing clothing introduce considerable amounts of MPs in the marine environment through sewage and stormwater and suggest that the increase of MPs fibres is related to the population density (Mvovo, 2021).

2.6 The coastal rocky shore ecosystem – intertidal and subtidal zones

South Africa has an extremely diverse and unique coastline due to oceanographic processes. The coastline falls on part of both the cool Atlantic Ocean, being extremely nutrient rich and productive, and the warmer Indian Ocean, allowing a higher diversity (Liebau, 2013). Apart from providing habitats for various marine organisms, the intertidal and subtidal zones act as a natural buffer zone from storm events and mitigate erosion (Spalding et al., 2014, Wu et al., 2022). These zones are commonly disturbed by human activity, which and often leads to drastic changes in community structures (Lasiak and Field 1995).

The intertidal zone is an area that puts biota in extreme conditions; the zone is exposed to high temporal and spatial variability (Elliott and Quintino, 2007). The most common habitat found in the intertidal zone is rocky shores, which are highly diverse (Thompson et al., 2002). Rocky shores in the intertidal zone are submerged during the high tide and exposed during the low tide. The intertidal rocky shores bring about an array of ecosystem functions and services. Two of the main functions are to improve water quality and promote biodiversity (Schaefer et al., 2020). In conjunction with the extreme conditions, anthropogenic activities like the stormwater outlets contribute to the degradation of coastal ecosystems (Francescangeli et al., 2020). Runoff waste from stormwater outlets tends to accumulate within the intertidal and subtidal zones, affecting benthic communities (Francescangeli et al., 2020). Previous studies have used benthic organisms in both the intertidal and subtidal zones to monitor the health of these ecosystems (Schaefer et al., 2020).

The subtidal zone is found just below the intertidal zone, however, the conditions may not be as extreme further away from the shoreline. The subtidal zone is known for its diverse marine ecosystems (Watts et al., 2011). Some of the most common ecosystems found in Cape Town are kelp forest and rocky reefs. Both the intertidal and subtidal zones are extremely competitive when it comes to occupying space and nutrients. Very often, organisms in these areas mistake MPs as food and these MPs eventually get transferred up the trophic levels (Desforges et al., 2015).

Like the intertidal zone, the subtidal zone is subjected to impacts of anthropogenic activities. Unlike the intertidal, the deeper subtidal communities are not exposed to as much variability and can be more vulnerable to short-term environmental changes (Joshua, 2015). The shallow subtidal zone is likely to be mostly exposed to a MP polymer that is denser than water, such as PET. However, the shallow subtidal and intertidal zones are found in extremely turbulent areas and buoyancy could have very little impact to the type of polymers found in biota since there is a lot of mixing occurring in these areas.

MPs are a common contaminant found in most marine ecosystems. MPs are becoming problematic as rivers and stormwater outlets are drivers for the accumulation of MPs in ecosystems like rocky shores (Rech, 2014). Since rocky shores are dominated by macroalgae species, MPs are often trapped due to the complex topography (Mudd et al., 2010). Studies have also suggested that the rocky shore ecosystem allows the breakdown of plastics into secondary MPs through mechanical action and abrasion (Hidalgo-Ruz et al., 2012). MPs are a threat to many marine ecosystems as they can be found offshore within extreme depths of the ocean floor or nearshore in coastal ecosystems. However, very few studies have examined MPs around rocky shores and rocky shore organisms (Morais et al., 2020), which is surprising since plastics are common along rocky coastlines worldwide (Alvarez et al., 2020).

Like rocky shores, sandy beaches are intertidal ecosystems that are commonly impacted by anthropogenic activities that cause the accumulation of MPs (Wu et al., 2022). MPs that are introduced into this ecosystem are a result of ongoing migration of MPs under the change of environmental conditions (Carcedo et al., 2015). The movement path of MPs in sandy beaches is complex as it includes drifting, beaching, settling, burying and resuspension (Wu et al., 2021). The complexity of their path is also influenced by inshore conditions (such as tides and winds) and characteristics of MPs (Eerkes-Medrano et al., 2015). Conditions are likely to cause MPs to be transported back and forth from sandy beaches to the ocean or deposited (by drifting) onto another intertidal ecosystem like rocky shores (Wu et al., 2022). Often the mean averages of MPs found in sandy beaches tend to be greater than the mean averages found in rocky shores (Wu et al., 2022).

Water, sediment and biota found in sandy beaches and rocky shores are commonly used to monitor the distribution of MPs at given locations. Invertebrates, such as mussels, are commonly used in various studies that are constantly used in monitoring programs. For this study we used three different feeding groups, which consisted of the following: filter feeders – mussels (*Mytilus galloprovincialis*), grazers – sea urchins (*Parechinus angulosus*) and carnivores – whelks

(*Burnupena spp.*). The mentioned organisms can be found in both the intertidal and shallow subtidal zones, making them suitable for the given study.

It is imperative that research is done around the stormwater drainage systems and MP distribution due to the lack of information around these areas. South Africa falls within the top 20 countries that mismanage plastic debris, and it is essential to increase our knowledge and have a better understanding of these areas (Jambeck et al., 2015).

2.7 General aim

To measure the intertidal and subtidal concentrations, characteristics and risks of microplastics at stormwater outlets (within water, sediment and benthic biota) in Cape Town.

2.8 Research objectives

- To compare concentrations of MPs in water, sediment, and selected species between “impacted sites” in the vicinity of intertidal stormwater outlets and “control sites” (i.e comparable sites without nearby outlets).
- To assess seasonal differences in the concentrations of MPs in sediments, the water column and selected species at stormwater outlets (0m and 5m depths).
- To compare concentrations of MPs in selected species between intertidal (0m depth) and adjacent subtidal (5m depth) habitats adjacent to intertidal stormwater outlets and control sites.
- To compare the risk indices of MPs between “impacted sites” in the vicinity of stormwater outlets and “control sites”.
- To identify the risk category that each sampled location is in due to MPs.
- To compare the condition of selected bioaccumulating species between “impacted sites” in the vicinity of intertidal stormwater outlets and “control sites” by using a formulated condition index.

Chapter 3 – Stormerwater outlets: A source contributing to microplastics in coastal zones via runoff around Cape Town.

3.1 Abstract

Stormwater outlets along the Cape Peninsula of Cape Town, South Africa are extremely abundant and close to one another. The catchment of these areas is unknown and runoff entering the coastline are not screened or filtered. This results in poor waste management and causes a degradation in the coastal marine environment due to unscreened stormwater runoff. This study looks at three different locations: Camps Bay, Mouille Point and Three Anchor Bay, that are impacted by stormwater outlets. The runoff discharged from stormwater outlets impacts the intertidal and subtidal zones, introducing higher amounts of MPs in water, sediment, and biota (mussels, sea urchins and whelks). Therefore, water, sediment and biota are analysed using methods from Group of Experts on the Scientific Aspects of Marine Environmental Protection, and 10% of MPs found are then verified using a FTIR. The abundance of MPs found in abiotic and biotic samples was based off one winter and summer season. MPs were found to have a higher abundance in water and sediment during the winter season, while biotic samples had a higher abundance of MPs during the summer season. The study finds that impacted stormwater sites along the Cape Peninsula, being Camps Bay (summer: 6.81 ± 1.65; winter: 3.92 ± 1.46), Mouille Point (summer: 4.56 ± 0.95; winter: 4 ± 1.39) and Three Anchor Bay (summer: 3.61 ± 1.07; winter: 3.96 ± 1.17) have a significantly higher abundance of MPs compared to control sites for both summer and winter seasons. This indicates that stormwater outlets are introducing MPs into the coastal marine environment. Furthermore, the data from this study is the first record of MPs around stormwater outlets in the selected areas and provides a baseline for further monitoring of MPs.

3.2 Introduction

The marine environment is constantly impacted by anthropogenic activities that bring a wide range of pollutants in the marine ecosystems. Plastic pollution has been a notable problem since 1970 and, in the 21st century, has been a noticeable global problem in the water environment (Eerkes-Medrano et al., 2015; Vegter et al., 2014). Approximately 80% of plastics are introduced into the marine environment from land-based sources via wind and water from large coastal cities

(Jambeck et al., 2015). According to Jambeck et al. (2015) approximately 4.8 – 12.7 million tonnes of plastic waste are estimated to be released into our coastal regions annually. The waste products that have attracted much attention in recent years are microplastics (MPs). MPs can be defined as polymers that are less than 5mm in size and can be found as either a primary or secondary MPs (Mvovo, 2021). Primary MPs are manufactured and come in the form of nurdles, while secondary MPs are formed from the breakdown of larger plastic products (Mvovo, 2021; van Wijnen et al., 2019). MPs are known to enter the marine environment through sewers, river systems and stormwater outlets (Yin et al., 2021, Jannö, 2016; Jönsson, 2016, Weideman et al., 2020).

Due to the urbanisation of the coastal region and with the coastal population on the rise, our coastal environment is prone to being affected by anthropogenic materials (Gartner et al., 2002). Poor waste management and waste management structures are increasing the degradation of coastal marine ecosystems (Francescangeli et al., 2020). Drainage structures such as stormwater outlets are poorly designed to treat runoff. Runoff, which contains high quantities of chemical and physical contaminants, is commonly discharged into the shallow coastal waters (Cox and Foster, 2013). Effluent from these outlets contain high amounts of ammonium, nitrate, phosphates, metals, organics, pharmaceuticals and MPs (Wanielista and Yousef, 1993).

Previous research done by Jannö (2016) and Jönsson (2016) states that rivers and stormwater outlets, depending on the season, are some of the key sources to introducing MPs into the marine coastal environment. Weideman et al. (2020) also state that stormwater outlets are one of the main ways in which plastic pollution is transported into the sea via runoff. These drainage structures are designed to easily transport large volumes of water from streets to prevent flooding (Weideman et al., 2020). Due to their poor design, stormwater outlets in South Africa, therefore, collect unwanted waste from the terrestrial land via runoff and deposit it in the coastal region without being screened and treated (Weideman et al., 2020).

It is estimated that South Africa contributes 0.09 – 0.25 million tonnes of plastics from land-based sources, with Cape Town being responsible for 40% of plastics entering the coastline from coastal cities (Collins and Hermes, 2019). Coastal ecosystems are therefore prone to be impacted by stormwater outlets. MPs have been documented all around the world in various matrices such as water (Zhou et al., 2018), sediment (Vaughan, Turner and Rose, 2017) and biota (Sparks and Immelman, 2020). Due to MPs being ubiquitous around the coastal region, water, sediment and biota such as filter feeders (mussels), grazers (sea urchins) and carnivores (whelks) are susceptible to MPs, as they can be found directly adjacent to stormwater outlets.

Many species on rocky shores that are often adjacent to stormwater outlets are vulnerable to being impacted by MPs. Non-selective eaters (Moore et al., 2001) such as mussels and sea urchins and/or filter-feeders are prone to being impacted by MPs. Since mussels are ubiquitous around South Africa's rocky shoreline, they are an ideal organism to monitor MPs (Li et al., 2016). MPs have been recorded in various other invertebrates like polychaete, in which Nel and Froneman (2018) recorded 0.28 MP particles/g dry weight. Many other invertebrates, especially on rocky shores, are vulnerable to MPs ingestion. Jiang et al. (2022) also state that MPs have been detected in many marine fishes, mollusks, zooplankton, mammals and birds and emphasise the likelihood of microplastic pollution on the rest of the marine ecosystem. Mussels, sea urchins and whelks are organisms that can be found in both the intertidal and subtidal zones in rocky shores along the Cape Peninsula, making them ideal to be used in the monitoring of MPs in this study.

Given the lack of MPs research around stormwater outlets in South Africa, the aim of this study is to investigate the presence of MP particles adjacent to three impacted stormwater sites in abiotic (water and sediment) samples in the intertidal zone and biotic (mussels, sea urchins and whelks) samples in the intertidal and subtidal zones along the Cape Peninsula of Cape Town, South Africa.

3.3 Methodology

3.3.1 Study area and sites:

The study areas are located along the Cape Peninsula, South Africa (Fig. 3.1). The area of this study focuses on selected intertidal stormwater outlets within the City of Cape Town district, along the southwest coast of the Cape Peninsula. The Cape Peninsula of Cape Town falls within an eastern boundary coastline in the cool Atlantic Ocean, which is dominated by the Benguela Current (March et al., 2022). The area is known to be dominated by south-easterly winds during the summer season that create upwelling, which is known to increase productivity, and predominantly northward winds during winter (de Vos et al., 2021).

The study consists of three areas, each area having an impact and control site. Control sites are ±200m away from the impacted sites. The study areas that were selected are: Camps Bay (-33.9528, 18.3749), Mouille Point (-33.8991, 18.4092) and Three Anchor Bay (-33.9063, 18.3975). Each study area is adjacent to a residential area and is accessible to recreational activities by the public. All locations were relatively sheltered sites, with the Three Anchor Bay control site being the most exposed. The geomorphology of the sampled area at Camps Bay was mainly sandstone, while Mouille Point and Three Anchor Bay consisted of Malmesbury shale and Malmesbury granite.

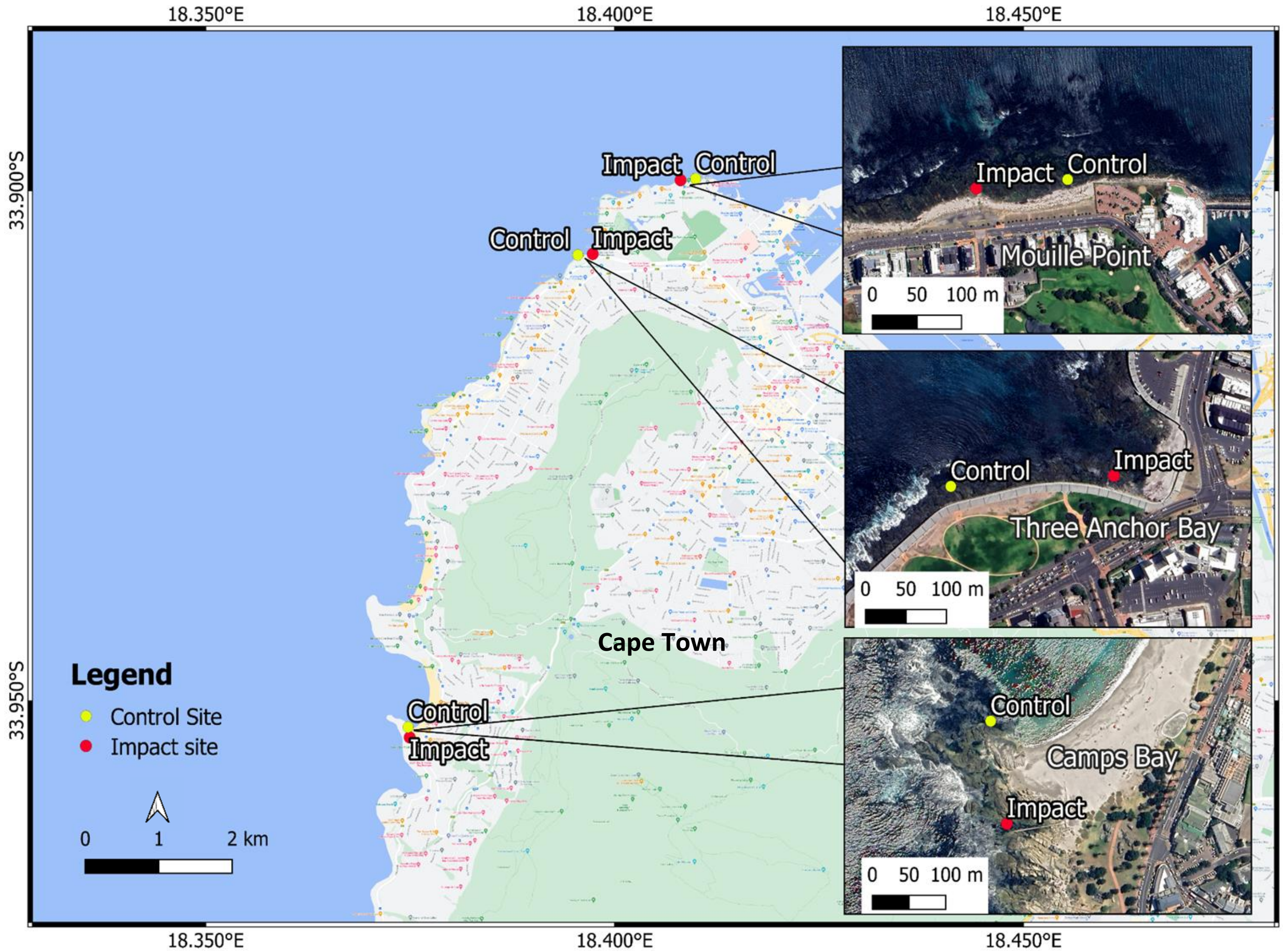


Figure 3.1: The Cape Peninsula study area and study sites chosen to assess impacts of the selected intertidal stormwater outlets.

3.3.2 Sampling method

Samples consisted of abiotic components (water and sediment) and three different biotic feeding groups: filter feeders (mussels – *Mytilus galloprovincialis*), grazers (sea urchins – *Parechinus angulosus*) and carnivores (whelks – *Burnupena spp.*). Two sampling periods took place, with a total of 1362 samples collected throughout the summer (642) and winter (720) sampling period. The summer sampling period took place from 11/12/2020 – 14/12/2020 and winter sampling period from 21/05/2021 – 27/05/2021.

3.3.2.1 Water

For water samples, five replicates of water were taken using a metal bucket at the intertidal zone. 100 litres of surface water were taken per replicate and filtered through a 250 μm mesh. Using a squeeze bottle, the particles remaining on the mesh was then transferred to a 50 ml falcon tube and then stored at -20°C until analysed. The collection of water was done downwind to prevent any contamination of samples.

3.3.2.2 Sediment

For sediment samples, five replicated samples were taken 5m apart from each other at the strandline. A 0.25 m x 0.25 m quadrant and a metal spoon were used to collect the top 5 cm of sediment, which was stored in a Ziploc bag before being processed.

3.3.2.3 Biota

Impact and control sites consisted of mussels, sea urchin and whelks, of which 20 individuals were collected of each organism in both the intertidal and subtidal zones. Subtidal samples were collected by snorkelling between 1-3 m depths, while intertidal samples were collected on rocky shores. Samples were inserted into Ziploc bags and then stored at -20°C until analysed.

3.3.3 Laboratory analysis

The following laboratory protocols for the laboratory analysis of water, sediment and biota were used from methods of GESAMP (2019):

3.3.3.1 Water

For laboratory analysis of water, all falcon tubes were left to defrost. Each individual sample was then added to a glass jar by rinsing the falcon tube out with deionised water. This process was repeated three times. Each sample was then digested by adding 10% KOH with a ratio of 1:2 and placed in the oven at 50°C for 24 hours. The digested sample was then added to a Buchner funnel and samples were filtered through it by using a vacuum pump. All samples are filtered onto a 20 µm nylon mesh and inserted into a pre-clean petri dish where they were allowed to dry before being analysed.

