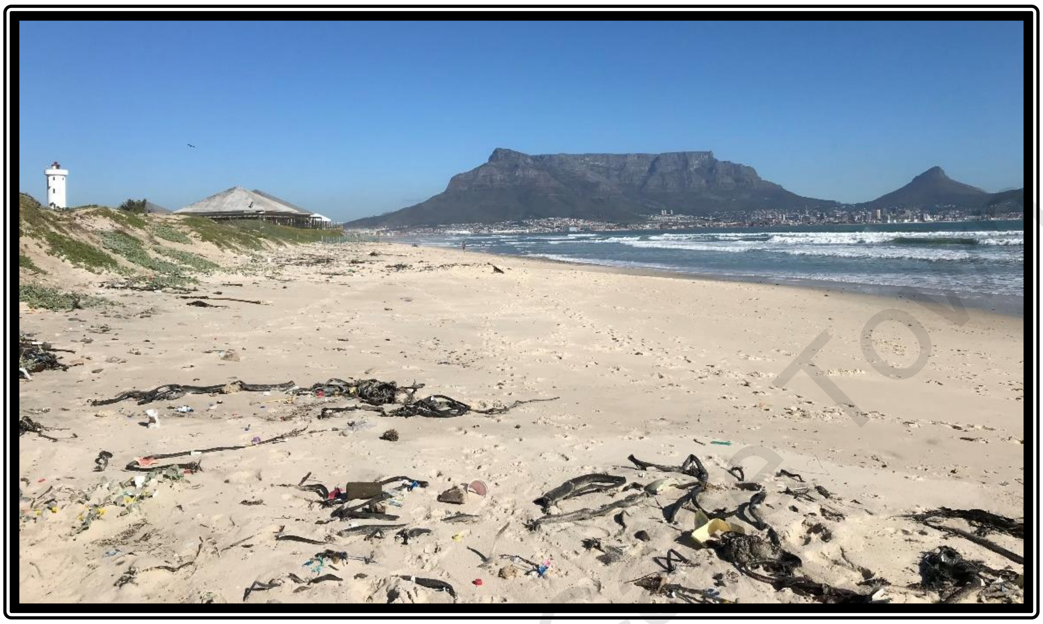
Seasonal and long-term change in the abundance, accumulation and distribution of beach litter within Table Bay, Cape Town, South Africa



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Abstract:

There is growing global concern with regard to the pollution of the world's ocean, particularly by marine debris and plastics. The daily accumulation rates of stranded beach litter were measured at two sites within Table Bay, repeating similar studies from 1994/95 and 2012. Milnerton is a popular recreational beach near the city, while Koeberg is a seldom visited beach in a nature reserve 39 km from the city. Daily sampling was conducted for ten days in winter (August), spring (October) and summer (November-December) 2019. Of the 39 602 items (116.6 kg) sampled in 2019, plastics (including expanded polystyrene) dominated at both sites in terms of numbers (Milnerton: 97.8 %; Koeberg: 98.7%) and mass (Milnerton: 45.2%; Koeberg: 58.9%). The accumulation rates were generally an order of magnitude greater at Milnerton than Koeberg. Plastics were dominated by single-use items (eg: expanded polystyrene clam shells, food wrapping and straws) and Milnerton's composition showed that there was a strong urban influence on the debris. Statistical analyses indicated there were large seasonal differences in accumulation rates at both sites. Milnerton's accumulation rate was ~8 times greater in winter (801.8 items·100 m^{-1}·day^{-1}) than in spring (97.4 items·100 m^{-1}·day^{-1}) and summer (86.4 items·100 m^{-1}·day^{-1}) in 2019. The winter peak was attributed to increased rainfall, which flushed the rivers, and to the reduced cleaning efforts in the catchments in the winter. The marine debris at Koeberg consisted of proportionally more buoyant items than Milnerton, items which can be transported vast distances, and debris at both sites was predominantly of local land-based origin. Across most sample years (1994/95, 2012 and 2019) and seasons (winter, and summer) Milnerton had significantly greater accumulation rates (min winter 1994/95: 286.7 items·100 m^{-1}·day^{-1} to max winter 2019: 801.8 items·100 m^{-1}·day^{-1} ; min summer 2019: 86.4 items·100 m^{-1}·day^{-1} to max summer 2012: 1698.0 items·100 m^{-1}·day^{-1}) than Koeberg (min winter 2019: 55.9 items·100 m^{-1}·day^{-1} to max winter 1994/95: 129.3 items·100 m^{-1}·day^{-1} ; min summer 2019: 45.7 items·100 m^{-1}·day^{-1} to max summer 2012: 151.4 items·100 m^{-1}·day^{-1}), attributed to many more sources of debris. Across all sample years, both sites had significantly greater winter accumulation rates than summer. A large decrease was seen in summer at both sites from 2012 to 2019, with a 95% (Milnerton) and 70% (Koeberg) reduction in total accumulation rates. The commencement of municipal cleaning efforts in the catchment areas and along the adjacent beach areas in the spring, which continued into summer, was likely a contributing factor to the decreases. Plastics (including expanded polystyrene) dominated the marine debris composition at both sites across all years and seasons and their proportions at both beaches have increased since 1994/95 from approximately 80 % to 95 %. It is evident that plastics are still prevalent in the environment. Improving waste management facilities and implementing effective cleaning measures throughout the year seem to be effective ways to reduce the marine debris problem. There is a need to shift away from single-use plastic items (such as straws, earbuds and food packaging) and to find more sustainable alternatives.

Table of Contents:

Plagiarism declaration: i

Acknowledgements: ii

Abstract: iii

Table of Contents: iv

Chapter 1: General Introduction 1

- 1.1 Marine debris: an ocean-wide pollution problem 1
- 1.2 Problems posed by marine debris 1
- 1.3 Sources and sinks of marine debris 3
- 1.4 Quantification and monitoring of marine debris 4
- 1.5 The marine debris problem: South Africa 6

Chapter 2: 9

Seasonal variation in the distribution, abundance and composition of marine debris within Table Bay, Cape Town, South Africa 9

- 2.1 Abstract 9
- 2.2 Introduction 9
- 2.3 Methods 10
  - 2.3.1 Study sites and local cleaning efforts 10
  - 2.3.2 Data collection and processing 11
  - 2.3.3 Material classification and analyses 12
  - 2.3.4 Statistical analyses 14
- 2.4 Results 15
- 2.5 Discussion 23

Chapter 3: 27

Long-term changes in marine debris within Table Bay, Cape Town, South Africa 27

- 3.1 Abstract 27
- 3.2 Introduction 27
- 3.3 Methods 29
  - 3.3.1 Data collation and classification 29
  - 3.3.2 Multivariate statistical analyses 29
- 3.4 Results 30
- 3.5 Discussion 40

Chapter 4: Conclusions 44

5. References 45

Chapter 1: General Introduction

1.1 Marine debris: an ocean-wide pollution problem

The pollution of the world's oceans is a significant issue that is attracting increasing global attention and concern, and the introduction of persistent debris into the marine environment is a major form of marine pollution (Derraik, 2002). Marine debris consists of any persistent, manufactured or processed solid material that is abandoned, discarded, disposed of, or lost in the marine environment (OSPAR Commission, 2007). Marine debris thus includes all items that are not of natural origin and are found in a marine or coastal environment, such as wood, glass, metal, rubber, clothing, paper and plastics (Cheshire et al., 2009; OSPAR Commission, 2007). Marine debris can be divided into mega-debris (> 1000 mm), macro-debris (20-1000 mm), meso-debris (5-20 mm) and micro-debris (< 5 mm), although the exact classes may vary slightly (Barnes et al., 2009).

Plastics dominate marine debris (Barnes et al., 2009; Derraik, 2002; Gall and Thompson, 2015; Jambeck et al., 2015; Thompson et al., 2009). Plastics are synthetic organic polymers that have multiple desirable properties, such as being lightweight, inexpensive, strong, durable and corrosion-resistant (Derraik, 2002; Ryan et al., 2009; Thompson et al., 2009). These properties make plastics ideal for the manufacture of a wide range of products, and this has led to their increased use since commercial development in the 1930s and 1940s (Jambeck et al., 2015). However, the properties that make plastics so desirable are also the ones that make them so deleterious to the marine environment, wildlife and humans (Derraik, 2002; Ryan et al., 2009; Thompson et al., 2009). Plastics are typically resistant to natural decay in the marine environment and tend to break down into smaller fragments (Pruter, 1987). Plastics tend to degrade slowly through weathering via ultraviolet radiation or physical abrasion and biofouling (Barnes et al., 2009; Ryan, 2015). The breakdown of large plastic items leads to formation of micro-plastics. From reviewing published literature, it has been found that most recent studies focus on microplastics, although macroplastics comprise a large component of the plastics in the world's oceans.

1.2 Problems posed by marine debris

Marine debris (particularly plastic debris) poses numerous threats to the marine environment, marine wildlife, human health and many human activities (Arabi and Nahman, 2020; Cheshire et al., 2009; Naidoo et al., 2020). Two of the most well-known and well-studied threats to marine wildlife are entanglement and ingestion (Derraik, 2002; Gall and Thompson, 2015; Gregory, 2009; Naidoo et al., 2020; Sheavly and Register, 2007; Thompson et al., 2009). Birds and turtles are commonly affected by entanglement and ingestion. However, many more species are also negatively affected. Another threat to the marine environment and marine wildlife is the transport of organisms via drifting plastic debris.

Organisms such as bacteria, diatoms, algae, barnacles and tunicates commonly attach to drift plastics (Gregory, 2009). The buoyant nature of many plastics can allow for attached organisms to be transported vast distances to previously inaccessible areas, thereby introducing alien species to those areas (Derraik, 2002; Gall and Thompson, 2015; Gregory, 2009; Naidoo et al., 2020; Sheavly and Register, 2007; Thompson et al., 2009). The breakdown of buoyant plastic items or the excess build-up of attached organisms can cause drift plastics to sink to the sea floor where they can smother benthic habitats (Gregory, 2009; Naidoo et al., 2020).

Plastic debris negatively affects humans in multiple ways, many of which are direct and have financial implications. However, plastic debris also impacts humans through indirect means and may impact other aspects of human wellbeing. Direct economic costs resulting from damage to an industry or economic activity may include: impact on fishing (damage to vessels and ghost fishing), transportation/shipping (damage to vessels) and the tourism industry (decreasing the aesthetic appeal) (Arabi and Nahman, 2020). Ghost fishing, the entanglement and unintentional fishing of marine species by discarded or abandoned fishing gear, can negatively impact fisheries (Arabi and Nahman, 2020; Derraik, 2002; Gregory, 2009). The stranding of plastics on beaches decreases their aesthetic appeal and this can significantly impact countries that rely on coastal tourism (Ballance et al., 2000). More indirect economic costs may be the impact on human health resulting from marine life ingesting plastic and the plastic entering the food chain. There is increasing concern with regards to the ingestion of plastics (predominantly microplastics), as many plastics contain hazardous chemicals, which may be transferred to the consumer and subsequently impact human health (Barnes et al., 2009; Naidoo et al., 2020; Thompson et al., 2009). Non-market costs of plastic debris in the marine environment impact the value which humans place on the marine environment over and above the value linked with the with actual use of the marine resources such as aesthetic value, cultural value and spiritual value (Arabi and Nahman, 2020). It is evident that plastic debris negatively impacts humans through multiple means, some of which are hard to quantify.