3.3.3.2 Sediment

The laboratory process of sediment was to dry it out for a minimum of 48 hours at 50°C. A 200g replicate of each sample is then digested in 10% KOH with a ratio of 1:2 to remove organic materials and stored at 50°C for 24 hours. A hypersaline solution (NaCL 360 $g \cdot \ell^{-1}$) (pre-filtered through a 10 µm mesh) was then added to the sediment and mixed well for roughly two minutes before allowing it to settle for 15 minutes, then filtered through a vacuum pump onto a 20 µm nylon mesh. This process was completed three times by using the same filtered saline solution of each sample. The mesh sample was then inserted into a pre-clean petri dish where it was allowed to dry before being analysed.

3.3.3.3 Biota

For laboratory analysis of biota, all organisms were left to defrost and then the soft tissue wet weight (STWW) was taken of each organism using a scale. The soft tissue of each individual sample was then added to a glass jar. 10% KOH was then added to the glass jar (at a point that it covers the soft tissue of the organism) to allow it to digest at 50°C for 24 hours. The digested sample was then filtered through a vacuum pump onto a 20 µm nylon mesh and inserted into a pre-clean petri dish where it was allowed to dry before being analysed.

3.3.4 Contamination precautions and recovery

To minimise contamination of microplastics in the laboratory, a cotton white coat was worn during all procedures. All samples that were stored for digestion were covered with foil before being filtered. All equipment used to process the samples were washed three times with deionised filtered water. As a preventative measure all windows and doors were closed during analysis. Various control samples were taken as a precaution against samples being contaminated. Controls at each site were taken by placing an empty jar at the sampled site location. For laboratory controls, damped filter paper was placed at the workstation. Controls that were taken during sampling and processing of samples are: site air control, lab air controls, and Ziploc blanks. Solutions made in the lab such as hypersaline and digestion solution were filtered through a 10 μm mesh to prevent contamination across samples.

Site air controls were used at each location that consisted of a plastic jar that was left open to identify the amount of MP contamination at each location. No MPs contamination was found in site air controls. Lab air controls were used by damping a filter paper and leaving it exposed in a petri dish while filtration of organism and identification of MPs took place. Contamination of MPs in the lab were divided by the number of samples analysed. During both filtration of organism and the identification of MPs the average contamination of MPs found was 0.03 MPs particles per sample. Due to the low amount of contamination found in the lab air controls the contamination was not considered for this study. For Ziploc bags, one Ziploc blank was taken from each Ziploc set (10 in a bag) to identify if they had any MP contamination prior to the samples entering the bag. Ziploc Bags was found to have no contamination of MPs.

Recovery success rate of MPs was done to identify the retrieval percentage of each method used to retrieve MPs from water, sediment, and biota for this study. Twenty neon purple-red MP fibres, sized between 1000-2000μm were added to five replicate samples for water, sediment, and biota. The recovery rate of each tested method was as follows: water – 100%, sediment – 85%, biota – 100%.

3.3.5 Microplastics analysis

Microplastics were visually identified using a Zeiss stereo microscope set at x40 magnification. MPs were identified based on their type (fibres, fragments, spheres, filaments), colour (white, transparent, red, yellow, black, blue) and size (<100, 100-500, 500-1000, 1000-2000, 2000-5000, >5000) (GESAMP, 2019).

3.3.6 FTIR analysis

Fourier-transform infrared spectroscopy (FTIR) was used to identify the type of polymers that MPs can be classified as using infrared. Only 10% of the total MPs found in samples were analysed by using a PerkinElmer Two ATR- FTIR, following methods of Sparks et al. (2021). A background scan was done before analyses of MPs on the FTIR, and the ATR crystal was cleaned before each sample to prevent inaccurate identification. FTIR scans were set at a spectral wave running from 4000 to 450cm^{-1}, intervals of data at 1cm^{-1}, resolution at 4cm^{-1} and scans at 10 per sample. The minimum size limit of MPs that were analysed with the FTIR were set to 500 μm. Polymers were identified and grouped into the most ideal plastic polymers by comparing the spectral scans found within the ST Japan library.

3.3.7 Data analysis

MPs data in this study were reported as the mean concentrations per litre for water, per kilogram dry weight (DW) for sediment and per gram STWW for biota. MPs data was evaluated using the Kolmogorov-Smirnov test for normality and the Levene's test for variance. Data was not normally distributed even after log transformation. Non-parametric Mann Whitney tests were used to analyse MPs between two groups, Kruskal-Wallis tests across more than two groups, and the variance of the data for statistical analysis was presented using standard error of the mean (SE) and significance of parameters set at a value of $p < 0.05$. Pairwise comparisons were done between impact sites across locations. All analyses and graphs were done using SPSS v28. GRADISTAT v9.1 was used to evaluate the grain size of sediment. It should be noted that no sediment was collected at the control site for Three Anchor Bay as there was no sediment available at the sampled area.

3.4 Results

A total of 1362 samples were collected within abiotic and biotic samples. The total MPs recorded in all samples were 4808 particles. The total mean average of MPs found in each sample type were 0.15 ± 0.01 particles/l (water), 52.11 ± 3.51 particles/kg DW (sediment), 2.3 ± 0.21 particles/gram STWW (mussels), 0.14 ± 0.01 particles/gram STWW (sea urchins), 1.61 ± 0.09 particles/gram STWW (whelks). The mean average of MPs found in individuals for mussel (3 ± 0), sea urchins (3 ± 0) and whelks (4 ± 0) were found to be higher compared to the mean of MPs within STWW. Out of 1362 samples, 85% of samples contained MPs particles, 95% of which were MPs fibres. The percentage of samples that contained MPs particles for each sample type were 100% for water and sediment samples, 91% of mussel samples, 70% of sea urchins samples and 91% of whelk samples. The types of polymers that were found in samples were polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), polystyrene (PS), polyvinyl chloride (PVC), Polyvinylidene fluoride (PVDF), polyvinyl acetate (PVA) and nylon. Non polymer MPs were classified into cotton, organics (wood, biological material etc.) and other (glass, silicon, rubber). During the seasonal sampling precipitation levels during the summer period were roughly between 0.1 mm – 0.2 mm of rainfall, while the winter sampling period had rainfall of 0.4 mm – 8.4 mm in Cape Town (worldweatheronline.com, 2022).

Results for total seasonal MPs abundance at impacted stormwater sites were found to be significantly higher than control sites during the summer (4.96 ± 0.39 particles per unit, U = 63239, $p < 0.001$) than winter (3.95 ± 0.78 particles per unit, U = 83544, $p < 0.001$) seasons (Fig. 3.2a). The total MPs found at impacted stormwater sites (U= 48847, $p < 0.001$) were also significantly higher during the summer season compared to winter seasons.

The abundance of MPs across sites at Camps Bay (summer: 6.81 ± 1.65 U = 8606, $p = 0.001$; winter: 3.92 ± 1.46, U = 10951.5, $p < 0.001$), Mouille Point (summer: 4.56 ± 0.95, U = 8316, $p = 0.001$; winter: 4 ± 1.39, U = 9491, $p < 0.001$) and Three Anchor Bay (summer: 3.61 ± 1.07, U = 4048.5; $p = 0.470$; winter: 3.96 ± 1.17, U = 7693., $p = 0.001$) during both seasons were significantly higher at impacted stormwater sites compared to control sites, with an exception of summer sites at Three Anchor Bay, which was not significant. The MPs abundance at impact sites across seasons at Camps Bay (U = 5105.5, $p < 0.001$) and Mouille Point (U = 4697, $p < 0.001$) were significantly higher during the summer period (Fig. 3.2c). A significant difference was seen across locations at impact summer sites (H = 2, $p = 0.004$). Pairwise comparison showed a significant difference between Camps Bay and Three Anchor Bay ($p = 0.001$) and Three Anchor Bay and Mouille Point ($p = 0.028$).

Table 3.1: The seasonal mean average with standard error of microplastics at impact and control sites in STWW and per individual in mussels, sea urchins and whelks.

Organism	Mean STWW	Mean individual
Summer		
Mussel impact	4.92 ± 0.59	5 ± 0.31
Mussel control	1.63 ± 0.44	3 ± 0.39
Sea urchin impact	0.21 ± 0.03	3 ± 0.21
Sea urchin control	0.17 ± 0.03	2 ± 0.16
Whelk impact	2.5 ± 0.19	4 ± 0.26
Whelk control	2.32 ± 0.25	4 ± 0.23
Winter		
Mussel impact	2.0 ± 0.22	4 ± 0.19
Mussel control	0.84 ± 0.18	2 ± 0.11
Sea urchin impact	0.13 ± 0.02	2 ± 0.18
Sea urchin control	0.04 ± 0.01	1 ± 0.08
Whelk impact	1.33 ± 0.12	2 ± 0.16
Whelk control	0.87 ± 0.08	2 ± 0.12

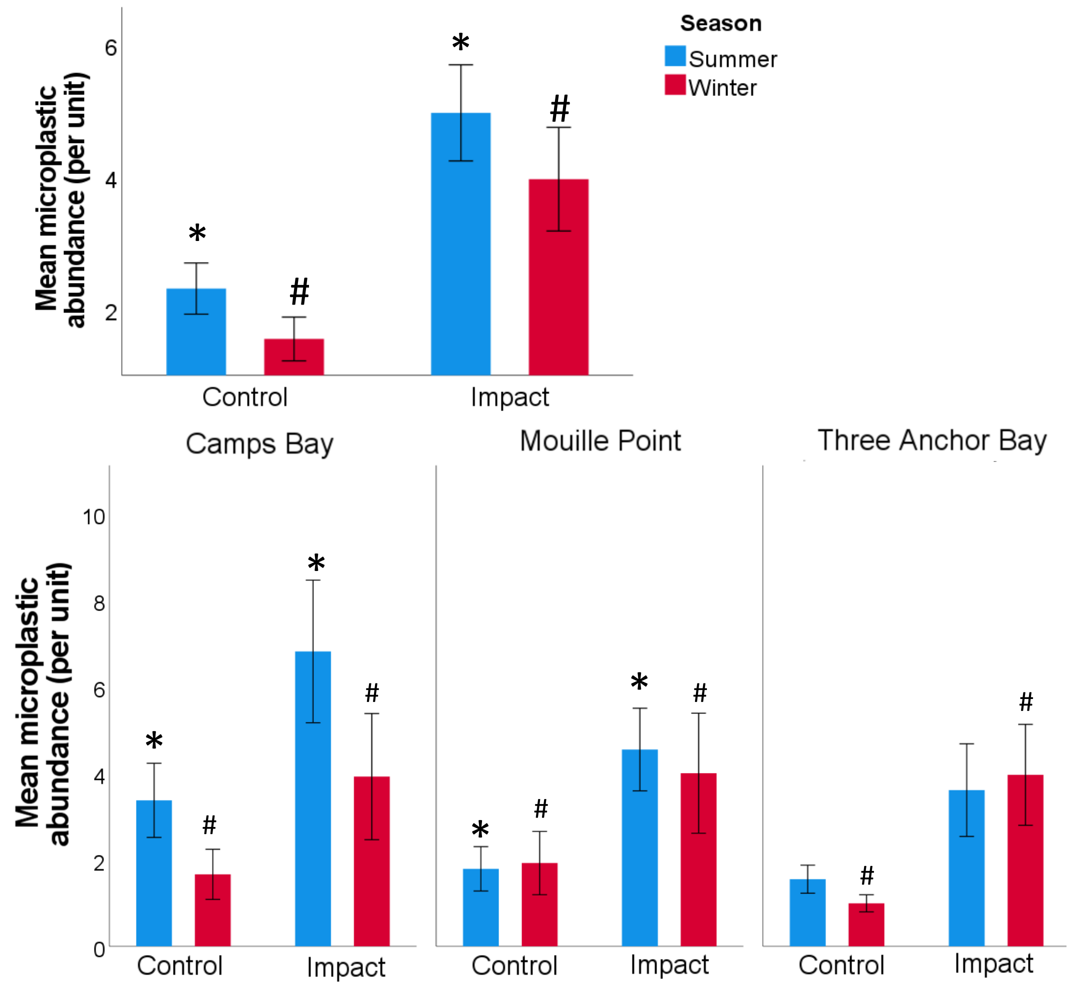


Figure 3.2: a) The total mean seasonal abundance of MPs per unit across impact and control sites b) found at Camps Bay, Mouille Point and Three Anchor Bay. Error bars represent 1 SE. Markings represent significance between impact and control sites.

3.4.1 Water

The total mean (SE) abundance of MPs particles found in per litre of water at impacted stormwater sites were 0.18 ± 0.02 particles/l which were significantly (U = 681.5, p = 0.001) higher compared to control sites with an average of 0.12 ± 0.01particles/l (Fig. 3.3a). The mean abundance of MPs for water at impact (U = 196, p = 0.001) and control sites (U = 164.5, p = 0.029) was significantly lower during summer with an average abundance of 0.13 ± 0.01 particles/l, while winter had an abundance of 0.24 ± 0.03 particles/l at impact sites and 0.09 ± 0.01 (summer) and 0.14 ± 0.02

(winter) for control sites (Fig. 3.3b). The abundance of MPs in water at impact sites was only found to be significantly higher compared to control sites during the winter season (U = 191.5, p = 0.001) (Fig. 3.3b). The mean abundance of MPs found in water at locations were 0.23 ± 0.06 particles/l for Camps Bay, 0.16 ± 0.02 particles/l for Mouille Point , 0.16 ± 0.02 particles/l for Three Anchor Bay at impact sites, and for control sites were 0.08 ± 0.01particles/l for Camps Bay, 0.11 ± 0.02 particles/l for Mouille Point, 0.16 ± 0.02 particles/l for Three Anchor Bay with Camps Bay (U = 88, p = 0.003) being the only location to be proven to be significantly higher at impact sites than control (Fig. 3.3c). No significance was proven across locations for water (H = 2, p = 0.530).

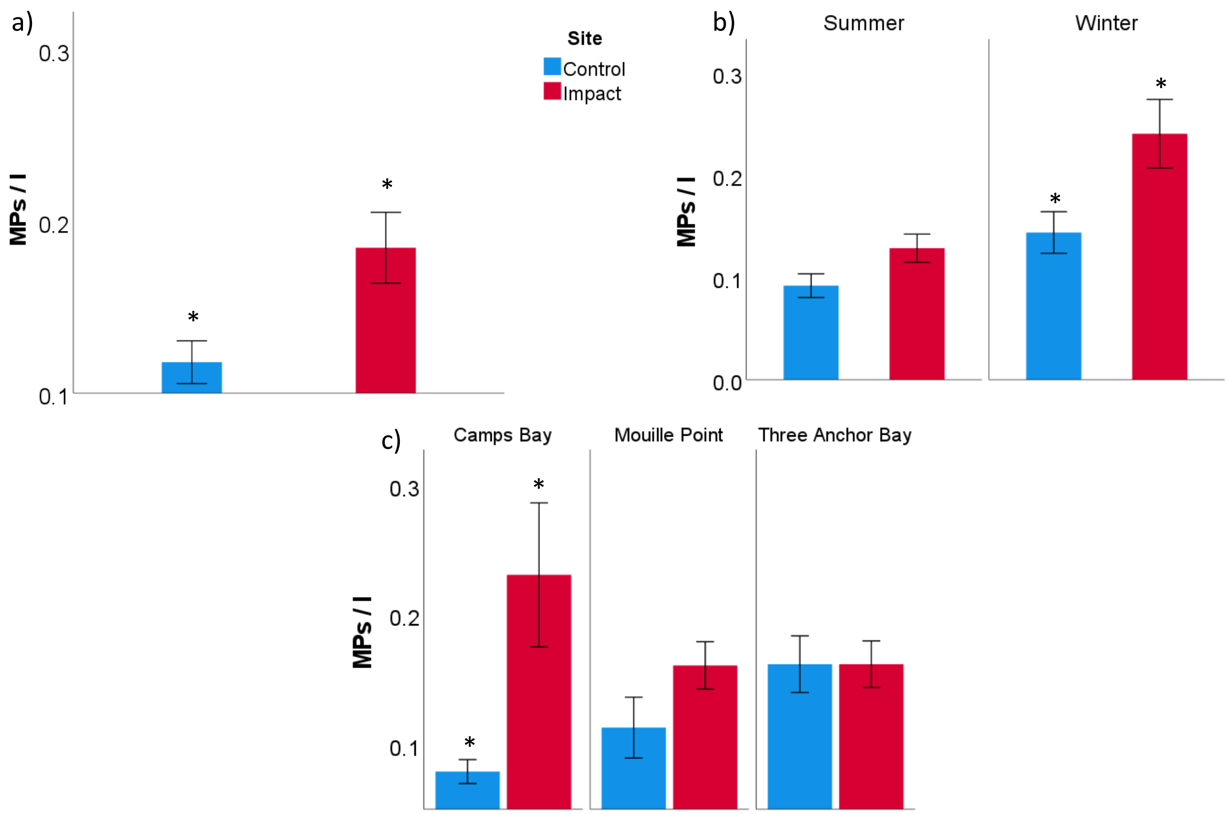


Figure 3.3: a) The total mean abundance of MPs per litre in water across impact and control sites b) across seasons (summer and winter) c) at Camps Bay, Mouille Point and Three Anchor Bay). Error bars represent SE. Asterisks represent significance between impact and control sites.

Water samples mainly consisted of fibres, which made up 97.46% of water samples, with only 2.54% being fragments (Fig. 3.4a). The type of MPs colours that were mostly found in water samples were black (36.18%) and blue (33.10%) (Fig. 3.4b). The MPs size that was mostly found in water samples were sizes between 2000-5000 um (39.10%) and 1000-2000 µm (35.67%) (Fig. 3.4c).

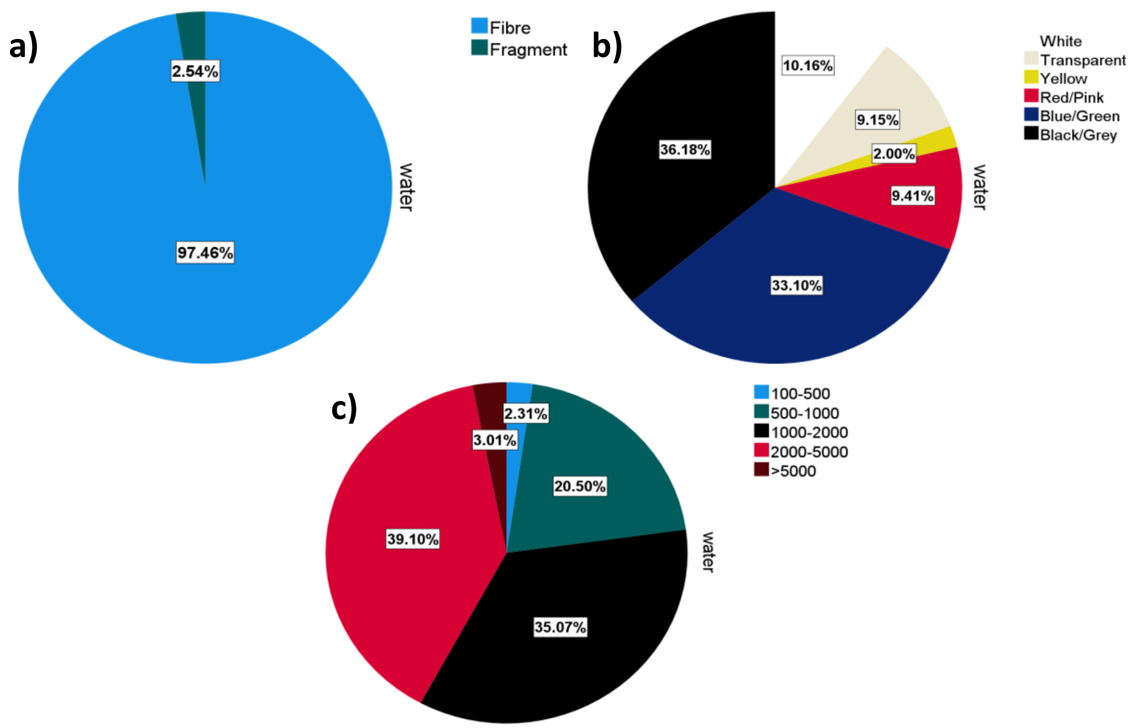


Figure 3.4: The percentage of MPs found in water at all sites, zones and locations. a) MP type b) MP colour c) MP size.