Plastic debris has infiltrated most of the world’s oceans, from stranding on local beaches (Nelms et al., 2017; Poeta et al., 2016b; Ribic et al., 2010; Ryan et al., 2018) to being transported vast distances and stranding on remote islands (Barnes, 2005; Convey et al., 2002; Eriksson et al., 2013). Plastic debris has been recorded on the seabed (Barnes et al., 2009; Ryan et al., 2020b) and even in the Southern Ocean (Suaria et al., 2020). There are few ocean regions, if any, that have not been exposed to marine debris and particularly plastic debris.

1.3 Sources and sinks of marine debris

Many marine debris studies have grouped sources of marine debris into two main categories, sea-based and land-based sources (Prevenios et al., 2018; Sheavly and Register, 2007; Verster and Bouwman, 2020). Sea-based sources are as a result of human activities that occur at sea. Common sea-based sources include commercial fishing vessels, merchant vessels, military vessels, research vessels, recreational boats and cruise ships, and offshore oil rigs (Cheshire et al., 2009; Sheavly and Register, 2007; UNEP, 2016). Sea-based debris may enter the ocean as a result of accidental loss, poor waste management practices or illegal dumping (Sheavly and Register, 2007).

Land-based sources are often the main sources of debris to the marine environment (Bauer-Civiello et al., 2019; Nelms et al., 2017; Ryan, 2020). It is commonly reported that land-based sources contribute approximately 80% of the anthropogenic debris in the marine environment; however, this may vary (Bauer-Civiello et al., 2019; OSPAR Commission, 2007). Land-based sources of marine debris include rivers, waste water/stormwater systems, windblown litter and recreational litter left by beach goers (Ryan et al., 2009). Urban centres are major sources of debris to the marine environment (Armitage and Rooseboom, 2000; Jambeck et al., 2015; Leite et al., 2014; Marais et al., 2004; Rech et al., 2014; Ryan et al., 2009; Silva et al., 2016; Weideman et al., 2020). Debris that has been discarded or inadequately managed may be blown or washed into rivers and stormwater systems, which serve as major transport routes and sources of debris to the marine environment (Armitage and Rooseboom, 2000; Marais et al., 2004; Rech et al., 2014; Ryan et al., 2009; Silva et al., 2016; Weideman et al., 2020). Factors that may influence the composition and quantity of debris in rivers and stormwater systems include the types of development present (commercial, industrial or residential), the density of development (high or low population density), the types of industry (different industries produce varying amounts of debris), the rainfall patterns, and the efficiency and effectiveness of waste management (Armitage and Rooseboom, 2000; Marais et al., 2004).

Rainfall patterns are important factors that influence the amount of debris entering the marine environment. Between rainfall events, litter may accumulate within rivers and stormwater systems and when a subsequent rainfall event occurs, large amounts of debris may be flushed into the ocean (Armitage and Rooseboom, 2000; Marais et al., 2004; Rech et al., 2014; Silva et al., 2016; Weideman et al., 2020). The deposition of marine debris on beaches and seabeds serves as a major sink of marine debris, in addition to active removal by cleaning efforts (Ryan et al., 2020b; Thompson et al., 2009). The sea floor serves as a long-term sink of marine debris, whereas beaches serve as a more short-term sink, as items may be re-exhumed. The characteristics of many plastics means that once they are deposited on a beach or on the sea floor they may persist there for a prolonged period (Ryan et al., 2020b). Therefore, it is important to have different means by which to assess and quantify marine debris.

1.4 Quantification and monitoring of marine debris

Monitoring marine debris is important to determine the amounts present, the accumulation rates and the effectiveness of remediation/mitigation measures (Ryan et al., 2020a; Thompson et al., 2009). Most studies assess the abundance of all types of debris within a size class, with plastics forming a large component of these studies (Thompson et al., 2009). However, few attempt to integrate across all size classes. There are multiple methods used to assess marine debris, each having their own associated advantages and disadvantages. Modelling the input and transport of marine debris is an important means by which to determine prominent sources, sinks and transport methods (Collins and Hermes, 2019; Jambeck et al., 2015). The use of drift buoys is another method by which transport can be assessed (Ryan, 2020). Key methods for quantifying and monitoring marine debris include: i) analysing marine debris interactions with wildlife, ii) at-sea surveys, iii) input monitoring and iv) beach surveys (Ryan et al., 2009).

Monitoring the interactions between marine debris and wildlife is a means to assess change; however, data collected will be specific to certain types of debris and species (Ryan et al., 2009). The entanglement of wildlife by plastics and ingestion of plastics are two of the most frequent interactions used for assessment; however, other less common interactions are also used (Derraik, 2002; Naidoo et al., 2020; Ryan et al., 2009).

At-sea surveys allow for direct changes to be assessed in the amount and composition of marine debris (Ryan et al., 2009). However, at-sea surveys are complicated by a number of factors such as ocean currents, ship disposals and accidental losses (Ryan et al., 2009). At-sea surveys are a costly undertaking and are complex, as intensive sampling is required to detect density changes due to the large spatial heterogeneity in densities of floating marine debris (Ryan et al., 2009). At-sea surveys are typically limited to assessing standing stocks and are not capable of assessing accumulation rates (Ryan et al., 2009). At-sea surveys primarily assess the balance between inputs and losses and do not directly indicate the effectiveness of mitigation measures. The abundance of floating marine debris can be assessed by using either direct observations or net trawls (Ryan et al., 2009). The use of direct observations allows for larger macro-debris to be detected and allows for large sample areas to be assessed. However, smaller marine debris items may be missed, and observer ability may differ (Ryan et al., 2009). Net trawls are less subjective than direct observations and allow for smaller debris to be detected; however, they are limited by the area they sample and the size of debris they sample (Ryan et al., 2009). At-sea benthic debris surveys also have been conducted using divers, trawls, submarines and remotely-operated vehicles (Ryan et al., 2009). Most seabed studies have focused on standing stock; however, some accumulation studies have been conducted.