FTIR analysis of fibres in water samples at Camps Bay found a high percentage of cotton (31%), PET (23.8%) and organic (13.1%) fibres (Fig. 3.5). Like Camps Bay, Mouille Point also found a high percentage of cotton (36.2%) and PET (27.78%) (Fig. 3.5). For Three Anchor Bay the main percentage of fibres were found to be other fibres (29.4%) and organic fibres (17.6%). The main polymer found at Three Anchor Bay was PVDF (21.6%) but, like Camps Bay and Mouille Point, a high percentage of cotton (11.8%) and PET (11.8%) were found as well (Fig. 3.5).

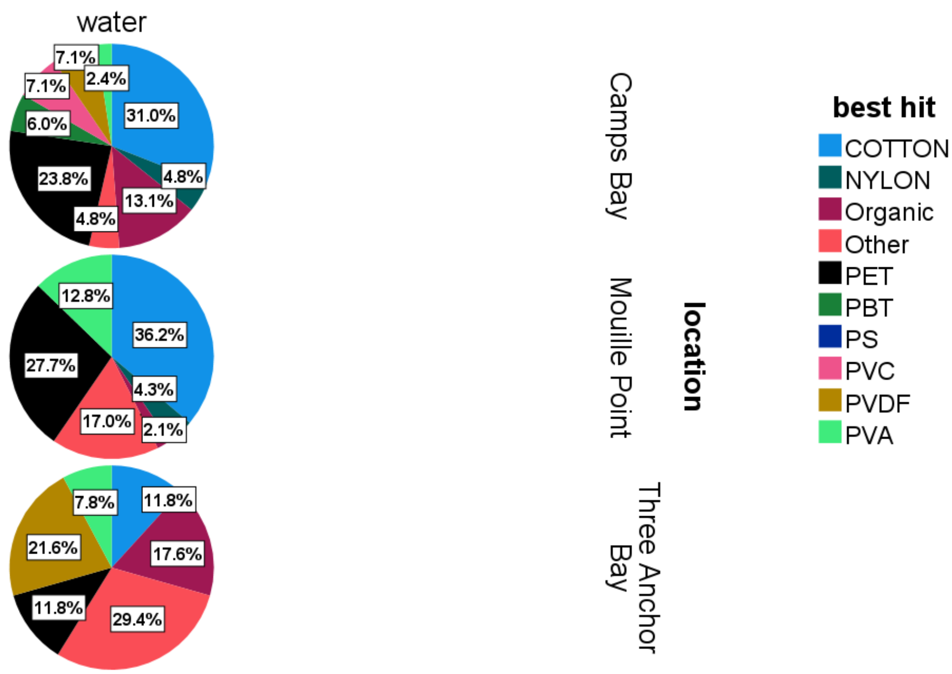


Figure 3.5: The percentage of MPs polymers (polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), polystyrene (PS), polyvinyl chloride (PVC), Polyvinylidene fluoride (PVDF), polyvinyl acetate (PVA) and Nylon found in water at sites and zones found at Camps Bay, Mouille Point and Three Anchor Bay.

3.4.2 Sediment

The total mean abundance of MPs found per kilogram DW of sediment was 63.29 ± 4.6 particles/kg DW at impact sites, which was significantly (U = 510.5, p = 0.001) higher compared to the abundance of MPs, which was 35.4 ± 2.48 particles/kg DW at control sites (Fig. 3.6a). Impacted sites for sediment during summer was 59.2 ± 5.65 particles/kg DW which was a lower mean average compared to winter of 67.3 ± 7.32 particles/kg DW. Like impacted sites, control sites for sediment during summer was 33.80 ± 3.38 particles/kg DW, which was lower compared to winter of 37 ± 3.74 particles/kg DW (Fig.3. 6b). Sediment for both summer (U = 126, p = 0.004) and winter (U = 129, p = 0.002) were significantly proven to have a higher mean average of MPs at impacted sites than control (Fig.3. 6b). The abundance of MPs in sediment found at impact (U = 129.5, p = 0.486) and control (U = 65.5, p = 0.247) sites across seasons were however not significant (Fig. 3.6b). The mean abundance of MPs for impact sites were 77.81 ± 8.72 particles/kg

DW at Camps Bay, 57.81 ± 7.19 particles/kg DW at Mouille Point, 54.25 ± 6.42 particles/kg DW at Three Anchor Bay, which were significantly higher (Camps Bay: U = 95, p = 0.001, Mouille Point: U = 82.5, p = 0.011) than control sites, which were 35.34 ± 3.17 at Camps Bay and 35.45 ± 3.99 at Mouille Point (Fig. 6c). No significance was seen across locations for sediment (H = 2, p = 0.077).

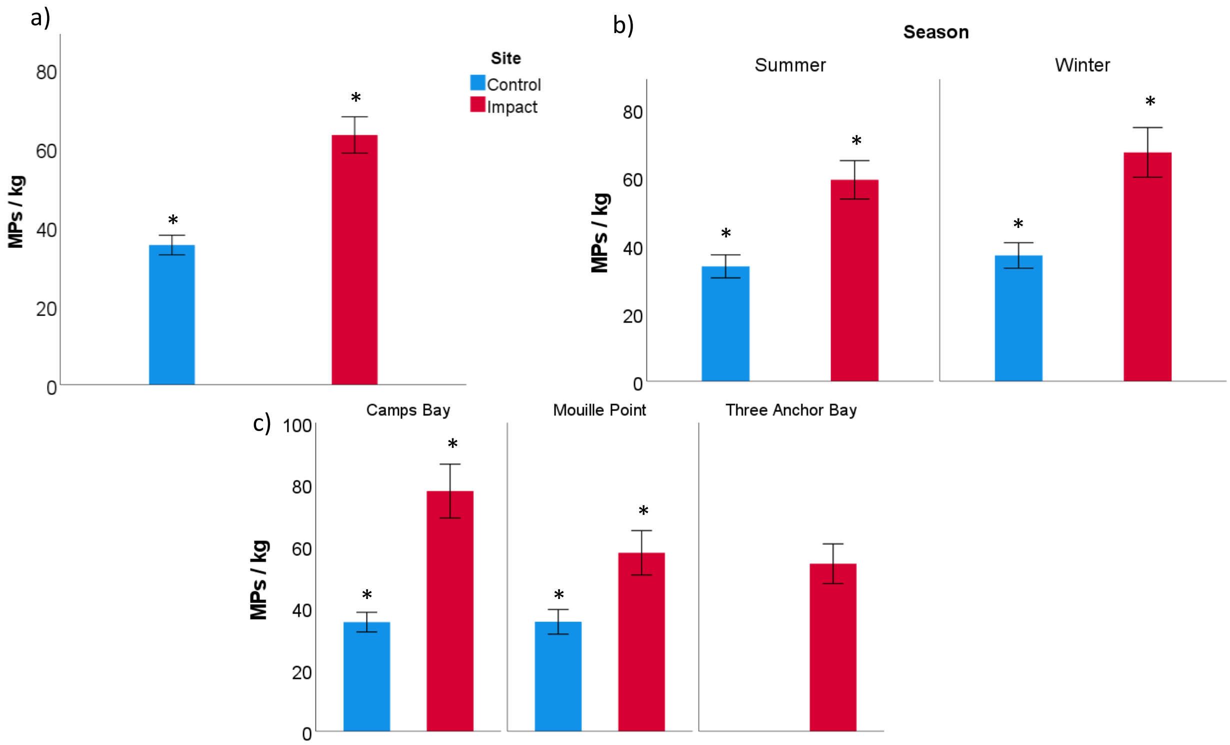


Figure 3.6: The total mean abundance of MPs per kilogram in dry sediment across impact and control sites b) across seasons (summer and winter) c) at Camps Bay, Mouille Point and Three Anchor Bay. Error bars represent SE. Asterisks represent significance between impact and control sites.

For sediment, the fibres made up 97.13% (Fig. 3.7a). Blue (31.12%) and black (30.85%) were the two colours predominantly found in sediment samples (Fig. 3.7b). The MPs size that was mostly found in sediment samples were sizes between 1000 – 2000 μm (40.10%) and 500 – 100 μm (31.36%) (Fig. 3.7c).

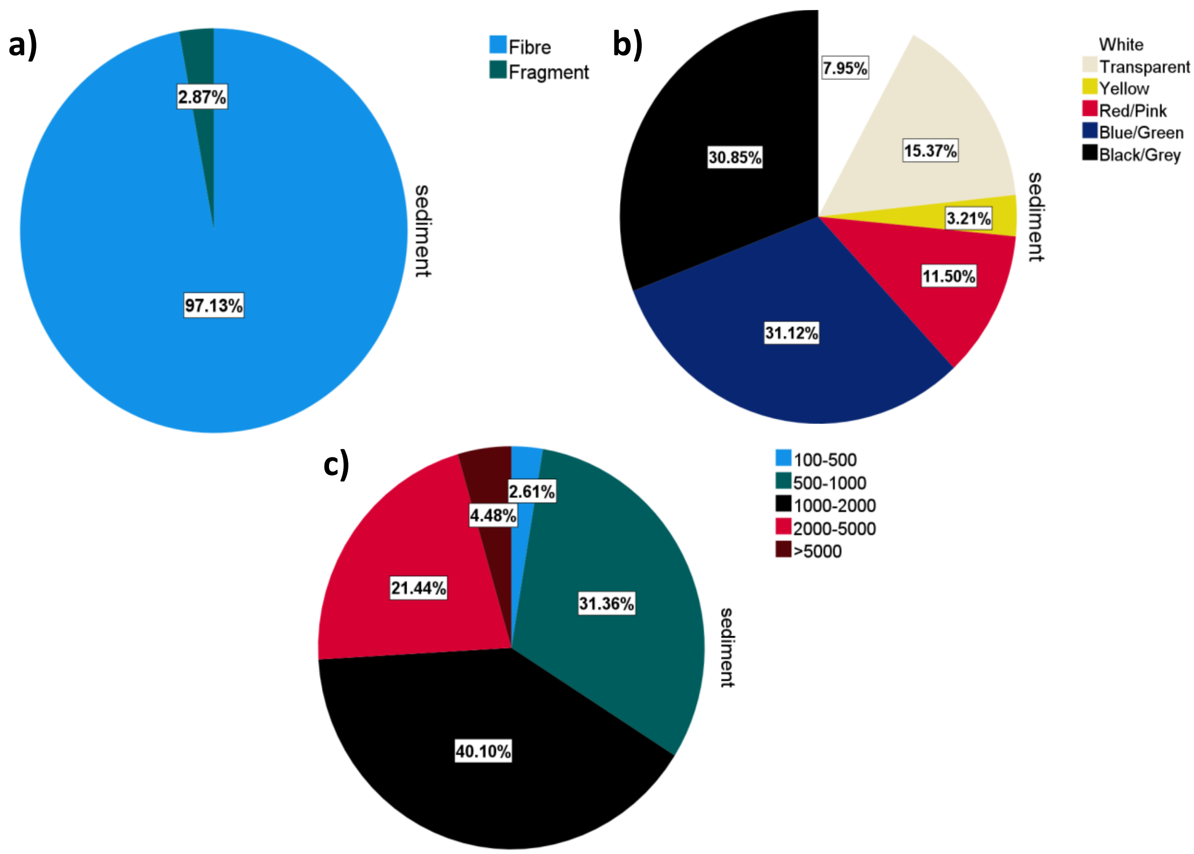


Figure 3.7: The percentage of MPs found in sediment at all sites, zones and locations. a) MPs type b) MPs colour c) MP size.

FTIR analysis of fibres in sediment samples at Camps Bay found a high percentage of PET (75%) (Fig. 3.8). Like Camps Bay, Mouille Point had a high percentage of PET (43.8%) as well as cotton (31.3%). Three Anchor Bay also found a high percentage of cotton (40%) and PET (36.7%) in sediment (Fig. 3.8).

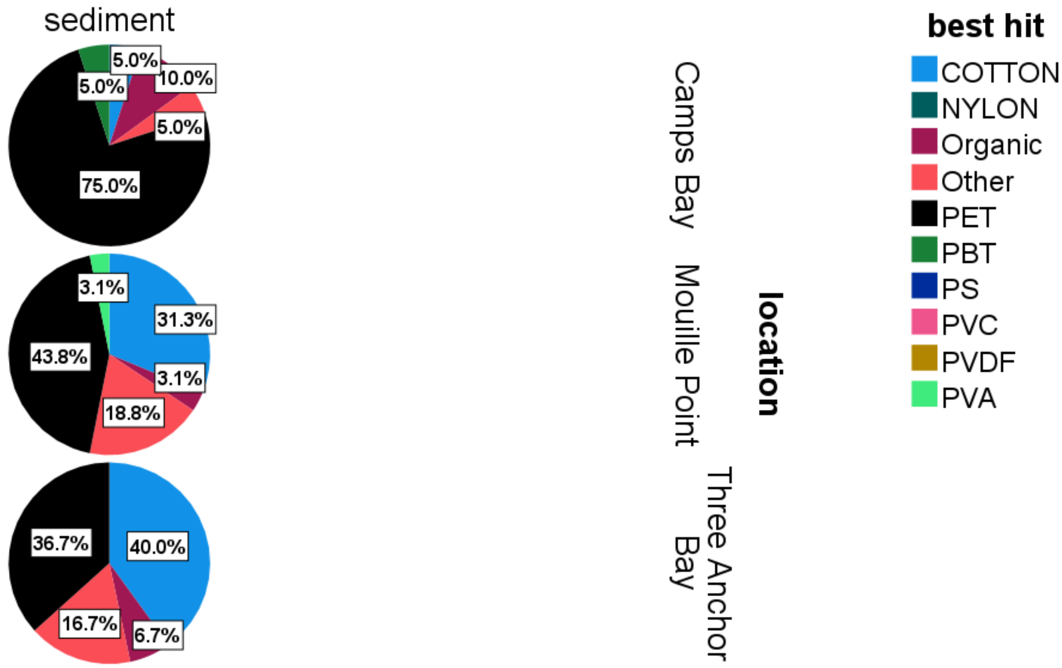


Figure 3.8: The percentage of MPs polymers (polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), polystyrene (PS), polyvinyl chloride (PVC), Polyvinylidene fluoride (PVDF), polyvinyl acetate (PVA) and Nylon found in sediment at sites and zones found at Camps Bay, Mouille Point and Three Anchor Bay.

Grain size analysis for summer showed that the majority of sediment were within the medium and coarse sand grain size followed by very coarse sand throughout all site locations (Table 3.2). Mouille Point's impact site, however, did have larger coarse sand particles compared to medium sand, while Camps Bay had much more medium sand compared to coarse sand. For the winter season the percentage of fine and medium sand dropped, and very coarse sand and very fine gravel increased (Table 3.2).

Table 3.2: The seasonal mean percentage of grain sizes of sediment (largest being very fine gravel and smallest fine sand) at Camps Bay, Mouille Point and Three Anchor Bay at impact and control sites.

Location	V FINE GRAVEL	V COARSE SAND	COARSE SAND	MEDIUM SAND	FINE SAND
Summer	**4,91%**	**15,68%**	**38,92%**	**37,44%**	**2,91%**
CB impact	3,67%	6,54%	7,37%	77,04%	4,80%
CB control	3,92%	13,31%	34,37%	39,60%	8,76%
MP impact	10,13%	26,73%	56,77%	6,23%	0,11%
MP control	1,97%	14,91%	51,68%	31,33%	0,09%
TAB impact	4,85%	16,92%	44,44%	32,97%	0,78%
Winter	**8,78%**	**20,55%**	**38,23%**	**30,74%**	**1,68%**
CB impact	12,27%	20,38%	18,47%	46,38%	2,48%
CB control	12,98%	21,49%	19,26%	42,87%	3,39%
MP impact	10,28%	27,16%	57,74%	4,64%	0,14%
MP control	1,76%	16,31%	58,72%	23,11%	0,10%
TAB impact	6,59%	17,41%	36,98%	36,71%	2,30%

3.4.3 Biota

The mean abundance of MP particles found in per gram of STWW of biota for impact sites for mussels (U = 6585.5, $p = 0.001$) were 3.56 ± 0.35 particles/gram STWW; sea urchins (U = 8257, $p = 0.001$) were 0.18 ± 0.01 particles/gram STWW; and whelks (U = 8560, $p = 0.043$) were 1.74 ± 0.11 particles/gram STWW. These figures were significantly higher compared to control sites for mussels (1.19 ± 0.22 particles/gram STWW), sea urchins (0.10 ± 0.0.1 particles/gram STWW), and whelks (1.49 ± 0.13 particles/gram STWW) (Fig. 3.9a). The mean abundance of MPs found in per individual for mussels (impact: 4, control: 2), sea urchins (impact: 2, control: 1) and whelks (impact: 3, control: 3) were higher than the mean abundance found in STWW.

The mean abundance of MPs found at impact sites during summer and winter season in mussels (summer – 4.92 ± 0.59 particles/gram STWW, U = 9500.5, $p < 0.001$; winter – 2.00 ± 0.22 particles/gram STWW, U = 9696.5, $p < 0.001$), sea urchins (summer – 0.21 ± 0.02 particles/gram STWW, U = 7635, $p < 0.001$; winter – 0.13 ± 0.02 particles/gram STWW, U = 7700, $p < 0.001$) and whelks (summer – 2.46 ± 0.19 particles/gram STWW, U = 31245.5, $p = 0.084$; winter – 1.32 ± 0.12 particles/gram STWW, U = 7480.5, $p = 0.017$) were significantly higher than that of control sites (no significance seen for summer whelks) (Fig. 3.9b). The abundance of MPs in mussels (U

= 4006.5, $p < 0.001$), sea urchins (U = 3801.5, $p < 0.001$) and whelks (U =2035, $p < 0.001$) were significantly higher during the summer season (Fig. 3.9b).