The most direct means to assess whether mitigation measures are having a significant effect is to monitor marine debris inputs (Ryan et al., 2020a, 2009). This poses a major challenge as there are multiple sea-based and land-based sources of debris to the marine environment. It is important to note that dumping at sea is illegal; however, this does not prevent it from happening. Estimates of compliance can be obtained from port reception facilities and the use of onboard observers to assess how much debris is entering the marine environment from ships (Ryan et al., 2009). Accidental loss from ships also needs to be considered. An effective means of monitoring land-based sources of debris to the marine environment is to monitor the inputs from rivers and stormwater systems as they are the main land-based sources (Armitage and Rooseboom, 2000; Bauer-Civiello et al., 2019; Marais et al., 2004; Rech et al., 2014; Weideman et al., 2020).A difficulty in monitoring river and stormwater inputs is the temporal heterogeneity in debris loads attributed to rainfall patterns (Weideman et al., 2020).

To date, beach surveys have been the most widely utilized method of assessing marine debris (Ryan et al., 2009). Initial beach surveys serve as baseline surveys from which changes in abundance, composition and distribution of marine debris can be assessed. The abundance of marine debris on beaches is attributed to several factors besides that of the debris present in the adjacent water. These factors include local currents and circulation patterns, beach structure, recent weather conditions, beach dynamics, local land-based sources, and municipal and community cleaning efforts (Ryan et al., 2009). There are two main methods by which beach surveys are conducted: standing stock surveys and accumulation rate surveys (Ryan et al., 2020a, 2009). Each has its own associated advantages and disadvantages and it is important to make the differentiation between the two.

Standing stock surveys can provide gross data on the abundance and distribution of marine debris (Ryan et al., 2009). Standing stock surveys can provide information on long term trends in the input and removal of debris. However, episodic events such as storms (which flush rivers and stormwater systems and re-exhume buried beach debris) may mask long term trends (Ryan et al., 2009). The characteristics of each beach need to be accounted for as some beaches may facilitate the accumulation of debris more than others. Recorded changes in marine debris loads may be attributed to increased accumulation rather than increased input into adjacent waters. Another challenge posed by standing stock surveys is the differential turnover rates of various marine debris types (Ryan et al., 2020a). Items such as expanded polystyrene (packaging foam pieces, polystyrene cups, polystyrene trays and clam shells) have high turnover rates and are likely be underestimated and under-sampled by standing stock surveys (Ryan, 2020). Changes in human activities along coastal areas may have a significant effect on assessing long term trends. With the growth of the human population, regions that previously would have been classified as ‘rural’ will likely become ‘urban’, thereby affecting the debris inputs to the region (Ryan et al., 2009).

Many of the challenges associated with standing stock surveys are avoided by conducting accumulation rate surveys (Ryan et al., 2020a, 2009). This method requires an initial clean to remove all debris, followed by frequent surveys which record and remove newly arrived debris (Ryan et al., 2009). Accumulation surveys require more effort and investment than standing stock surveys. Accumulation surveys have been conducted with sample frequencies which vary from infrequent, quarter-yearly sampling to more frequent weekly and even daily sampling (Eriksson et al., 2013; Lamprecht, 2013; Poeta et al., 2016a; Prevenios et al., 2018; Ribic et al., 2010; Swanepoel, 1995). The duration of accumulation rate surveys and particularly the sampling frequency are important factors that will affect a survey (Ryan et al., 2014; Smith and Markic, 2013). Less frequent sampling frequencies are likely to underestimate and under-sample debris, especially items such as expanded polystyrene that have high turnover rates (Ryan et al., 2020a, 2014; Smith and Markic, 2013). Therefore, it has been recommended that daily sampling is the best frequency with which to sample (Smith and Markic, 2013). The need to limit beach cleaning efforts and the exhumation of buried debris are two challenges that affect accumulation studies (Ryan et al., 2020a). Municipal and community beach cleaning efforts decrease the numbers of items collected while the exhumation of buried debris (e.g. the churning up of sand by beach goers and stormy weather conditions) increase the number of items collected (Ryan et al., 2020a). Efforts can be made to prevent municipal and community beach cleaning efforts and recording daily conditions can allow for unusual results to be assessed.

A major challenge posed by beach surveys is the difficulty in making comparisons between surveys, as different protocols are used (Cheshire et al., 2009). This is often as a result of each study having different questions, thereby developing their own protocols to address their questions. Surveys often differ in sampling duration, sampling intervals, recorded information (mass and count), debris classification and adequate site descriptions. Some study surveys utilize indicator items, which may be useful for the questions the study wishes to address, but indicator items may fail to detect changes in non-target categories (Ribic, 1998). Efforts have been made to standardize protocols so that greater inter study comparability may be achieved (Cheshire et al., 2009; OSPAR Commission, 2007; Ryan et al., 2020a). Beach surveys continue to be a valuable means by which to assess and monitor marine debris.