The mean abundance of MPs at impact sites in Camps Bay for: mussels was 4.2 ± 0.83 particles/gram STWW, sea urchins was 0.28 ± 0.03 particles/gram STWW and whelks was 2.00 ± 0.19 particles/gram STWW, which was significantly higher than control sites (mussels = 4324, $p < 0.001$; sea urchins = 4777.5, $p < 0.001$; whelks: U = 2527.5, $p < 0.001$). The mean abundance of MPs for biota at Mouille Point impact sites for mussels were 4.12 ± 0.51 particles/gram STWW, sea urchins were 0.11 ± 0.01 particles/gram STWW and whelks were 1.64 ± 0.19 particles/gram STWW, which was only significantly higher than control sites in mussels (U = 5373, $p < 0.001$) and sea urchins (U= 3806.5, $p = 0.035$). At Three Anchor Bay, the abundance of MPs at impact sites in mussels were 2.47 ± 0.36 particles/gram STWW, sea urchins were 0.13 ± 0.19 particles/gram STWW and whelks were 1.58 ± 0.19 particles/gram STWW, which was only significantly higher compared to control sites in mussels (U = 2933, $p = 0.012$) (Fig. 3.9c). Impact sites across locations for mussels (H = 2, $p < 0.001$) and urchins (H = 2, $p < 0.001$) were significantly different, while whelks (H = 2, $p = 0.105$) were not significant. Pairwise comparisons showed a significant difference between mussels at Three Anchor Bay and Camps Bay (p = 0.030), Three Anchor Bay and Mouille Point (p < 0,001), and Camps Bay and Mouille Point (p < 0.22). Pairwise comparison for sea urchins showed a significant difference between Mouille Point and Camps Bay ($p < 0.001$), and Three Anchor Bay and Camps Bay ($p < 0.001$).

Impacted intertidal samples for mussels (4.99 ± 0.50 particles/gram STWW), sea urchins (0.23 ± 0.02 particles/gram STWW) and whelks (2.34 ± 0.13 particles/gram STWW) had a higher mean average of MPs compared to subtidal impact sites (Fig. 3.9d). Impacted sites in the intertidal and subtidal were higher than control sites (Fig. 3.9d). The mean average of MPs at impacted intertidal zones was found to be significantly higher for mussels (U = 2355.5, $p < 0.001$), sea urchins (U = 4311.5, $p < 0.001$) and whelks (U = 710.5, $p < 0.001$), compared to subtidal impacted sites (Fig. 3.9d).

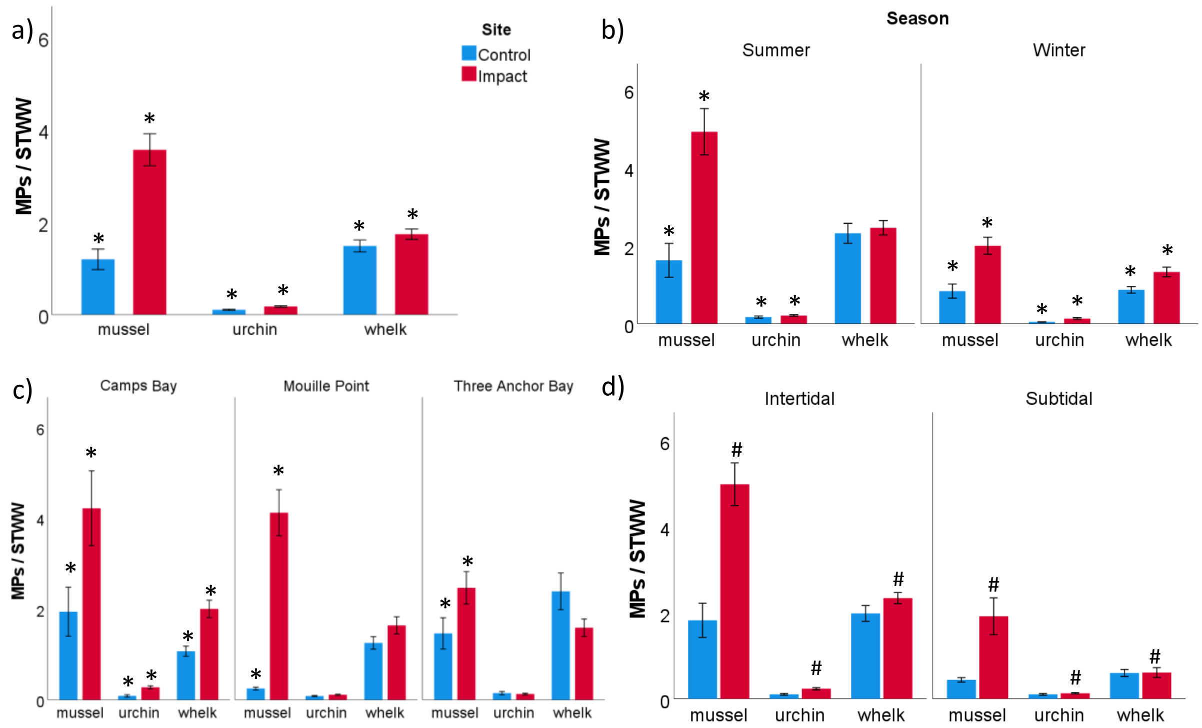


Figure 3.9: a) The total mean abundance of MPs per STWW in fauna (mussels, sea urchins and whelks) across impact and control sites… b) across seasons (summer and winter) c) at Camps Bay, Mouille Point and Three Anchor Bay d) In the intertidal and subtidal. Graphs a-d are log scale). Error bars represent SE. asterisks represent significance between impact and control sites and hash represent significance between impact intertidal and subtidal.

For biota, the fibres made up most of the MPs found in mussels (92.41%), sea urchins (95.74%) and whelks (99.50%) (Fig. 3.10a). For mussels, black was the predominant colour (32.94%) followed by transparent (20.55%). For sea urchins, transparent was the predominant colour (31.51%), followed by black (25.17%). For whelks, blue was the predominant colour (33.44%), followed by black (27.39%) (Fig. 3.10b). For mussels, the predominant sizes were 1000 –2000 µm (35.49%) followed by 500 –1000 µm (27.22%) and 2000 – 5000 µm (22.78%). For sea urchins, the predominant sizes were 2000 – 5000 µm (33.67%) followed by 1000 –2000 µm (28.67%) and 500 – 1000 µm (21.80%). For whelks, the predominant sizes were 1000 – 2000 µm (37.75%) followed by 2000 – 5000 µm (25.77%), and 500 – 1000 µm (25.28%) (Fig. 3.10c).

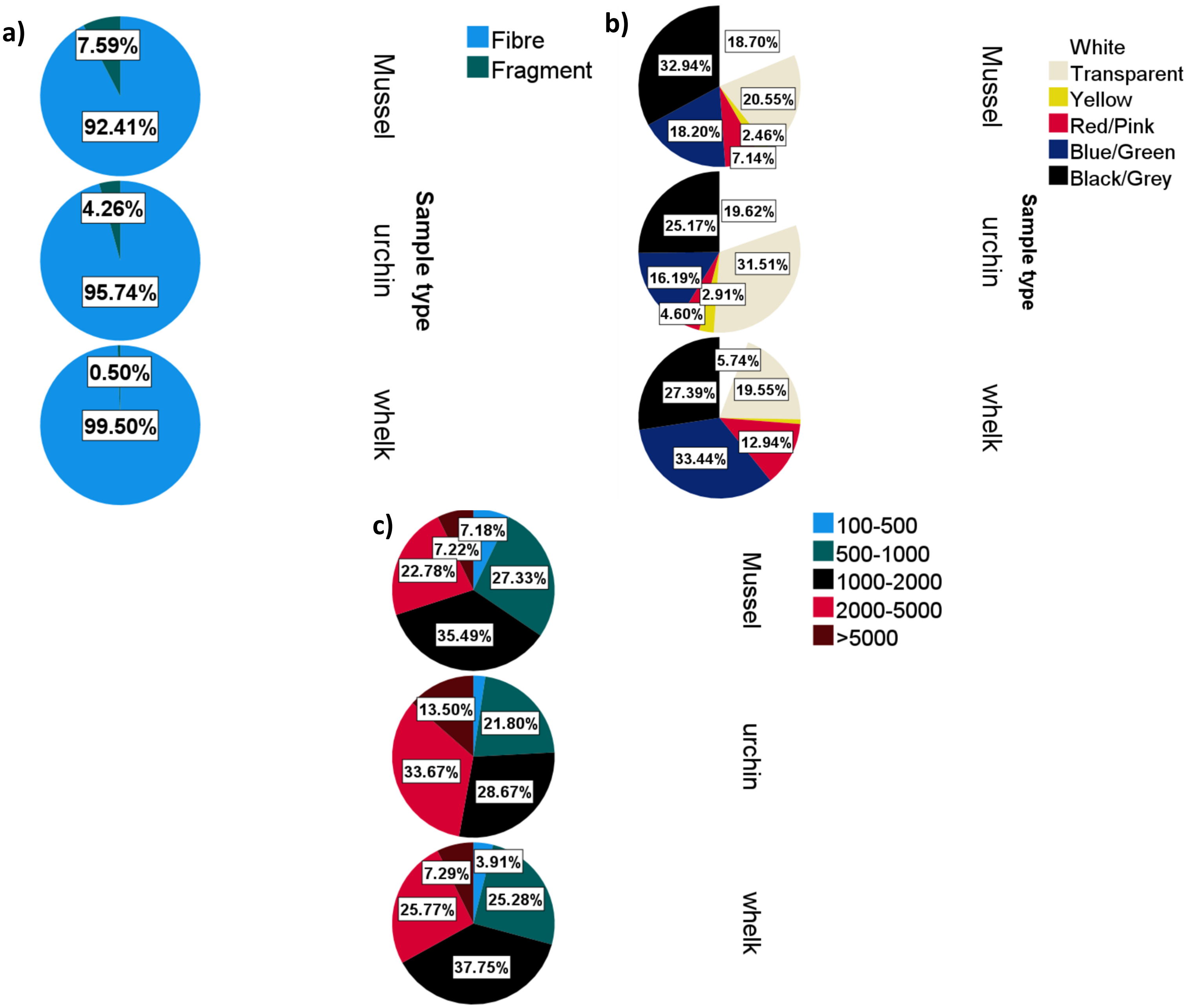


Figure 3.10: The percentage of MPs found in fauna (mussels, sea urchins and whelks) at all sites, zones and locations. a) MP type b) MP colour c) MP size.

Cotton was found to be the predominant fibre (48.8%) in mussels at Camps Bay, followed by other fibres (24.4%). The main polymer type found was PET (17.1%) (Fig. 3.11). For mussels at Mouille Point, FTIR scans were predominantly other fibres (35%) and organic fibres (35%), with

PET (15%) being the main polymer found, with a small percentage of cotton fibres (10%) found within samples (Fig. 3.11). FTIR scans for mussels at Three Anchor Bay showed that other fibres (45.2%) were predominantly found, followed by cotton (35.7%) and PET (9.5%) also being the main polymer type found.

At Camps Bay, FTIR scans for fibres found in sea urchins showed predominantly other fibres (57.1%) followed by PET (28.6%). Mouille Point had predominantly other fibres (25%) and PET (25%) with a relatively high percentage of cotton (18.8%) and organic fibres (18.8%) found in samples (Fig. 3.11).

FTIR scans for fibres found in whelks at Camps Bay showed that other fibres (45%) were mainly found, followed by PET (20%) and a prominent percentage of cotton (12.5%). At Mouille Point, scans showed that other organic fibres (52.9%) were predominantly found, followed by cotton (35.3%) and PET (11.8%). For Three Anchor Bay, the majority of scans were other fibres (68.8%) followed by PET (18.8%) and cotton (12.5%) (Fig. 3.11).

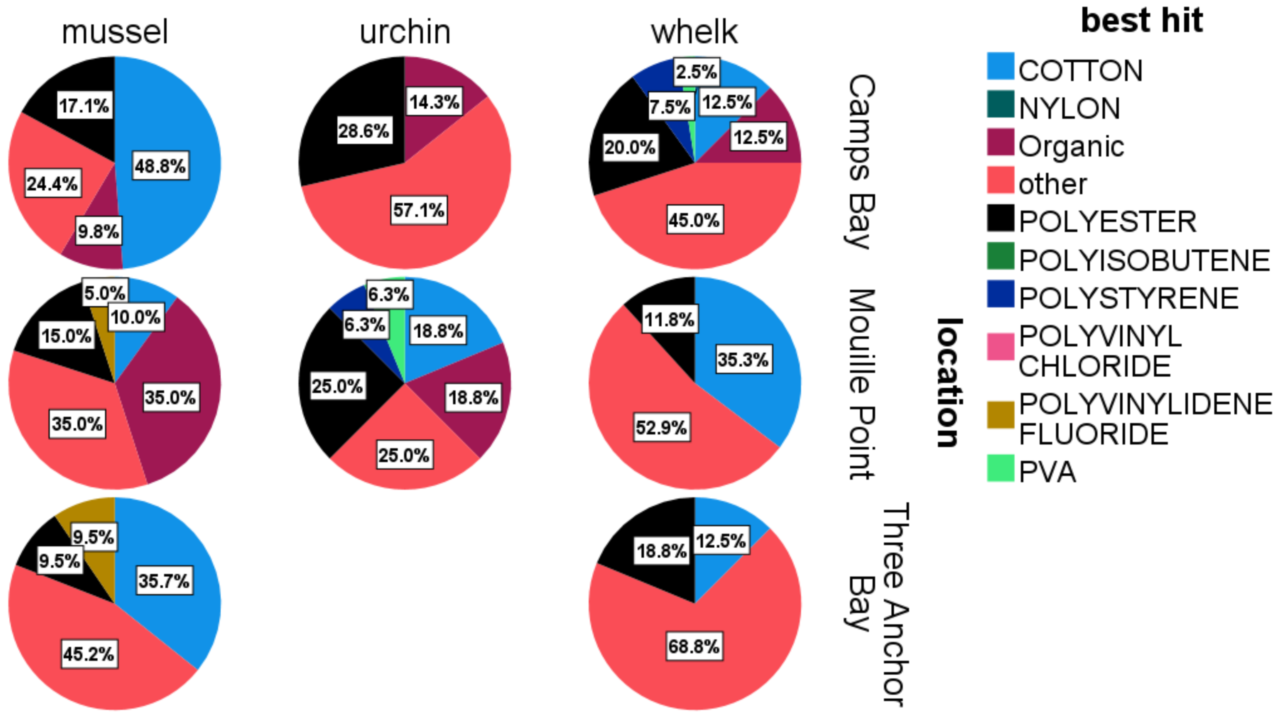


Figure 3.11: The percentage of MPs polymers (polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), polystyrene (PS), polyvinyl chloride (PVC), Polyvinylidene fluoride (PVDF), polyvinyl acetate (PVA) and Nylon) found in fauna (mussels, sea urchins and whelks) at sites and zones found at Camps Bay, Mouille Point and Three Anchor Bay.

3.5 Discussion

There is a lack of knowledge around the distribution of MPs around stormwater outlets and even more so on MPs found in organisms in rocky shores. This study was done to examine whether stormwater outlets are a source to introduce MPs into the coastal ecosystem. Previous studies have mentioned that stormwater outlets are a source of introducing higher amounts of MPs in coastal regions (Jannö, 2016; Jönsson, 2016; Preston-Whyte et al., 2021; de Villiers, 2018). This study proves that indeed the assumption of stormwater outlets do bring about a higher abundance of MPs particles, as the total MP abundance was found to have a significantly higher mean average at impacted stormwater sites compared to control sites. The overall abundance of MPs in the summer season was proven to have a higher mean abundance at both impacted stormwater sites and control sites compared to winter (Fig 3.2). The spike of MPs abundance during the summer season can be visually observed across all locations. We can assume that retention times of bays plays a major role in the abundance found within samples with the influence of upwelling and downwelling. A study by Schumann (1999) indicates that the South Africa region is mainly dominated by upwelling during the summer (November to March) than winter season, when westward winds (southeasterly winds) are common. After an upwelling event, a relaxation period follows, with the decay in wind, thus allowing calmer and less mixing and allowing nearshore heating of surface water (Send et al., 1987). Therefore, these events are capable of being linked to higher abundance of MPs found in biota as MPs can settle closer to the shore due to calmer conditions.

Although statistical analysis did not find a significant difference across all locations, Camps Bay recorded the highest mean MPs abundance compared to Mouille Point and Three Anchor Bay. It was visually observed that Camps Bay's stormwater outlet had a stronger flow rate of runoff compared to Mouille Point and Three Anchor Bay. This could have caused a higher input of MPs into the Camps Bay impacted site region. A study done by Klein et al. (2022) found that an increase in population caused higher concentrations of MPs within the intertidal water. Out of the three locations, Camps Bay does have the highest population, however, population numbers at Mouille Point were lower than Three Anchor Bay (https://census2011.adrianfrith.com). Although high plastic densities are linked with urban centres (Naidoo et al., 2015; Ryan et al., 2018) previous studies in South Africa have shown that plastic pollution is not correlated to the population density (Nel et al., 2017). It should however be noted that coastal waste water treatment work (WWTW) that are present along the Cape Peninsula, discharges excessive amounts of effluent in the near shore and are too sources of introducing high numbers of MPs (de Villiers, 2018). The WWTW can be found adjacent to sampled sites at Camps Bay and Mouille Point (de Villiers, 2018), which could be one of the causes for higher numbers of MPs found at these sampled sites. Another possibility is that the catchment areas are flowing through a larger area or the catchment is impacted by more anthropogenic activities compared to other locations. However, all of these factors are unknown, making it abstruse to relate whether the catchment is running through an industrial, residential or more pristine area.

Table 3.3: Mean abundance of MPs in water, sediment, mussels, sea urchins and whelks across various regions

Country /region	Mean abundance (SE)	Reference
Surface seawater (per litre)		
Camps Bay (Impact), South Africa	0.23 ± 0.06	This study
Mouille Point (Impact), South Africa	0.16 ± 0.02	This study
Three Anchor Bay (Impact), South Africa	0.16 ± 0.02	This study
South Africa	257.9 ± 53.36- 1215 ± 276.7 m^{-3}	(Nel and Froneman, 2015)
South Australia	2.95 ± 0.42- 16.31 ± 2.42	(Klein et al., 2022)
Jiaozhou Bay, China	46 ± 28	(Zheng et al., 2019)
Yellow Sea, China	130 ± 200	(Sun et al., 2018)
Northern Yellow Sea, China	500 ± 300	(Zhu et al., 2018)
Beach sand (particles per kg DW)		
Camps Bay (Impact), South Africa	77.81 ± 8.72	This study
Mouille Point (Impact), South Africa	57.81 ± 7.19	This study
Three Anchor Bay (Impact), South Africa	54.26 ± 6.42	This study
Cape Peninsula, South Africa	101 ± 147 (SD) F/dm^3	(de Villiers, 2018)
Qinzhou Bay, China	20 - 12852	(Li et al., 2018b)
Fishing port beach, China	180 - 457	(Pervez et al., 2020)
Marina Beach, India	20 - 1540	(Sunitha et al., 2021)
Gulf of Thailand, Thailand	420	(Bissen et al., 2020)
Koksijdde-bad,Belgium	56.9 - 102.1	(Claessens et al., 2011)
Groenendijk, Belgium	48,7 - 156.2	(Claessens et al., 2011)
Mussels (particles per gram STWW)		
Camps Bay (Impact), South Africa	4.2 ± 0.83	This study
Mouille Point (Impact), South Africa	4.12 ± 0.51	This study
Three Anchor Bay (Impact), South Africa	2.47 ± 0.36	This study
South Australia	6.67 ± 1.25	(Klein et al., 2022)
South Africa	2.33 ± 0.2	(Sparks, 2020)
China	1.52 - 5.36	(Qu et al., 2018)
Belgium	2.6-5.1 (10 g STWW)	(de Witte et al., 2014)
Germany	0.36 ± 0.07 - 0.47 ± 0.16	(Van Cauweeberghe and Janssen, 2014)
Whelks (particles per gram STWW)		
Camps Bay (Impact), South Africa	2.00 ± 0.19	This study
Mouille Point (Impact), South Africa	1.64 ± 0.19	This study
Three Anchor Bay (Impact), South Africa	1.58 ± 0.19	This study
Persian Gulf	12.8 - 20	(Naji et al., 2018)
Sea urchin (particles per gram STWW)		
Camps Bay (Impact), South Africa	0.28 ± 0.03	This study
Mouille Point (Impact), South Africa	0.11 ± 0.01	This study
Three Anchor Bay (Impact), South Africa	0.13 ± 0.19	This study
Greece	1.95 (σ = 1.70)	(Hennicke et al., 2021)
Tajao and El Poris, Spain	9.2 ±3.0 (SD) - 10.0 ± 4.5(SD)	(Sevillano-Gonzalez et al., 2022)
North coast, China	2.20 ±1.50 – 10.04 ± 8.46 (SD)	(Feng et al., 2020)

It should be noted that FTIR categories for cotton were separated from organic fibres to give a better interpretation of the amount of cotton fibres found in the area. The reasoning for the separation of cotton from organic fibres is because the sampled locations are directly adjacent to residential areas and it was likely that high amounts of cotton fibres would be found.

3.5.1 Water

The total abundance of MPs found in water was significantly higher at impacted stormwater sites compared to control sites (Fig. 3.3a). This illustrates that MPs are entering water in the coastal region via run off from stormwater outlets. A study done by Nel and Froneman (2015), however, found an extremely high amount of MP particles in surface water that had an abundance of 257.9 ± 53.36 - 1215 ± 276.7 m^{-3}, while impacted sites from this study ranged from 0.16 ± 0.02 particles/l to 0.23 ± 0.06 particles/l (Table 3.3). When compared to other global studies seen in table 3.3, this study had the lowest number of MPs found in surface water.

MPs in water were found to be higher during winter compared to summer, showing that the abundance of MPs increases in the winter period around stormwater outlets due to excessive runoff entering the coastal area from precipitation (Fig. 3.3b). This is because the water is directly influenced by the amount of runoff entering the impacted area. Our winter sampling period experienced a higher precipitation compared to summer, meaning there was an excessive amount of runoff, which caused MPs to be more ubiquitous in coastal water at the impacted sites. A study into MPs abundance by Jiang et al. (2022) finds MP abundance in water was higher during the wet season compared to the dry season. This suggests that stronger plastic waste recycling strategies should be implemented in preparation for the wet season. As mentioned by de Villiers (2018), stormwater outlets that are potential source to introduce MP in the marine environment is expected to enhance in MP abundance during the first early winter rain fall (May-June). A previous study also states that the movement of water plays a vital role in the abundance of MP particles found within bays (Doyle, 2019). It should, however, be noted that the wave exposure towards coastal ecosystems were also proven to have no influence on the load of MPs in water (Ehlers et al., 2022).

Out of the three chosen locations, Camps Bay was found to have the highest abundance of MPs in water (Fig. 3.3c). The flow rate of runoff entering the impacted site at Camps Bay was visually observed to be faster than Mouille Point and Three Anchor Bay, which means that MPs should be more ubiquitous in this area. It can also be seen that water at Three Anchor Bay had no significance across impact and control sites (Fig. 3.3c).

In water samples, mainly fibres were found, with the two main colours being black and blue. Studies from Nel and Froneman et al. (2015) reveal that MPs along the South African coastline had an extremely high percentage of MP fibres, which is also noted in all samples of this study. The most common size of MPs that were found in samples ranged between 2000 – 5000 μm and 1000 – 2000 μm which are larger MP particle sizes.

At Camps Bay and Mouille Point, FTIR scans recorded a high amount of cotton, followed by PET fibres. The main products of which clothing is made up are cotton and PET, and since sites are located directly adjacent to residential areas, high amounts of fibre particles were found in samples. Browne et al. (2011) mentions that fibres generally originate from inland water sources due to domestic washing. Washing of a single garment is said to produce roughly thousands of fibre particles that are released into wastewater (McIlwaith et al., 2019). However, MPs are not only limited to entering stormwater outlets via domestic washing. There are a large number of synthetic fibres (Miller et al., 2017) and they are highly likely to be found all over the environment due to anthropogenic activity (packaging, transportation, construction etc.) (Geyer et al., 2017) and movement via water and wind (Petersen and Hubbart, 2021). Since stormwater structures act as a conduit to prevent flooding, their catchment areas are considered as transport pathways for MPs as they are collected from the terrestrial terrain via runoff and transported to the coastal marine environment.

At Three Anchor Bay, FTIR scans recorded a high amount of waste products that fell in the ‘other’ category that were not registered as a polymer. PVDF polymer also made up a high percentage of Three Anchor Bay water samples. It should be noted that PVDF is commonly used as a heat resistant plastic in piping, fittings, seals, chemical tank liners, pumps, and valve parts. Notably, construction on the Sea Point Promenade was taking place at the time of sampling, as well as construction and renovation of various buildings in the surrounding areas. It is likely that PVDF piping, seals, pumps and valve parts were used in the construction projects, which led to increased numbers of PVDF being found at the impacted site.

3.5.2 Sediment

Sandy beaches are one of the most studied environments when it comes to MPs research (Pinheiro et al., 2019). MPs that have been identified on the strandline represent MPs that are recently deposited on the beach from the previous tide cycles. Due to the lack of research around stormwater outlets, sediment from impacted stormwater outlets was analysed. It was found that the mean total abundance of MPs in sediment at impacted stormwater sites was higher compared to control sites (Fig. 3.6a). The mean abundance of sediment sites found in Camps Bay, Mouille Point and Three Anchor Bay was, however, lower or fell within the same range of other studies across the globe (Table 3.3). The average mean of sediment along the Cape Peninsula of Cape Town found that the highest average of sediment, being the Camps Bay impact site (77.81 ± 8.72 particles/kg DW), was lower compared to de Villiers's study (2018) (101 ± 147 (SD) F/dm^3). Like water, sediment was found to have a higher mean MPs abundance in winter compared to summer. Jiang et al. (2022) also find that sediment had a higher MP abundance during the wet season compared to the dry season. Precipitation is most likely the key reason for the increase of MPs in sediment, as more runoff is likely to enter the coastal zones. MPs are likely easier to be washed up and settle in sediment compared to biota. Bom et al. (2022) also suggest that, during high energy events, MPs in sediment are capable of being resuspended back into coastal waters due to wave action, which can influence the concentrations of MPs.

The grain sizes percentage across locations was found to be mainly made up from medium and coarse sand. During winter we see a shift in the grain size percentage as the percentage of fine and medium sand decreases while the very coarse sand and very fine gravel increases (Table 3.2). The movement from finer to coarse sand can be linked with higher wave activity causing finer grain particles to be washed up with more coarse sand being exposed (Clark et al., 2017). Potentially, the movement of grain sizes from finer to coarse could be linked to the resuspension of MPs in sediment.

A trend can be seen of MPs abundance found at impacted sites across all locations, which shows that sediment found at impacted sites were significantly higher than control sites (Fig. 3.3c). Like in water, the abundance of MPs found in sediment were found to be higher in winter compared to summer. Due to MPs being ubiquitous in water during winter, tides wash MPs into the intertidal. Sediment particles can trap MPs from washing back inshore, which causes the high abundances.

MPs that are often trapped in sediment can cause a blockage of water filtration, thus decreasing nutrients, and can bring about higher temperatures (Lamprecht, 2013). The abundance of MPs found in water directly influenced the abundance of MPs found at locations as seen in both figure 3.3c and 3.6c. Camps Bay had the highest mean abundance of MPs at impacted sites for water and sediment.

Like water, the main MP type that was found in sediment were fibres, which made up 97.13% of MPs particles found. A previous study by Martin et al. (2017) also finds a higher percentage of fibre MPs in sediment core samples, which made up 85% of MPs found. The main colour of MPs found in sediment were blue and black, with a size range of 1000 – 2000 μm and 2000 – 5000 μm. PET was the polymer that was commonly scanned in sediment at each location. A high number of scans also register as cotton at Mouille Point and Three Anchor Bay.

3.5.3 Biota

Biota samples found at impacted stormwater sites recorded a higher mean number of MPs in individuals compared to control sites (Fig. 3.9a), with mussels being the organism to consume the highest number of MPs per STWW. The mean average of MPs in STWW was found to be less than the mean found in per individual across mussels, sea urchins and whelks (Table 3.1). Like the mean abundance in STWW, the mean abundance found in per individual was the highest in mussels at impact sites during the summer and winter season and the lowest for sea urchins (Table 3.1). This study found that 90.7% of mussels, 69.7% of sea urchins and 91.1% of whelks that were sampled had MPs particles. Previous MPs surveys have found that up to 47.5% of mussels sampled from coastal waters in China and the Mediterranean Sea had MPs particles in the soft tissue (Li et al., 2016).

3.5.3.1 Mussels

Since mussels are non-selective filter feeders, they were found to have the highest abundance of MPs compared to sea urchins and whelks (Fig. 3.9a). A study done by Setala et al. (2016) discovered that filter-feeding bivalves tend to ingest significantly higher amounts of MPs beads compared to other feeding groups. Non-selective filter feeders digest through most particles in the water column based on the size, making them susceptible to MPs contamination (Moore et al., 2001). However, it should also be known that MPs in mussels tend to decrease once water quality improves (Birnstiel et al., 2019). The mean average of mussels at impact sites was notably higher compared to a study done by Sparks (2020) on mussels in South Africa. Sparks (2020) found an average of 2.33 ± 0.2 particles per/gram within mussels, the majority being fibres, while the highest average of MPs in mussels found at impact sites in Camps Bay were 4.2 ± 0.36 particles/gram STWW. The lowest impact site, Three Anchor Bay, also had a higher average of 2.47 ± 0.36 particles/gram STWW compared to the study of Sparks (2020). When compared to other countries, the abundance of MPs in mussels for this study were more or less in the same range or lower, with the exception of a study done on mussels in Germany by Van Cauweeberghe and Janssen (2014) that had an abundance of 0.36 ± 0.07 - 0.47 ± 0.16.

3.5.3.2 Sea urchins

Like mussels, urchins are non-selective eaters. However, they graze on algae on the benthos, so digesting MPs would depend on the availability and the ability of MPs to attach to either rocks or algae (Sevillano-Gonzalez et al., 2021). According to a study from Barkhau (2022), most bivalve filter feeders like mussels that are found along rocky shores are susceptible to ingesting MPs particles due to their feeding strategy. Piarulli et al. (2020) and de Borros et al. (2020) suggest that the organism;s feeding mode can be linked to the amount and the type of MPs particles that are ingested and not necessarily on the type of habitat or trophic group, which is why sea urchins that are non-selective grazers have a lower mean abundance of MPs compared to mussels. According to a study by Mudd et al. (2010), macroalgae species found on rocky shores often trap MPs due to the complex topography, thus making it available to be ingested by grazers like sea urchins. Compared to other studies done by Sevillano-Gonzalez et al. (2022) in Spain (9.2 ± 3.0 (SD)-10.0 ± 4.5(SD)) and Feng et al. (2020) in China (2.20 ± 1.50 – 10.04 ± 8.46 (SD)), this study found a considerably low number of MPs in sea urchin, with the highest abundance at Camps Bay impact site being 0.28 ± 0.03 particles/STWW.

3.5.3.3 Whelks

Whelks were found to have the second highest mean MPs in STWW for both seasons and across all three locations (Fig. 3.9). Whelks are one of the predators of mussels and other invertebrate species found in rocky shores, and the abundance of MPs is directly influenced by the intake of other organisms due to predation (Hunt and Scheibling, 1998; Ekaratne and Goonewardena, 1994). It is expected to observe a lower abundance of MPs particles in predators compared to prey as MPs content is expected to dilute as it moves up the food web, according to the theory of trophic level dilution (Alava, 2020). There is, however, very little information within rocky shores regarding verification of MPs on many other common rocky shore invertebrates such as snails as most literature is based on filter feeders (Doyle et al., 2019). Thus, it is difficult to compare our findings of MPs particles found in whelks in this study to other findings of gastropods since whelks are carnivorous organisms. A study was however done by Naji et al. (2018) in the Persian Gulf on the *Thais mutabilis*, which is a predator snail like the *Burnupena sp*. The study found an average of 5.50 ± 2.70 per gram STWW while this study found an average of 1.74 ± 0.11 per gram STWW, which could mean that the type of organism that whelks are consuming at impacted sites of this study has a much lower abundance of MPs compared to Persian Gulf. Like most samples, whelks had a high percentage of fibres found in them and an experimental study done by Xu et al. (2022) found that fibres in the *Reishia clavigera* (whelks' species) had a higher accumulation of fibres than fragments over longer exposure periods.

The mean MPs found in fauna samples during the summer sampling period were more abundant compared to samples found in the winter sampling period (Fig. 3.9b). This is the complete opposite result compared to water and sediment. It was expected that, with the increase of MP load in water, there would be an increase in the MPs in biota as Qu et al. (2018) found an increase in MP load in mussels with the increase in MP load in water. It is expected that more pollutants are released during the rainy season, but flushing is also stronger during this period (Du et al., 2020). Taylor et al., (2011) therefore stated that the release of runoff is not necessarily linearly proportional to the total loading of pollutants. It could be suggested that the morphodynamics of coastal areas, with the influence of stormwater outlets or river systems, play a major role in the spatial distribution and concentrations of MPs (Pinheiro et al., 2019), as various studies have found the loading to increase during winter and others in summer.

As seen in this study, the increase of MPs load increased during summer for biota but decreased in water and sediment. Although the winter sampling period had a higher precipitation than the summer period, retention times of bays are much longer due to calmer conditions allowing less flushing to occur (Taylor et al., 2011), which was experienced in the summer sampling period. Longer retention times allow pollutants such as MPs to settle in bays, causing them to be more ubiquitous. As mentioned above, upwelling periods in South Africa tend to be followed by long relaxation periods that brings about calmer sea conditions, allowing for MPs to settle. The accumulation of MPs also depends on ejection and excretion of these organisms, as the uptake minus removal activity makes up the concentration of MPs found within the body tissue (Ding et al., 2021; Li et al., 2018a). Most fibres, being the main type of MPs found in this study, are said to be retained longer within organisms causing accumulation of MPs (Mayoma et al., 2020).

Biota intertidal samples were found to have higher mean values of MPs compared to samples in the subtidal zones (Fig. 3.9d). One reason for the intertidal having a higher influence of MPs distribution is because stormwater outlets are directly adjacent to the intertidal and runoff is excreted into the intertidal zone. Another reason is that MPs, depending on the type, are buoyant and therefore will not reach the benthos in the subtidal where invertebrates were collected. Sampled areas, however, are prone to a lot of mixing and turbulence which could allow MPs to reach the benthos. Most samples also consisted of PET which is denser than water allowing it to sink to the benthos. It is common to find high amounts of PET in samples as a study by Jiang et at. (2022) also experienced a high percentage of PET of 56% of the total MPs sampled from Jiaozhou Bay.

Fibres were the predominant type of MPs found in all fauna samples. According to Barrows et al., (2017) 91% of MPs in coastal waters are fibres, thus making the probability of them being digested by fauna high. Another study done by Doyle et al. (2019) also found that 97% of MPs found in *L. littorea* (grazers) were fibres. Black, blue and transparent were found to be the most common colours found in mussels and whelks and transparent, black and white in sea urchins. Colours like blue and black are easily confused, especially under poor lighting microscopes. Previous studies on sea urchins also found high amounts of blue, black or transparent MPs in sea urchins (Hennicke et al., 2021; Sevillano-Gonzalez et al., 2022; Feng et al., 2020). The most common sizes of fibres that were found in fauna samples were in the range of 2000 – 5000 μm,1000 – 2000 μm and 200 – 1000 μm. The length of MPs is in the same class range of previous studies done on mussels, sea urchins and whelks (Sevillano-Gonzalez et al., 2022; Feng et al., 2020).

All fauna samples at each location experienced a high percentage of ‘other’ contaminants that were recorded by the FTIR. Other common fibres that were constantly recorded were cotton and PET. We can assume that cotton and PET are often picked up in our samples because of the catchment area, which flows through a residential area that is adjacent to our impacted stormwater outlets. The reason for the high percentage of cotton and PET is mentioned under the discussion for water and sediment. Previous studies also found that PET was commonly found in samples in Hong Kong (Xu et al., 2020) and Thailand (Thushari et al., 2017).

3.6 Conclusion

The Cape Peninsula of Cape Town is a broad stretch of coastal land that is impacted by numerous stormwater outlets that have unknown catchment areas. These stormwater outlets are extremely close to one another, which made site selection extremely difficult for control sites. However, it was clear in our results that stormwater outlets indeed bring about an abundance of MPs into our coastal regions, as impacted sites had higher mean numbers of MPs compared to sites that were ±200m away from impacted stormwater outlets. As proven in this study, MPs brought into the coastal region are introduced into the aquatic environment via runoff, and it was expected that higher amounts would be found during winter season. However, this was not the case for biotic samples. As previous studies done by Taylor et al. (2011) show, the input of runoff is not linearly proportional to the total load of pollutant as flushing plays a huge role in the number of pollutants found in bays. The distribution of MPs also found a higher abundance of MPs within the intertidal zone compared to subtidal zone. MPs numbers in the intertidal were far more abundant compared to the subtidal, mainly because the intertidal falls directly adjacent to stormwater outlets.

Furthermore, continuous monitoring of these sites would be ideal by continuing with collecting abiotic samples and mussels, which are the main invertebrate impacted by MPs around stormwater outlets. This study and continuous monitoring around stormwater outlets will be ideal to assist and advise waste management on precautions to take in order to reduce impacts of MPs entering the coastline via runoff. It is advisable that some sort of MPs technology should be implemented around stormwater outlets to filter MPs from runoff before it enters coastal waters.

Chapter 4 – Environmental risk assessments on microplastics around stormwater outlets in Cape Town, South Africa.

4.1 Abstract

The Cape Peninsula of Cape Town is impacted by numerous stormwater drainage systems that discharge contaminated runoff into coastal waters. These stormwater systems are perfect for carrying MPs and distributing them into the marine environment. The aim of this study is to assess the risk that MPs from stormwater systems have on the environment by using risk indices and condition indices as a guideline. The risk indices that were utilised in this study were the contamination factor (CF), pollution load index (PLI), polymer risk index (H) and pollution risk index (PRI) risk assessment calculation. The calculations were used to calculate the risk of MPs in water, sediment and three different feeding groups: mussels (filter feeders), sea urchins (grazers) and whelks (carnivores). The results of these calculations found that stormwater outlets were indeed causing MPs to have a high CF and moderate PLI at Camps Bay, Mouille Point and Three Anchor Bay, while H and PRI values were only found to be high at Camps Bay. The condition index of biota found that due to stormwater outlets introducing MP into coastal water, the condition of mussels was found to be significantly in a poorer state with the increase in MPs abundance. Due to MPs causing a higher risk at Camps Bay, Mouille Point and Three Anchor Bay in three different types of samples, it is imperative that waste management implements precautions to reduce the number of MPs entering coastal waters via stormwater runoff.