1.5 The marine debris problem: South Africa

Much work has been done assessing marine debris in South Africa (Collins and Hermes, 2019; Naidoo et al., 2020; Ryan, 2020; Ryan et al., 2020b, 2018; Ryan and Swanepoel, 1996; Verster and Bouwman, 2020). Beach surveys have been conducted since the 1980s (Ryan and Moloney, 1990) and input monitoring has been conducted since the 1990s (Weideman et al., 2020). As with many global marine debris studies (Barnes et al., 2009; Derraik, 2002; Gall and Thompson, 2015; Jambeck et al., 2015; Thompson et al., 2009), plastics predominate South African marine debris (Ryan, 2020; Ryan et al., 2018; Verster and Bouwman, 2020). South Africa was ranked 11th in a study by Jambeck et al. (2015) that assessed global land-based plastic inputs to the ocean, and it was estimated that South Africa leaks 90,000 to 250,000 tonnes of plastic into the sea per year. However, this estimate is likely inflated (Ryan, 2020; Verster and Bouwman, 2020; Weideman et al., 2020). The value suggested by Jembeck et al. (2105) was based on an estimate of 56 % mismanaged waste, with little actual supporting data (Verster and Bouwman, 2020). Key reasons considered to contribute to the loss of plastic debris to the environment were the lack of waste removal infrastructure, logistical challenges of informal settlements and outlying communities, poor waste management and littering. Concerns were raised that some of the quantitative assumptions were incorrect and that this led to an over-estimation of the actual amounts. This highlights the difficulty of extrapolating a model result for a large geographical area as they may have their own unique set of conditions. Verster and Bouwman (2020) estimated a more conservative 15,000 to 60,000 tonnes of marine plastic per year, approximately six times less than the Jambeck et al. (2015) estimate.

Land-based sources predominate South Africa's marine debris inputs, and four main coastal urban centres (Cape Town, Port Elizabeth, East London and Durban) serve as major sources of litter into the marine environment (Ryan, 2020; Weideman et al., 2020). The rivers and storm water systems that drain these urban catchment areas serve as major transport routes and sources of debris to the marine environment (Armitage and Rooseboom, 2000; Marais et al., 2004; Weideman et al., 2020). It would be expected that the composition of marine debris stranded on urban beaches would resemble that of terrestrial origin, but differences can be explained by differential transport and varying material life spans (Ryan, 2020). In 2015, 82 South African beaches were sampled for macro-debris and the most common items recorded were expanded polystyrene trays, plastic lids/caps, hard plastic fragments, cotton buds (earbuds), food packaging (chips, sweets) and plastic straws (Ryan, 2020). A recent study conducted in Cape Town assessing the inputs of litter from storm water drains showed that plastics were the most common anthropogenic material (64% by number and 52% by mass) (Weideman et al., 2020). The most common types of plastic were single-use packaging, particularly food packaging such as chip packets and sweet wrappers, as well as foamed plastics such as polystyrene trays and clam shells (Weideman et al., 2020). Their results show that there is a strong urban influence on the debris collected. A recent study by Chitaka and von Blottniz (2019) assessed the accumulation rates and characteristics of marine debris along five beaches in Cape Town. They found that plastic debris contributed 94.5-98.9% of the marine debris by number and that the top ten most identifiable items accounted for 40-57% of the plastic debris (Chitaka and von Blottnitz, 2019). Most of the plastic debris consisted of single use items such as expanded polystyrene clam shells, food wrapping and straws. These are all items which are commonly found on Cape Town beaches and waterways.

In 1994 Swanepoel (1995) conducted research that assessed marine debris at two beaches within Table Bay, Cape Town, South Africa; this study served as a baseline study for assessing changes in marine debris at Milnerton and Koeberg beaches. Subsequently, Lamprecht (2013) conducted research at the same sample sites, using the same sampling protocols, which allowed for long-term comparisons to be made. The results of both studies showed that Milnerton had greater accumulation rates than Koeberg and this was attributed to there being many more sources of debris to the site. Both studies showed that the debris at both was predominantly of local origin. Lamprecht (2013) showed that the amounts plastic debris had increased by two orders of magnitude in the 18 years since Swanepoel (1995) had sampled the sites, and this reflects the increased use of plastic during the past decade.

In this study I assessed the daily accumulation rate of marine debris at the same two beaches, Milnerton and Koeberg, in Cape Town, South Africa. The dissertation has been structured into four chapters. This first chapter provides background information and a global and local context for the research. Chapter 2 describes data collected during three 2019 sample periods, focusing on differences in marine debris seen between sample sites at Milnerton and Koeberg, in winter (August), spring (October) and summer (November-December). Based on previous studies (Lamprecht, 2013; Swanepoel, 1995), it was hypothesized that Milnerton should continue to show greater litter loads than Koeberg and that winter would have greater accumulation rates than summer based. It was hypothesized that the total winter accumulation rate for Milnerton would be significantly greater than the other months as there would be increased flushing of rivers. Chapter 3 compares the results of the 2019 accumulation study with those in 1994/95 (Swanepoel, 1995) and 2012 (Lamprecht, 2013). Chapter 3 focuses on how marine debris has changed over time at the two sample sites at Milnerton and Koeberg, with the expectation that there might be a continued increase, given the increased production and release of debris into the marine environment. Chapter 4 summarises the main conclusions of the study and provides recommendations for future work.

Chapter 2:

Seasonal variation in the distribution, abundance and composition of marine debris within Table Bay, Cape Town, South Africa

2.1 Abstract

To assess seasonal and site-specific changes of marine debris, daily accumulation rates were recorded at two sites within Table Bay, Cape Town, South Africa. Milnerton and Koeberg beaches were sampled for 10 days in winter, spring and summer 2019. Plastics (including expanded polystyrene) dominated at both sites in terms of numbers (Milnerton 97.8 %; Koeberg 98.7%) and mass (Milnerton 45.2%; Koeberg 58.9 %). Single-use items dominated plastics. The composition of marine debris was relatively consistent at both sites, but the amounts collected varied. Milnerton's total accumulation rate was ~8 times greater in winter than in spring and summer. This difference was attributed to increased rainfall, which flushed the rivers, and to reduced municipal cleaning efforts in winter. Storm events influenced the accumulation rates, particularly at Milnerton. Milnerton showed seasonal changes in abundance and composition of marine debris. The total accumulation rate was significantly larger in the winter (801.8 items·100 m^{-1}·day^{-1}) than in summer (86.4 items·100 m^{-1}·day^{-1}); however, the number of material types sampled in summer (the holiday season) was greater than in winter, attributed to a greater input from beachgoers. Koeberg marine debris consisted of predominantly buoyant items, which can be transported vast distances. The debris at both sites was predominantly from local land-based sources. It is evident that, for the effective reduction of marine debris within Table Bay, better waste management needs to be implemented. This can be done through increasing cleaning efforts in catchment areas and by regular municipal beach cleans. With a focus on increasing efforts in the rainy season. There also needs to be a shift away from single-use plastics, which cause much harm to marine environments.