4.2 Introduction

The coastline is prone to being impacted by MPs polymers since they are ubiquitous around stormwater outlets. However, mainly distribution research on MPs has been done, focusing on the abundance of MPs in a specific location, and very little is focused on the actual impact of MPs. There's been a global need for risk assessment towards MPs and governments worldwide have expressed the urge for a risk assessment framework (Bucci and Rochman, 2022). Currently there is no solid structured model in place to evaluate environmental risk (Prarat and Hongsawat, 2022). The evaluation of risk assessments has been explored in seawater (Pan et al., 2021) and sediment (Sparks and Awe, 2022). The pollution load index (PLI) was proposed by Tomlinson et al. (1980) to standardise the assessment for MPs pollution levels. They proposed using the MPs concentration and dividing it by the baseline concentration to give the MP contamination factor (CF), and by using the CF, one is then able to obtain the PLI. MPs polymers have been assessed by using the hazard scores of plastic polymers created by Lithner et al. (2011). By using the polymer hazardous scores, the polymer risk index (PRI), which is an equation set out by Hakanson (1980), can be utilised to assess the PRI, which can further be used to calculate the pollution risk index assessment.

In order to assess the level of quality the environment is currently in, a risk assessment test will be done. For this study, the following risk assessment test will be used: microplastic contamination factor (CF), microplastic pollution load index (PLI), polymer risk index (H), pollution risk index (PRI) and organism condition index. These calculations can all be considered to help us understand the level of risk and the current state of our ecosystems that are adjacent to stormwater outlets.

Using risk indices, we can derive what condition/level the environment is at due to the abundance and type of MPs found in the area. MPs are common in biota and can influence the condition of organisms. Other assessments, such as the condition index, can be done to give critical information about physiological state and growth of the organism (Andral et al., 2004). Nevez et al. (2015) state that very little data is available regarding the risk assessments of MPs in biota and there is a generalised concern about the ways in which MPs pose a risk to organisms via ingestion and the movement of MPs up the food change.

According to Rubin et al. (2021) studies that attempted to use real environmental MPs for the latter risk assessment studies are not as efficient, due to the tedious sample extraction procedure and heterogeneity in the particles and material, size, shape, colour and surface contamination. The evaluation from real environmental samples from a wide size distribution may often lead to an underestimation of hazardous risk (Jeong et al., 2016). For this study, the risk indices and condition indices will be utilised to do a risk assessment to inform management about decision making. Given the lack of research around risk indices, the aim of this study is to identity the state at which the environment is in adjacent to three stormwater outlets (Camps Bay, Mouille Point and Three Anchor Bay) in South Africa, Cape Town, and to identify the condition of biota due to ingesting MPs.

4.3 Materials and methods

4.3.1 Study area and sites:

The study areas were selected along the Cape Peninsula of Cape Town, South Africa (Fig. 4.1). Three locations were selected: Camps Bay, Mouille Point and Three Anchor Bay. Each location was impacted by a stormwater outlet, being the impacted site, and roughly 200m away from it was the 'control site'. Refer to Chapter 3 for the description of the study area and sites sampled.

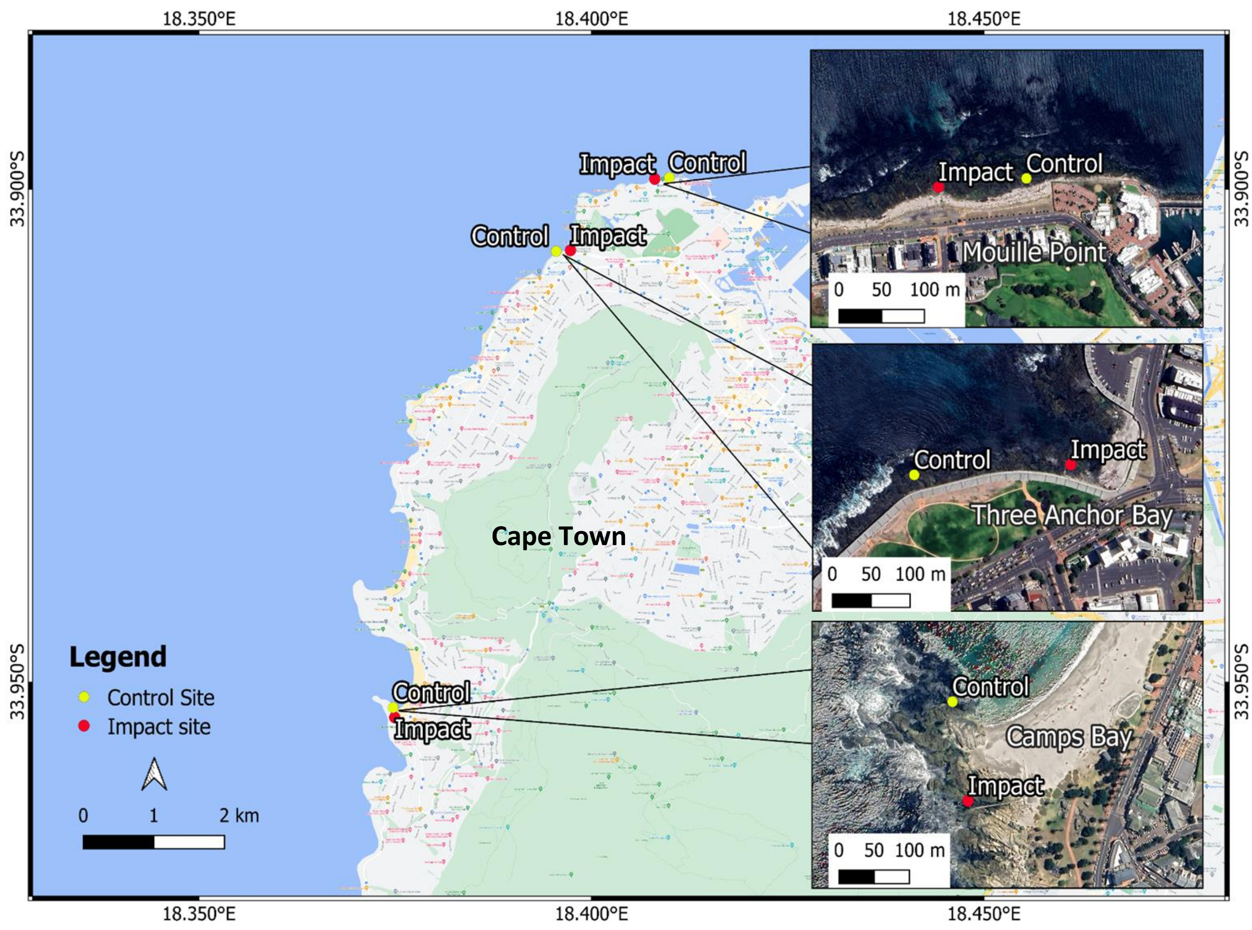


Figure 4.1: The Cape Peninsula study area and study sites chosen to assess impacts of the selected intertidal stormwater outlets.

4.3.2 Microplastic sampling and analyses

Refer to Chapter 3, Section 3.3 for the description of the MP sampling and analysis.

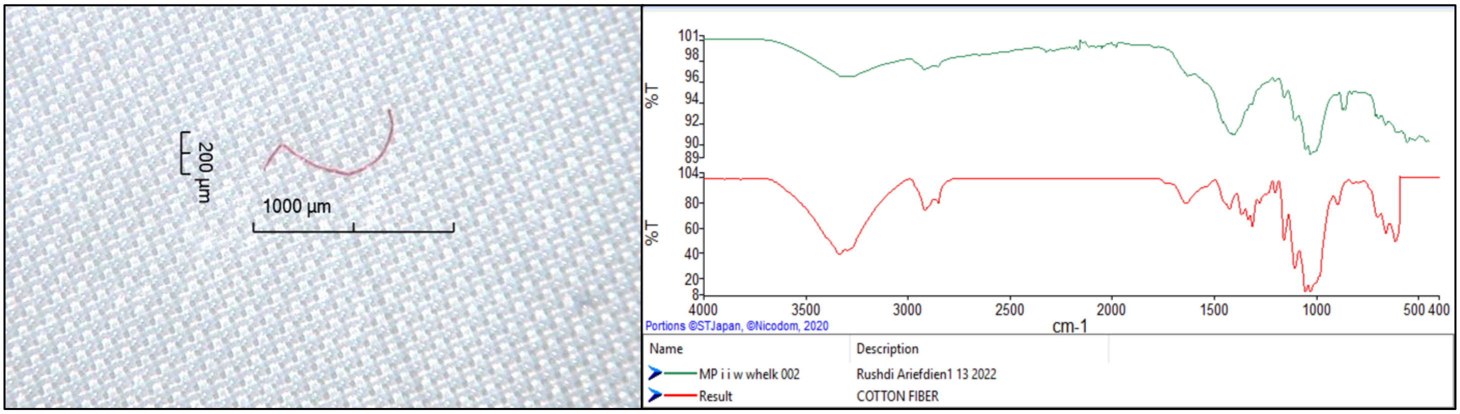


Figure 4.2: Example of microplastics fibre that was scanned with the FTIR.

The FTIR identifies the polymers and groups them with the most ideal plastic polymers found in the library (ST Japan Library) (Fig. 4.2). The spectral wave was adjusted to a range of 4000 – 450 cm doing 10 scans per sample. A background scan was done before scanning sampled MPs.

4.3.3 Risk indices

Hazard scores are used to, calculate the risk of MPs in fauna and the environment and indices used, are the MP contamination factor (CF), MP pollution index (PLI), the polymer risk index (H) and pollution risk index (PRI). The level of risk ranges from low to moderate, high, very high and dangerous (Table 4.1). Depending on the score we get from these calculations, we can then categorise the impacted area/sampled area. It has been hypothesised that areas with a higher MP source input will result in a higher burden on the surrounding marine environment (Nel et al., 2016).

Table 4.1: Levels of each risk category for microplastic contamination.

Polymer Risk Index (H)	< 10	10 – 100	101 – 1000	1000 - 10000	> 10000
Pollution Risk Index (PRI)	< 150	150 – 300	300 – 600	600 – 1200	> 1200
Contamination Factor (CF)	< 1	1 - 3	3 - 6	> 6	
Pollution Load Index (PLI)	< 1	1 - 3	3 - 4	4 - 5	> 5

Microplastic indices can be calculated in order to provide risk assessments of the potential effects that MPs have on the sampled area. These assessments categorise the risk the environment/organisms are in based on the calculated values. The CF is an assessment that compares the concentration of MPs ($C_{microplastics}$) to the background/baseline concentration ($C_{baseline}$):

$$CF_i = \left(\frac{C_{microplastic}}{C_{baseline}}\right)$$

The $C_{baseline}$ values were selected from the lowest mean value according to its respective sample type. All baseline values were found at control sites as there are no historic values for the area, and this is considered to be acceptable (Kabir et al., 2021).

The PLI uses the CF to identify the risk the PLI has on the environment. The PLI was calculated as follows:

$$PLI_{site} = \sqrt[2]{CF_i}$$

The toxicity levels of MPs polymers can be analysed based on the Lithner et al. (2011) method. Each polymer has a hazardous score assigned to it, allowing to assess the risk of the polymers on the environment/organisms. The polymer risk index (H_i) calculation is as follows:

$$H_i = \sum \quad P_n \times S_n$$

P_n can be calculated using the ratio of a polymer type recorded at each site location and Sn is the assigned polymer hazard score given by Lithner et al. (2011).

The pollution risk index (PRI) is calculated as follows:

$$PRI_i = \sum H_i \times PLI_{site}$$

The calculation for PRI_i shows the ecological hazard level of polymers when associated with the polymer risk index.

MPs, along with other pollutants that are excreted from stormwater outlets, can affect growth rate, digestive systems and reproductivity (Bertucci and Bellas, 2021). The condition indices (CI) were calculated to determine how well the organism is doing at the given time.

The condition index (CI) for mussels and sea urchins was calculated using the following calculation according to Kanduč et al. (2018):

$$CI_{mu} = \frac{wet\ weight\ \ x100}{total\ weight}$$

The condition index (CI) for whelks was calculated using the following calculation used by Rahman and Barkati (2006):

$$CI_s = \frac{Dry\ tissue\ weight}{Total\ weight\ (Dry\ shell + Dry\ tissue)} \times 100$$

4.3.4 Data analyses

The test for normality for MPs data was not met even after being log transformed. The non-parametric Mann-Whitney test was used to determine the difference in MPs concentration and condition index between sites. Variance of data was measured using the mean and standard error of the mean (SEM) and significant values were set at $p<0.05$.

4.4 Results

The risk category for all impacted stormwater sites for CF was found to fall within the high (III) category, with Camps Bay having the highest CF. All control sites for CF were found to be one category below impacted sites, which was the moderate (II) category (Fig. 4.3a). The PLI risk assessment across all impact and control sites at Camps Bay, Mouille Point and Three Anchor Bay were found in a moderate (II) risk category (Fig. 4.3b). The polymer risk index and PRI found that the Camps Bay impacted stormwater site was the only site that was found in a high (III) risk category (Fig. 4.3c and 4.3d).

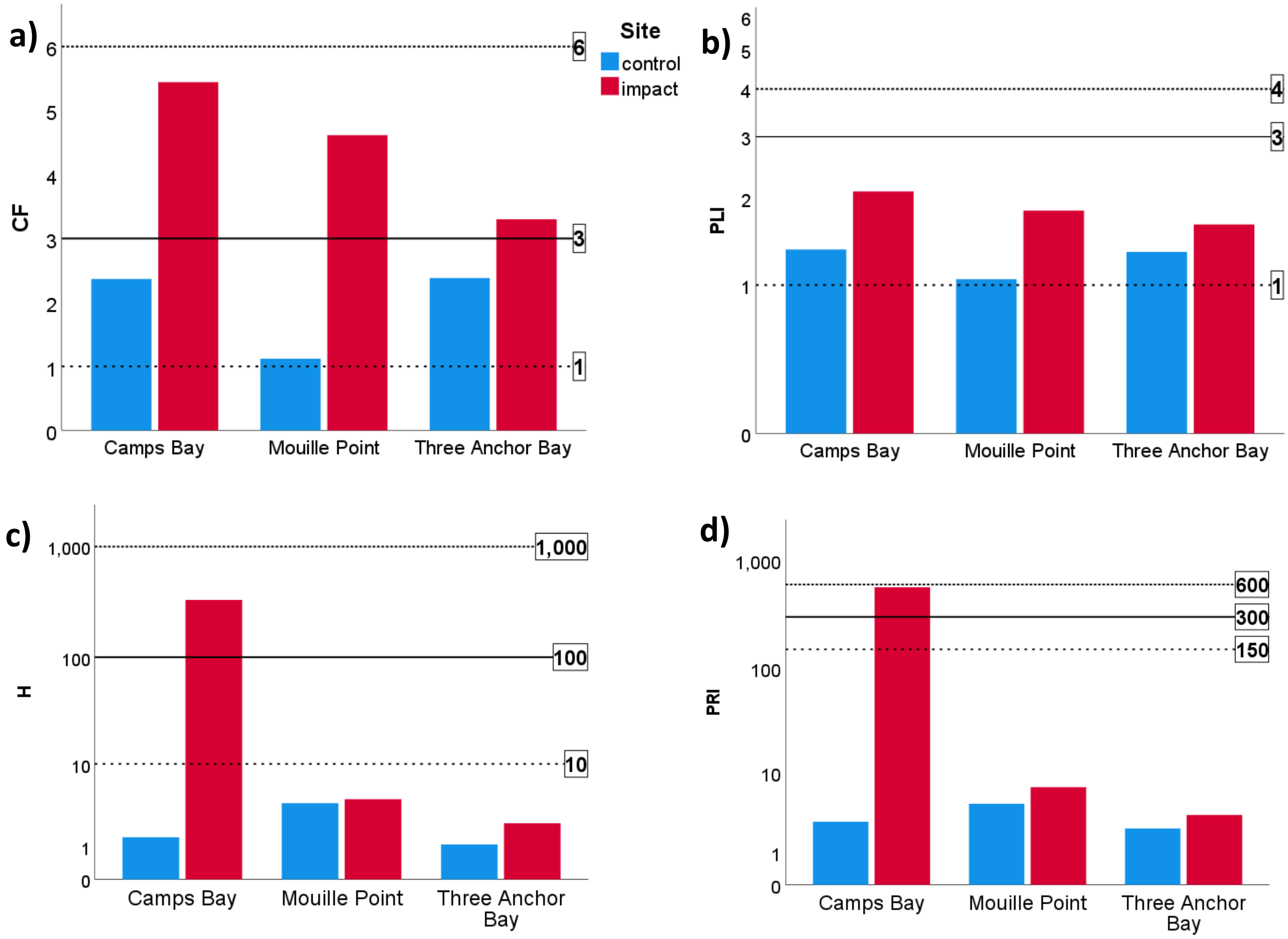


Figure 4.3: The risk assessment of all sample types found at Camps Bay, Mouille Point and Three Anchor Bay at impact and control sites a) Microplastic contamination factor. B) Microplastic pollution load index (log scale). c) Polymer risk index (log scale). d) Pollution load index (log scale).

4.4.1 Water

The seasonal CF for water showed that impacted sites during winter were the only sites found at a high (III) risk category (Fig. 4.4a). The PLI for all water sites was found to be in the moderate (II) risk category (Fig. 4.4b). For the polymer risk index and pollution risk index of water, the Camps Bay impacted stormwater site was the only site that fell within the very high (IV) and dangerous (V) risk categories (Fig. 4.4c and 4.4d).