2.2 Introduction

Marine debris is a topic that has gained increased global attention over the past few decades and much work has been done assessing marine debris in South Africa (Collins and Hermes, 2019; Naidoo et al., 2020; Ryan, 2020; Ryan et al., 2020b, 2018; Ryan and Swanepoel, 1996; Verster and Bouwman, 2020). The predominant sources of debris to South African coastal waters are known to be land-based, with rivers and storm water systems serving as major sources of debris to the marine environment (Armitage and Rooseboom, 2000; Marais et al., 2004; Weideman et al., 2020). There have been several studies in Cape Town assessing inputs and accumulation rates of debris (Armitage and Rooseboom, 2000; Lamprecht, 2013; Marais et al., 2004; Swanepoel, 1995; Weideman et al., 2020)

Within Cape Town's Table Bay, studies by Swanepoel (1995) and Lamprecht (2013) showed that Milnerton consistently had greater mean accumulation rates (1994: 464.0 items·100 m^{-1}·day^{-1} to 2012: 1458.0 items·100 m^{-1}·day^{-1}) than Koeberg (1994: 34.0 items·100 m^{-1}·day^{-1} to 2019: 102.0 items·100 m^{-1}·day^{-1}). Swanepoel (1995) attributed this difference to Milnerton being located closer to the urban centre of Cape Town and having many more sources of debris than Koeberg. Both studies recorded large differences in mean accumulation rates between sample months and Swanepoel (1995) showed that at Milnerton there was a significantly greater mean accumulation rate in December compared to October. This was attributed to there being an increase in beach goers at the sites during the holiday season in December.

I recorded the daily accumulation of stranded debris at the same two beaches, Milnerton and Koeberg, in August, October and November-December 2019. My main aims were to assess how marine debris differed between sites and with change of season. I hypothesized that the accumulation rate of marine debris would be greater at Milnerton as it is located closer to the urban centre and has many more sources of debris than Koeberg. It was expected that the composition of marine debris collected at Milnerton would resemble that of the debris collected in storm water systems and rivers as they are prominent sources of debris to the area. It was hypothesized that the composition of marine debris would differ between sites because of the differential transport of materials and due to the sites having different debris sources. It was hypothesized that the accumulation rate would be greatest in winter (August) as storm and rainfall events would lead to the flushing of rivers and storm water systems.

2.3 Methods

2.3.1 Study sites and local cleaning efforts

Table Bay is a relatively small and shallow bay located on the west coast of South Africa and is open to the sea from the south west to the north (Van Ieperen, 1971, Figure 2.1a). The coast is mostly sandy and coastal areas to the north have sand dunes covered in shrubs. Local winds influence the currents within the bay (Van Ieperen, 1971). There are three large catchment areas that feed into Table Bay from industrial, commercial and residential areas (Weideman et al., 2020). The City of Cape Town has a population of approximately 4.6 million people (World Population Review, 2020).

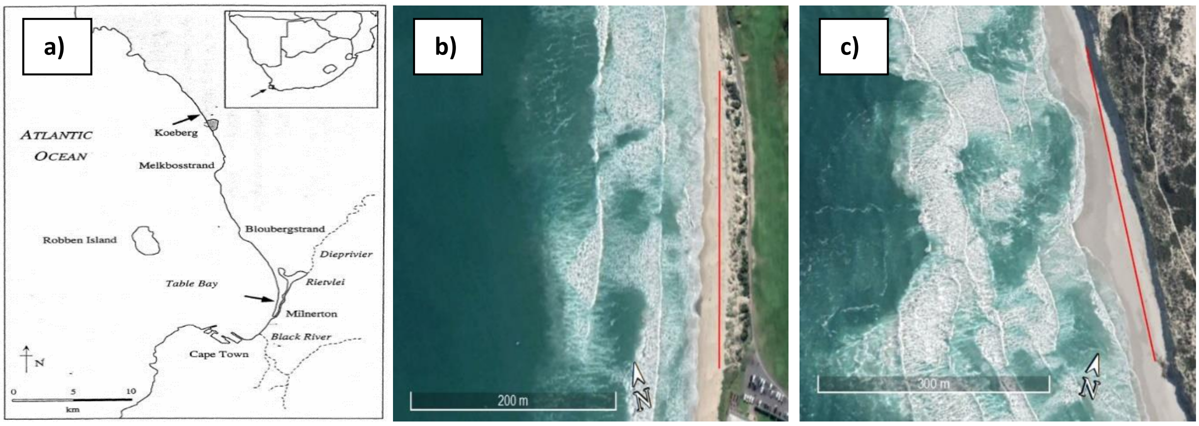

Figure 2.1: Map of Table Bay showing the study areas. a) The location of the two study areas within Table Bay (after Swanepoel, 1995); the two arrows indicate the location of the study areas , b) 250 m long Milnerton study area (Google Earth Pro, 2020a) and c) 500 m long Koeberg study area (Google Earth Pro, 2020b) .

Milnerton beach is a popular recreational beach located approximately 12 km from Cape Town's city centre (Figure 2.1 a and b). The Black and Diep river mouths both enter the sea to the south of Milnerton beach and serve as prominent litter sources to the bay (Figure 2.1 a). The Black and Diep river mouths link together in the Diep Estuary, which is a large temporarily closed system that connects the rivers to the ocean. The estuary was open for the duration of the study and this was confirmed by visual inspection. Koeberg beach is located approximately 26 km farther north than Milnerton and is located within a nature reserve, with limited public access (Figure 2.1 a and c). These beaches were chosen as they have similar physical structures; however, they vary in their proximity to the urban centre (Cape Town). Both Milnerton and Koeberg beaches are sandy beaches. Milnerton beach is located ~200 m from a frequented carpark, whereas Koeberg beach is located within a nature reserve.

Previously, both sites have been cleaned by local authorities, but cleaning has been sporadic. From September 2019, local authorities started to implement cleaning measures at the Milnerton beach study site. River nets were also deployed post winter in both the Black and Diep rivers. Local community organizations also participate in cleaning the Black River, Diep River and Milnerton beach. Local authorities and community beach cleaning organizations were informed about the study and asked to refrain from cleaning the study areas during sample periods. Signs were used to inform general beachgoers about the study, asking them to refrain from cleaning the beaches during the sample periods.

2.3.2 Data collection and processing

The study period extended from August to December 2019. Daily accumulation rates were measured for ten days in August (4-13 August), October (2-11 October) and November-December (29 November-8 December). Hereafter these sample periods are referred to as the 2019 August, October and December sample periods. Each sample period represents a different season: winter (August), spring (October) and summer (December). The sample periods were chosen to account for seasonal variation and variation attributed to the 'holiday season' (December), when there is an increase in the number of beachgoers at

Milnerton. Sample periods were set to roughly match those of previous studies while avoiding spring tides, which increase the risk of undercutting and the exhumation of buried debris. Undercutting as a result of increased tide activity/storm events leads to a change in beach profile, results in the exhumation of previously buried debris and would skew the debris sampled. Beach profiles were assessed visually at the beginning of each sample period and were assessed throughout sample periods to monitor changes. This allowed for unusual results to be interrogated and explained.

A study area with a beach length of 250 m was demarcated on Milnerton beach between the sea and the storm highwater mark (33.8805° S 18.48749 °E to 33.87785°S; 18.48804°E) and a study area with a beach length of 500 m at Koeberg beach (33.65403° S 18.41763 °E to 33.65004°S 18.41501°E; Figure 2.1 b and c). Prior to each sample period, both study areas were cleaned of all macro-debris (items > 10 mm). This was done with two pre-cleans by large teams of volunteers prior to each sample period. To ensure a high level of pre-cleaning was achieved, two people would scan back over the sites to collect any debris that was missed. The same two people involved with the scanning of the pre-clean were also the same people involved with collection during the sample periods. This ensured that any biases would be consistent. The beaches were cleaned between the low water mark and into the adjacent vegetation to prevent the latter being a debris source. All anthropogenic items > 10 mm arriving after pre-cleaning and during each sample period were recorded. This included items recently washed ashore, re-emerging items, items left by beachgoers and items drifting laterally from the uncleaned areas. During the sample periods, 10 m buffer areas were cleaned on either side of each study area to decrease the lateral shift of items from uncleaned areas into the study areas. The collected items were transported back to the University of Cape Town where they were cleaned, dried, counted and weighed to 0.1 g (items < 100 g) or 1 g (items > 100 g).

2.3.3 Material classification and analyses

Each item was classified by material type (Table 2.1) and was assigned a functional group based on its likely function (Table 2.2). Expanded polystyrene was treated separately from other plastics because of its unique properties being that it breaks down into numerous pieces and is very buoyant. Expanded polystyrene appears on beaches in an episodic fashion and can overwhelm the numbers of other plastic types. Most of the functional groups pertain to plastics and all non-plastic items were grouped into a non-plastic functional group (Table 2.2).

Table 2.1: The nine material types used to classify marine debris items collected in Table Bay and a description of some of the items representing each material type.

Material type	Description
Plastic	Bottles, lids, food wrappers, earbuds, hair curler pins, eating utensils, foam pieces, bubble wrap, bags, condom wrappers, plasters, soft drink labels, cups, tubs, packaging, lollipop sticks, diapers, pens, straws, rope, user items (pipes, toys, buckets etc.), miscellaneous pieces
Expanded Polystyrene	All expanded polystyrene items such as packaging foam pieces, polystyrene cups/pieces, polystyrene trays/pieces
Wood	Planks/boards, ice cream sticks, matches and any other worked wood items
Cardboard/paper	Paper, cardboard, tissues, food boxes, paper bags
Cigarette butts	Cigarette butts
Glass	Glass bottles, glass shards, light bulbs
Metal	Beer/soft drink cans, metal pieces, metal wire, can lid rings, aerosol cans, lids, foil, batteries
Rubber	Balloons, condoms, rubber pieces, rubber toys
Other	Ceramic pieces, clothing, material items, cloth, wax candles, ceramic tiles

Table 2.2: The 16 functional groups used to classify marine debris items collected in Table Bay and a description of some items in each functional group.