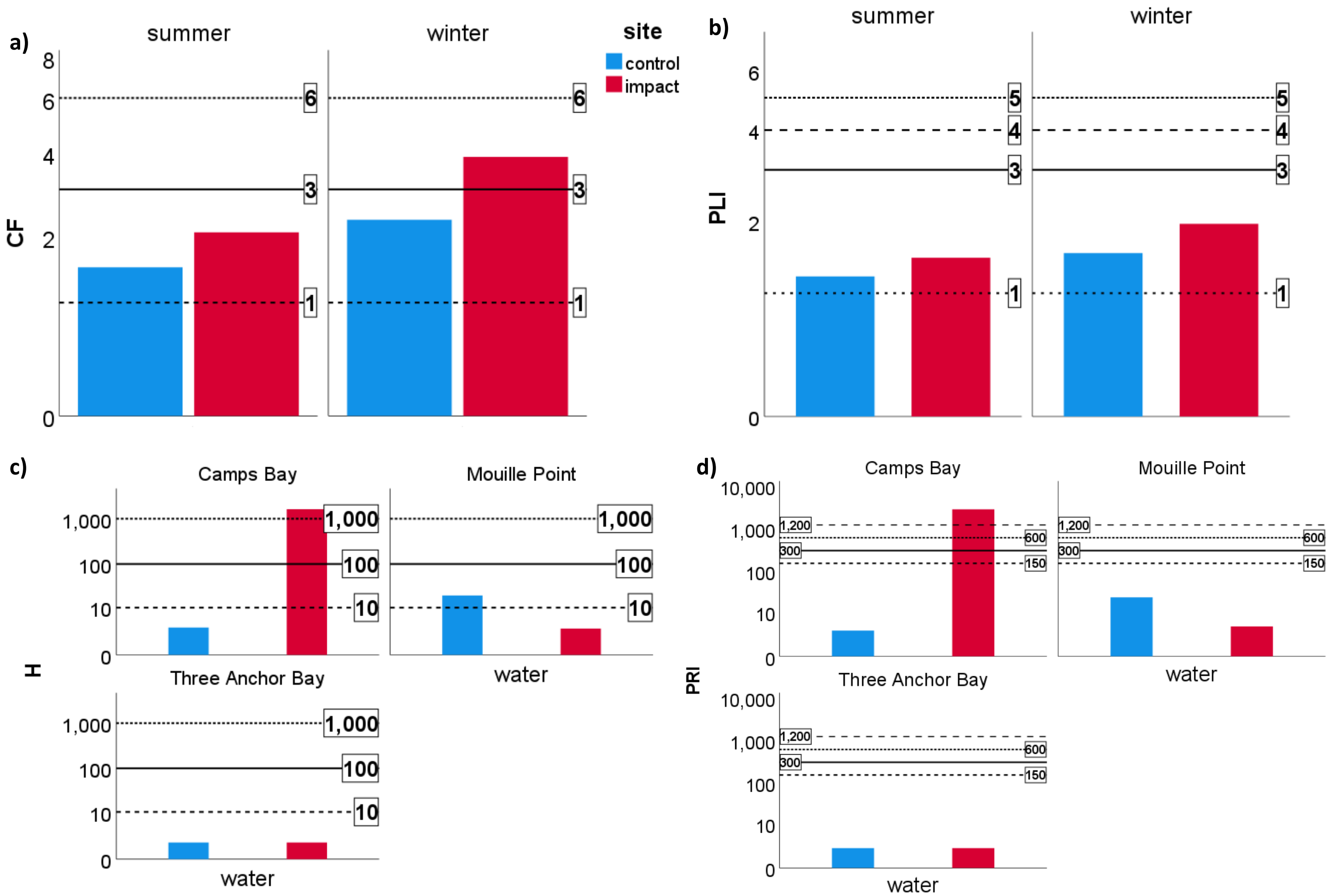


Figure 4.4: The seasonal risk assessments of water at impact and control sites (log scale) a) Microplastic contamination factor. B) Microplastic pollution load index. c) Polymer risk index at Camps Bay, Mouille Point and Three Anchor Bay. d) Pollution load index Camps Bay, Mouille Point and Three Anchor Bay.

4.4.2 Sediment

The CF and PLI risk assessment for sediment found that sediment during summer and winter seasons at impacted stormwater sites were in a moderate (II) risk category, while control sites were in a low-risk category (Fig. 4.5a and 4.5b). For the polymer risk index and pollution risk index for sediment, the risk assessment found that sediment at impacted stormwater sites were in the lowest risk category, being low (I) while no risk was calculated for control sites.

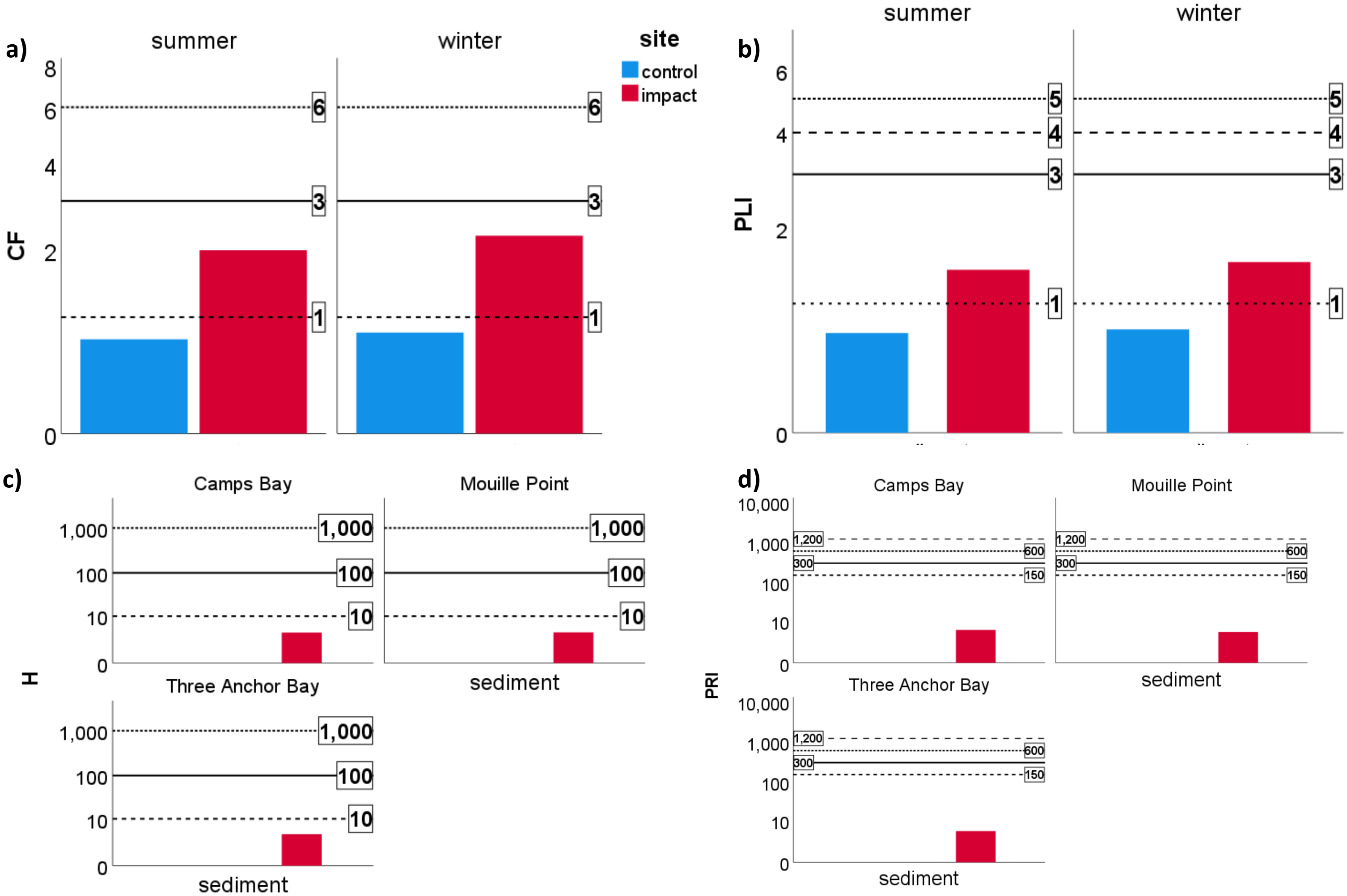
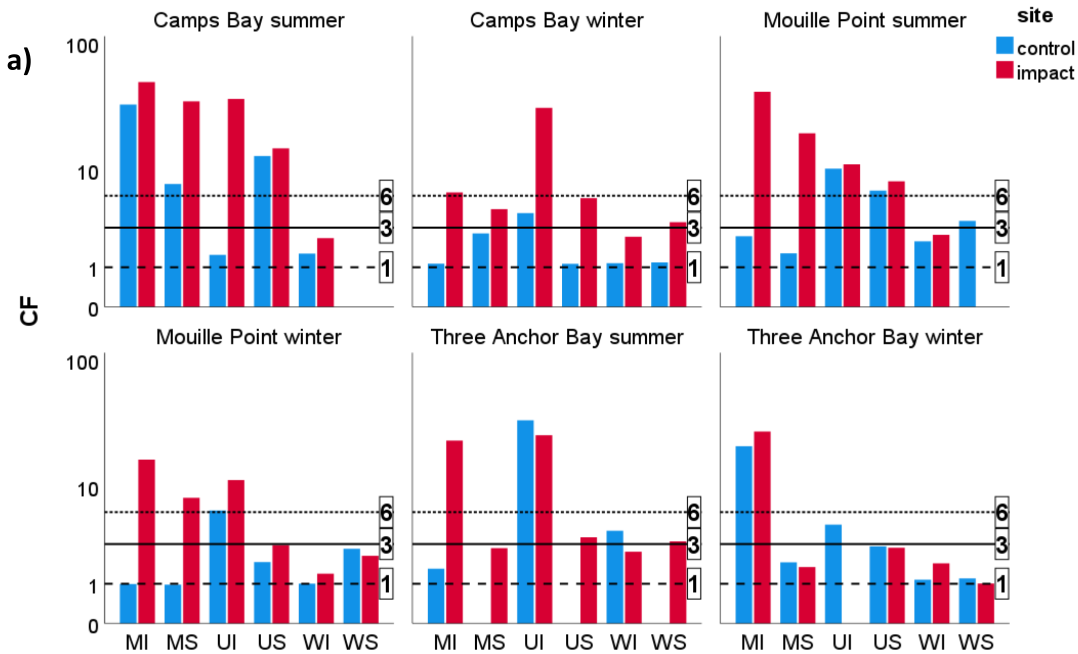


Figure 4.5: The seasonal risk assessments of sediment at impact and control sites (log scale) a) Microplastic contamination factor. B) Microplastic pollution load index. c) Polymer risk index at Camps Bay, Mouille Point and Three Anchor Bay. d) Pollution load index Camps Bay, Mouille Point and Three Anchor Bay.

4.4.3 Biota

The CF risk assessment for impact on intertidal mussels and sea urchins were found to be in the very high (IV) risk category across all locations, with the exception of Three Anchor Bay sea urchin (Fig. 4.6a). The CF for subtidal mussels were at a high (III) risk at Camps Bay during winter, very high (IV) risk at Camps Bay during summer and at both seasons for Mouille Point, and moderate (II) risk for both seasons at Three Anchor Bay. The seasonal CF for whelks in the intertidal and subtidal were only found to be at a high (III) risk category at Camps Bay winter subtidal, Mouille Point summer control and Three Anchor Bay summer impact. All control sites were found to have a lower CF risk assessment score than impact sites, however, some control sites for mussels and urchins were found in the same risk category as impacted sites being very high (IV). Most controls were found at a moderate (II) risk category.

For the PLI, mussels in the intertidal and subtidal were the only organisms that were mainly to be found at a higher risk category than control sites. Mussels were mainly found in the dangerous (V) risk category or very high risk (IV) at all three locations, mainly during the summer season. Like mussels, the PLI for sea urchins at impacted sites in the intertidal and subtidal can be found at higher risk categories, being dangerous (V), very high (IV) or high (III), and this can be seen across all locations during the summer seasons. Whelk samples at all impacted and control sites were at a constant risk category across all locations, which was a moderate risk (II). The PLI for all biota control samples were mainly at a moderate risk (II) or at a lower risk compared to impacted sites. There was an exception for intertidal mussels at Camps Bay during summer that was at a dangerous (V) risk, and subtidal sea urchin that was at a high (III) risk, intertidal sea urchins at Mouille Point during summer that was at a high (II) risk and intertidal sea urchins at Three Anchor Bay were at a dangerous (V) risk during summer.



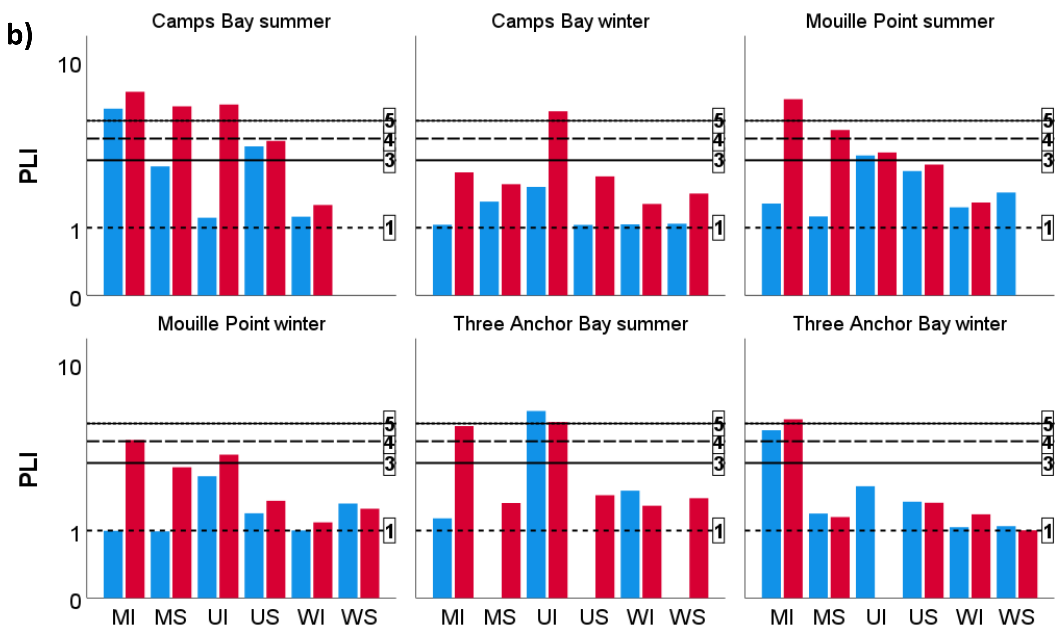


Figure 4.6: The seasonal risk assessments of mussels intertidal (MI), mussels subtidal (MS), urchins intertidal (UI), urchins subtidal (UI), whelks intertidal (WI), whelks subtidal (WS) at impact and control sites (log scale) a) Microplastic contamination factor. b) Microplastic pollution load index.

For the polymer (H) and pollution risk index (PRI) for mussels, sea urchins and whelks at impact and control sites in Camps Bay, Mouille Point and Three Anchor Bay were found to be in the low (I) risk category (Fig. 4.7a and 4.7b). The H for whelks at the impact site in Camps Bay, however, was found to be in the moderate (II) risk category (Fig. 4.7a).

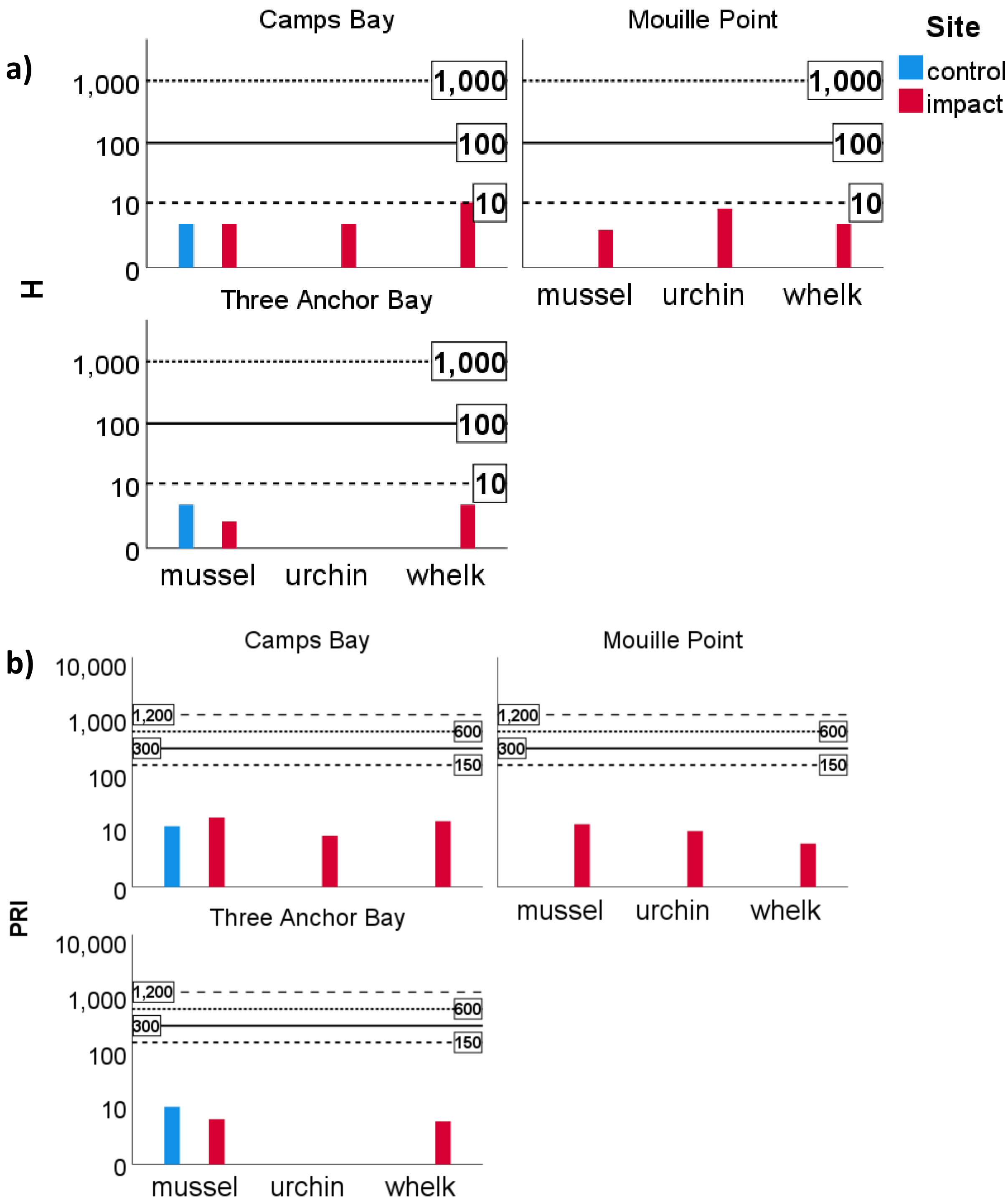


Figure 4.7: The risk assessments of mussels intertidal (MI), mussels subtidal (MS), urchins intertidal (UI), urchins subtidal (UI), whelks intertidal (WI), whelks subtidal (WS) at impact and control sites (log scale) a) Polymer risk index at Camps Bay, Mouille Point and Three Anchor Bay. b) Pollution load index Camps Bay, Mouille Point and Three Anchor Bay.

For summer samples, the condition index for mussels ($p < 0.01$) was the only sample type to be significant across impact and control sites. For winter. the condition index for mussels ($p < 0.01$) and whelks ($p < 0.005$) was found to be significant.

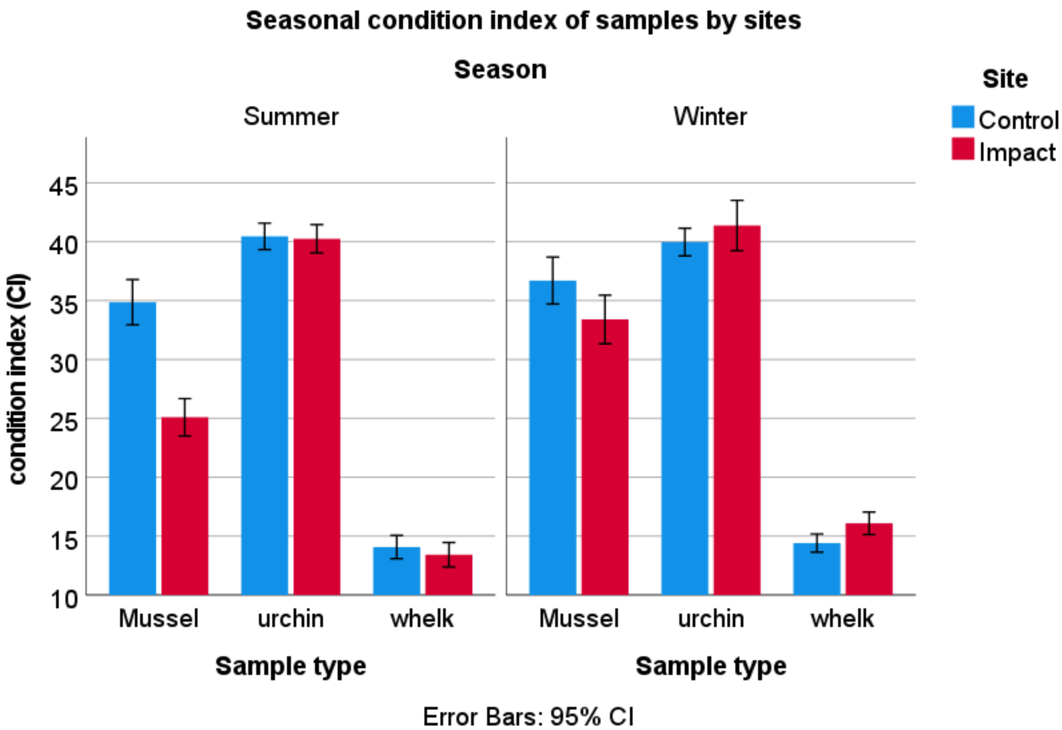


Figure 4.8: Seasonal condition index of biota from all locations at impact and control sites

4.5 Discussion

In line with chapter 3, impacted stormwater sites were found to have a significantly higher MPs abundance found in samples compared to control site samples. This can be seen in both summer and winter sample periods, with summer samples recording higher mean abundance of MPs. It was anticipated that more pollutants would be released during the rainy season, but flushing is also more intense during this period (Du et al., 2020). Taylor et al. (2011) stated that the flow of runoff is not necessarily linear with the total loading of pollutants. Seasonal concentrations of MPs found across locations were significantly higher in summer compared to winter in biotic samples, while being higher in abiotic samples during winter seasons, giving us an idea that flushing only influences the abundance of MPs in fauna around stormwater outlets rather (Fig. 3.2a and 3.2b). MPs numbers in the intertidal during summer at impacted sites were prominent. This is due to longer retention times, no flushing, MPs buoyancy and runoff being discharged directly into the intertidal zone (Du et al., 2020; Taylor et al., 2011). Out of the three locations, the Camps Bay impacted stormwater site was found to have the highest abundance of MP for all samples, which is likely due to the intense flow rate of runoff entering the impacted site. Mouille Point and Three Anchor Bay had a slower flow rate (visually observed).

FTIR scans of MP fibres as seen in chapter 3 show that most fibres scanned were proven to be cotton fibres and other fibres in all samples, and the polymer that was commonly found in samples was PET. The above-mentioned fibre types varied in sample types and were commonly the most dominant fibre types found in samples. There was a high percentage of other fibres that were not registered as a polymer, such as bamboo, wood and glass (refer to chapter 3). The high percentage of cotton fibres and PET can be linked to the stormwater systems catchment mainly falling within residential areas at all three locations. Although the catchment areas are unknown, we can assume the stormwater systems are linked to the residential areas found adjacent to the outlet. The high percentage of cotton fibres and PET can be associated with washing of clothing and other fabric materials as one garment is said to release thousands of fibres into domestic runoff (Browne et al., 2011, Mishra et al., 2019; McIlwaith et al. 2019).

The risk assessment done for this study is the first of its kind around the selected stormwater outlet locations and can serve as a baseline study to compare further monitoring on a temporal scale. Using the above-mentioned formulas, it was found that the total CF found at Camps Bay, Mouille Point and Three Anchor Bay was in a high (III)-risk category, compared to controls that were at a moderate (II) risk (Fig. 4.3a). The reasoning for the high-risk category of CF is due to the mean abundance of MPs found at impacted stormwater sites. This proves that impacted stormwater sites are causing a higher risk when it comes to contamination factor index at our three locations. Although the CF was found in a high (III) risk category for impacted sites at each location, the PLI for impact and control sites at each location was found in the moderate (II) risk category (Fig. 4.3b). However, as mentioned by Kabir et al., (2022) all PLI values greater than one is considered contaminated and since all sites and samples were above one PLI it is considered to be contaminated by MPs. Kabir et al., (2022) also mentioned that mostly urban residential areas were found to be at a high or very high-risk category. However, this was not the case in this study as the overall sites were found to be at a moderate PLI risk category, while only samples of certain biota were at a high or very high risk.

For the H and PRI, all control and impact sites found at each location were found in the low (I) risk category, with the exception of Camps Bays impact site, which was found in the high (III) risk category (Fig. 4.3c and 4.3d). Although the H and PRI at impact and control sites for each location were found in the same risk category, impact sites still had a higher H and PRI value. As for Camps Bay, it had the highest mean abundance of MPs at the impacted stormwater site compared to other locations. The type of polymers found at Camps Bay also had an influence on the hazardous score, which resulted in a higher H and PRI index compared to other locations.

4.4.1 Water

As seen in figure 4.4a, the CF can be seen to be at a higher risk category at impact sites compared to control sites. However, the impact sites for water during the winter season were found to be at a higher risk category compared to during summer. The reason why the CF risk assessment found that winter impact sites were at a higher risk (Fig. 4.4a) is due to the mean abundance of MPs being the highest during the winter period. For PLI all sites were found in the same risk category (Fig. 4.4b), however, impacted stormwater sites had a higher PLI value than control sites, and all winter sites were higher than summer sites. The PLI category for water was also found to be lower compared to a study done by Prarat and Hongsawat (2022) in Thailand that found water to be at a very high risk category. Prarat and Hongsawat also states that the PLI level is directly linked to the abundance of MPs found, which can be observed for all samples. For the H and PRI of water, Camps Bay's impacted stormwater site was found to be the only site in the dangerous (V) risk category (Fig.4.4c and 4.4d). This is due to polymers such as PVC and Nylon that were found in water samples which are highly toxic polymers. Another study done by Kabir et al. (2022) also found that all stations that were in a high-risk category consisted of polymers like PVC and Nylon. The category at which water for Camps Bay's impacted site is found, is the highest risk category (Table 4.1) according to the risk assessments. The water at Camps Bay's impacted site is at a high-risk according to the type of polymer MPs found in water samples. The abundance of MPs found at Camps Bay was also higher compared to other locations (refer to chapter 2 results). Although abundance of MPs found in samples are not directly proportional to the H category level (Kabir et al. 2022).

4.4.2 Sediment

According to risk assessment calculations for CF and PLI, the concentration and load of MP are at a moderate state (Fig. 4.5a and 4.5b). Although the risk assessment found sediment to be at a moderate risk, it is still clear that the cause of sediment being in this risk category is due to the stormwater outlets. This can be seen as impact sites are found to be at moderate risk, while the risk assessment found control sites are at a low (I) risk category. According to Sparks and Awe (2022), a sampled site was adjacent to a stormwater outlet and the risk assessment for PLI fell within a moderate category, as observed at stormwater impact sites at Camps Bay, Mouille Point and Three Anchor Bay. Another study done by Prarat and Hongsawat (2022) in Thailand also found that sediment was at the same PLI risk category as sediment for this study. The H assessment for Sparks and Awe (2022) however was found to be in a moderate risk category while impacted stormwater sites at Camps Bay, Mouille Point and Three Anchor Bay were in a low (I) risk category (Fig. 4.5c). The PRI risk assessment for Sparks and Awe (2022) sediments at an impacted stormwater site were found in the same risk category as impacted stormwater sites found at locations in this study, being a low (I) risk category. These assessments are mostly influenced by the type of polymers found in samples and it can be assumed that the stormwater outlets catchment areas from both studies are from a residential area and contain fibre particles that are mainly PET, cotton, other fibres and organic fibres as seen in chapter 3. This is the reason why the H and PLI assessment are at a low risk, since chapter 3 found a large percentage of fibres that were scanned in sediment samples under the FTIR were found to be cotton, other fibres or organic fibre materials. These types of fibres do not have a hazardous score and therefore do not contribute to the H and PRI assessment. Hence, control sites had no values.

4.4.3 Biota

For the CF and PLI, intertidal mussels at impacted sites were found to be the most polluted fauna in the intertidal zones across all locations, falling within very high (IV) and dangerous (V) risk category. The CF and PLI for subtidal mussels and sea urchins varied between the very high (IV) and dangerous (V) risk category, but were mainly found to be lower than intertidal samples and at a moderate risk (II). The PLI for subtidal mussels and intertidal sea urchins were also found to vary across locations. The PLI value can be seen to be at a high (III), very high (IV) or dangerous (V) risk category during the summer period of each location, while during the winter period it was constantly found in the moderate (II) risk category. Control sites were also found to be in a very high (IV) or dangerous (V) risk category at times in mussels and urchins. This is most likely due to the feeding type of mussels and food availability. For both the CF and PLI, a lower value in subtidal samples were observed and often found in a lower risk category compared to intertidal samples (Fig. 4.6a and 4.6b). A reason for this trend is due to retention times and feeding types. Mussels are non-selective filter feeders and sea urchins are non-selective grazers. They both ingest anything that they come across that is relative in size, making them prone to MPs contamination. Although sea urchins did not have a high mean abundance of MPs per soft tissue weight like mussels, due to the low background mean of MPs found at one of the control sites in sea urchins, other sites were found to be extremely contaminated when compared using the risk assessment calculations. Another reason why impact and control sites during winter were in a lower category or had a lower CF or PLI value than summer sites is due to retention times. Longer retention allows pollutants to settle in bays since there is no flushing that occurs, causing MPs to be more ubiquitous during the summer season. Although it is expected that the winter sampling period would have a higher risk due to precipitation and more runoff flowing into the bays than the summer period, winter tends to have rougher sea conditions that allows for flushing to occur that essentially transports pollutants out of bays (Taylor et al., 2011). There is no trend in the seasonal CF and PLI for whelks, as most control sites and impact sites for whelks were mainly found in the moderate (II) risk category (Fig. 4.6a and 4.6b). Out of all three locations, Camps Bay summer samples can be seen as the worst location as impacted samples for mussels and sea urchins in the intertidal and subtidal were found to be at a very high (IV) risk for CF and at a dangerous (V) risk for PLI.

The polymer and pollution risk index assessment are influenced by the type of plastic polymers that are found in samples. These polymers contribute to the hazardous score affecting the value of either H or PRI stating whether biota has a high or low risk based on the category that the value falls within. As seen in figure 4.7a and 4.7b, the risk category found across almost all samples at impact sites in Camps Bay, Mouille Point and Three Anchor Bay were in the low (I) risk category while most control sites were found to have no value. This may be because most fibres found in biota were either cotton, other fibres or organic fibres and these fibres do not have any hazardous score that contribute to the H and PRI values. Overall, all biota found within impact and control sites at Camps Bay, Mouille Point and Three Anchor Bay is at a low risk due to the H and PRI assessment.

4.5 Condition index

Conditions of whelks were found to be higher at the impacted sites and this is likely due to fewer samples being collected during the timeframe, giving a poor interpretation of the data collected. Mussels for both summer and winter samples had a lower condition index at impacted stormwater sites compared to control sites. This means that discharged runoff via stormwater systems is indeed causing a decline in the health status of mussels (Pampanin et al., 2005) and the physiological activity of these organisms is under environmental stress (Lucas and Beninger, 1985). Over 90% of the MPs collected in biota was found to be MP fibres with mussels having the highest intake of MPs compared to other biota. The uptake of MPs fibres in mussels can be directly linked with the condition index. Previous studies done by Green (2016) and Xu et al. (2017) reported on the decrease in respiration rates and reduction in clearance and filtration rates due to the influence of MPs. Various exposure studies have found that inorganic particles tend to increase pseudofeces, decrease and increase clearance filtration rates, and cause declines in assimilation efficiencies, metabolic rates and oxygen consumption (Penning et al., 2013; Madon et al., 1998). MPs ingested by organisms also cause starvation, gut damage, reduced digestive efficiency and a reduction in energy storage. This may be the reason why the CI was found to be lower in impacted mussels (Watts et al., 2015), as they had the highest uptake of MPs fibres compared to other biota, as well and had the poorest condition index. The mean MPs per unit found in mussels during summer were also higher compared to winter and it’s clear that the condition of mussels and other organisms improved during the winter sampling period.

Due to the risk assessment calculations of the total MPs found at each location, we can conclude that MPs introduced by stormwater outlets are causing a higher CF. The CF was also seen to vary across risk categories for water, sediment and biota from a moderate to very high-risk category. This illustrates that samples found at the three sampled locations are indeed experiencing a risk of contamination on a moderate to very high risk around stormwater outlets. The PLI index, however, was found in the same risk category at both impact and control sites, with impact sites having a higher PLI value than control, which can be observed for both water and sediment samples. On the other hand, biota samples for the PLI assessment the loading for mussels and urchins in both the intertidal zone and subtidal zone for summer and winter varied from a moderate to very high risk category. This could mean that that the loading of MPs within biota had a higher influence compared to water and sediment. The H and PRI assessment across locations found that the Camps Bays impact site was the only location found to be at a higher risk (high risk). The main contribution to the high H and PRI values observed at Camps Bay was because of water, which was the only sample type to experience a very high risk for H and PRI at Camps Bay. Furthermore, it is suggested to have further monitoring of these assessments to observe whether there is any annual temporal change within the risk assessment calculations. Due to Camps Bay being at a high-risk for CF, H and PRI, waste management should be advised in order to implement further precautions to reduce the number of MPs entering coastal waters in the Camps Bay location via stormwater runoff.

4.6 Conclusion

After viewing the results from four different risk indices, we can conclude that stormwater outlets found at Cape Peninsula of Cape Town, South Africa, are indeed an environmental risk. Due to the risk assessment calculations of the total MPs found at each location we can conclude that MPs introduced by stormwater outlets are causing a higher CF. The CF was also seen to vary across risk categories for water, sediment and biota from a moderate to very high risk category. Samples found at the three sampled locations are indeed experiencing a risk of contamination on a moderate to very high risk around stormwater outlets. The PLI, however, was found in the same risk category at both impact and control sites, with impact sites having a higher PLI value than control, which was observed in both water and sediment samples. On the other hand, biota samples for the PLI assessment showed that the loading for mussels and urchins in both the intertidal zone and subtidal zone for summer and winter varied from a moderate to very high risk category. This could mean that the loading of MPs within certain organisms has a higher influence compared to water and sediment. The H and PRI assessment across locations found that Camps Bays impact site was the only location found to be at a higher risk category (high-risk category) than control sites. The main contribution to the high H and PRI values observed at Camps Bay can be linked to water samples, which were the only sample type to fall within the very high risk category (IV) for H and PRI at Camps Bay. Furthermore, it is suggested to further monitor these assessments to observe if there is any annual temporal change within the risk assessment calculations. Due to Camps Bay being at a high-risk for CF, H and PRI, waste management should be advised to implement further precautions to reduce the number of MPs entering coastal waters in the Camps Bay location via stormwater runoff. Although other locations did not have a high H or PRI value, they were found to be just as contaminated (due to CF) as Camps Bay. It is therefore suggested that some sort of control measures need to be put in place to reduce the contamination of MPs entering Mouille Point and Three Anchor Bay via stormwater runoff.

Another conclusion is that due to runoff entering the coastal waters via stormwater systems the condition of mussels was significantly affected by the intake of MPs. The intake of MPs directly influenced the condition of mussels as it was observed that the condition of these organism improved when the abundance of MPs fibres decreased. Ongoing monitoring should take place, especially within mussels, to observe the condition of these organisms around stormwater outlets.

Chapter 5 – General Conclusion

The Cape Peninsula of Cape Town, South Africa, is affected by stormwater drainage systems. Most of these drainage systems have catchment areas that are unknown and it is difficult to determine whether the catchment areas are mainly pristine or impacted by either residential or commercial areas. Regardless, the drainage systems along the Cape Peninsula are poorly managed and poorly designed as they allow untreated or unscreened runoff into coastal marine waters. This allows various types of pollutants such as MPs into our bays, which impacts marine ecosystems.

Based on the results of the study, stormwater drainage systems at Camps Bay, Mouille Point and Three Anchor Bay all demonstrated that impacted stormwater sites were indeed a source of introducing prominent amounts of MPs into the area. The total MPs abundance at impact site (U= 48847, $p < 0.001$) at all three locations were found to be significantly higher during the summer season than comparable winter. Impact sites for summer (U = 63239, $p < 0.001$) and winter (U = 83544, $p < 0.001$) were also proven to have a significant higher abundance of MPs than comparable control sites.

For water samples impact sites (U = 681.5, $p = 0.001$) were significantly higher than comparable control sites, however, winter samples (U = 196, $p = 0.001$) had a significant higher mean abundance than summer. For sediment impact sites (U = 510.5, $p = 0.001$) were significantly higher than comparable control sites. However, no significance was proven in the seasonal variation of MPs for both impact (U = 129.5, $p = 0.486$) and control sites (U = 65.5, $p = 0.247$).

Unlike water, impacts sites for mussels (U = 4006.5, $p < 0.001$), sea urchins (U = 3801.5, $p < 0.001$) and whelks (U =2035, $p < 0.001$) were significantly higher during the summer season than winter season. Mussels (U = 6585.5, $p = 0.001$), sea urchins (U = 8257, $p = 0.001$), and whelks (U = 8560, $p = 0.043$) were however significantly higher at impact sites than comparable control sites.

The higher mean of MPs found around stormwater sites directly influenced the CF and PLI risk indices calculated, putting impacted stormwater sites into a higher risk category compared to control sites. None the less the CF indices found that all impact sites at Camps Bay, Mouille Point and Three Anchor Bay was at a high risk category. The PLI number above one was considered to be a contaminated area, all impact sites at each location were above one falling in the moderate PLI risk category. The H and PRI was only found to be at a high-risk category for Camps Bay and this was due to highly toxic MPs polymer (PVC and nylon) that were found in water.

Filter feeders, mussels had the highest mean MPs per unit at impacted sites and their condition was also found to be the poorest. This makes it clear that impacted stormwater sites are directly influencing the health of mussels. Higher means of MP were recorded during the summer season, which was not expected. It is likely that MPs were able to settle at Camps Bay, Mouille Point and Three Anchor Bay during the summer period (dry season) as retention times were longer compared to winter season (wet season) where more flushing would occur. It was, however, clear to see that risk indices and the condition index of certain organisms was directly influenced, putting each area into a poor state.

Recommendation

Due to the continued existence of stormwater systems found at Camps Bay, Mouille Point and Three Anchor Bay, it is imperative that ongoing monitoring is done around impacted stormwater sites. Waste management teams are also required to come up with mitigation measures in order to ensure that fewer MPs are distributed by stormwater drainage systems, as well as other waste drainage systems entering the marine environment. Management should look at utilizing sustainable drainage systems (SuDs) in these areas to allow for less stormwater entering the marine environment during the rainy season. Better treatment of stormwater that focuses on removal of MPs should be implemented.

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