Functional group	Description
Bags	Barrier bags, carrier bags (shopping packets), packets, ziplock bags
Bottles	Pill bottles, milkshake bottles, drink bottles
Disposables	Cigarette butts, lighters, sponges, plastic eating utensils, tape wheels, earplugs, pens
Earbuds	All types of earbuds (also referred to as cotton buds)
Food wrapping	Biscuit wrappers, chip packets, ice cream wrappers, lollipop wrappers, sweet wrappers, drink labels, other food wraps
Lids	All plastic lids and related items (lid rings, lid pieces, etc.)
Lollipop sticks	Plastic lollipop sticks
Miscellaneous pieces	All unidentified plastic sheet items which are > 10 mm in size
Medical/hygiene	Condom wrappers, hair curlers, needle cases, makeup tubes, loofas, pill sheets, syringes, plasters, toothbrushes, tweezers
Other packaging	Bubble wrap, packing cables, packing foam, flexible packaging, tape, tarpaulin
Expanded polystyrene	Packaging foam pieces, white trays/tray pieces, cups/cup pieces, black trays/pieces
Ropes	Plastic fibres, polypropylene rope
Straws	All plastic straws
Tubs	All tub related items
User items	Plastic items which have multiple uses such as hard polyurethane foam, broom heads, buckets, heavy duty plastic piping, vacuum hoover heads, floor tiles, shopping trolley pieces and pipes
Non-plastics	All non-plastics items

2.3.4 Statistical analyses

Abundance and mass data were converted into accumulation rates (items·100 m^{-1}·day^{-1} and g·100 m^{-1}·day^{-1}) to allow comparisons between the sample sites. Biplots of daily accumulation rates in terms of abundance and mass were assessed for each material type to see if there were correlations. The daily accumulation rates (items·100 m^{-1}·day^{-1}) were fourth-root transformed to reduce the large skew in the data.

Daily rainfall and wind data (strength and direction) for the Table Bay area were obtained from the Koeberg power station's weather station while tide data were obtained from the 2019 South African Tide Tables (South African Navy Hydrographic Office, 2019). Hourly wind data were averaged daily including all wind directions, while rainfall data were summated daily. Weather data obtained from Koeberg were used as a proxy for Milnerton. Biplots were used to assess whether the fourth-root transformed daily accumulation rates correlated with maximum tide height (m), wind speed (m·s^{-1}) or rainfall (mm) for each site. Correlations for wind speed and rainfall were assessed with a one-day lag.

General linear models (GLMs) were run for each site to assess which environmental variables or combination of environmental variables influenced the transformed accumulation rates (R Core Team, 2018). The response variable was the transformed accumulation rate (items·100 m^{-1}·day^{-1})$^{0.25}$ while the explanatory variables tested were: wind speed (m·s^{-1}), rainfall (mm), tide height (m) and the interaction of these variables. The stepAIC function within the multcomp package in R (Hothorn et al., 2008) was used to derive the best GLM model for each site based on AIC (Akaike's information criterion) scores. To confirm assumptions of normal distributions and homogeneous residuals, qqplots, histograms and scatter plots of residuals against fitted values were inspected. Figures were created using the ggplot2 package within R (Wickham, 2016).

To assess whether the fourth-root transformed daily accumulation rates differed between months for each site, one-way ANOVAs (analysis of variance) were applied to the data. The ANOVA tests were run with a 5 % significance level. To confirm assumptions of normal distributions and homogeneous residuals, qqplots, histograms and scatter plots of residuals against fitted values were inspected. Post-hoc Tukey tests were conducted for each site using a 5 % significance level to assess which months' transformed accumulation rates were significantly different from each other.

A data table was created with accumulation rate data (items·100 m^{-1}·day^{-1}), where rows represented the 16 functional groups (Table 2.2) and columns represented samples. Each sample was assigned its own unique identifier which stated its site, month and day. The data were fourth-root transformed so that the large differences in accumulation rates among functional groups were reduced. A resemblance matrix was created using a Bray Curtis similarity measure. Principal Coordinate (PCO) plots were created from the resemblance matrix to assess separation between sites and months. To assess whether the beach litter composition differed between sites (Milnerton and Koeberg) and sample periods, multivariate analyses were conducted using the PERMANOVA+ add on of PRIMER V6 multivariate data analysis package (Anderson et al., 2008). PERMANOVA (Permutational

Multivariate Analysis of Variance) analyses used 9999 unique permutations under the reduced model method and the sums of squares were calculated using type III partial sums of squares. The PERMANOVA was applied to the resemblance matrix with two fixed factors (Site and Month).

A subsequent pairwise-PERMANOVA was run on the resemblance matrix to assess which combinations of beach litter compositions in the different months were significantly different from each other for each site. The pairwise-PERMANOVA was run on a combined factor (Site and Month) for pairs of levels of factor Month. To assess which functional groups contributed to the dissimilarity in beach litter composition between sites and months, a one-way combined factor (Site and Month) SIMPER (Similarity Percentages - species contributions) analysis was conducted on the transformed data using Bray Curtis similarities.

2.4 Results

In total, 39 602 items (116.6 kg) were collected at both sites across all three sample periods: 24 641 (91.1 kg) items at Milnerton and 14 960 (25.5 kg) items at Koeberg. Plastic predominated beach litter composition at both sites in terms of numbers and mass (Figure 2.2). In terms of numbers, plastic and expanded polystyrene combined comprised 97.8% of the beach litter at Milnerton and 98.7% at Koeberg (Figure 2.2 a and c), but only 45.2% and 58.9% by mass (Figure 2.2 b and d). Wood (most of which were large items from marine use) comprised 38.5% of the beach litter mass at Milnerton and 38.1% at Koeberg (Figure 2.2 b and d). The following materials had strong correlations between daily number and mass accumulation rates (plastic $r = 0.902$ polystyrene $r = 0.636$, cigarette butts $r = 0.998$, glass $r = 0.724$, and rubber $r = 0.748$). The following materials had weaker correlations between daily number and mass accumulation rates but were still significantly correlated. (cardboard/paper $r = 0.301$, metal $r = 0.276$, other $r = 0.189$ and wood $r = 0.278$). Large variance in mass per item lead to the reduced correlations. Hereafter, daily number accumulation rates (items·100 m^{-1}·day^{-1}) were used to assess beach litter composition. This was done as most material types showed a strong correlation between daily number and mass accumulation rates, and plastic (which dominated beach litter composition in terms of numbers and mass) showed a high correlation.

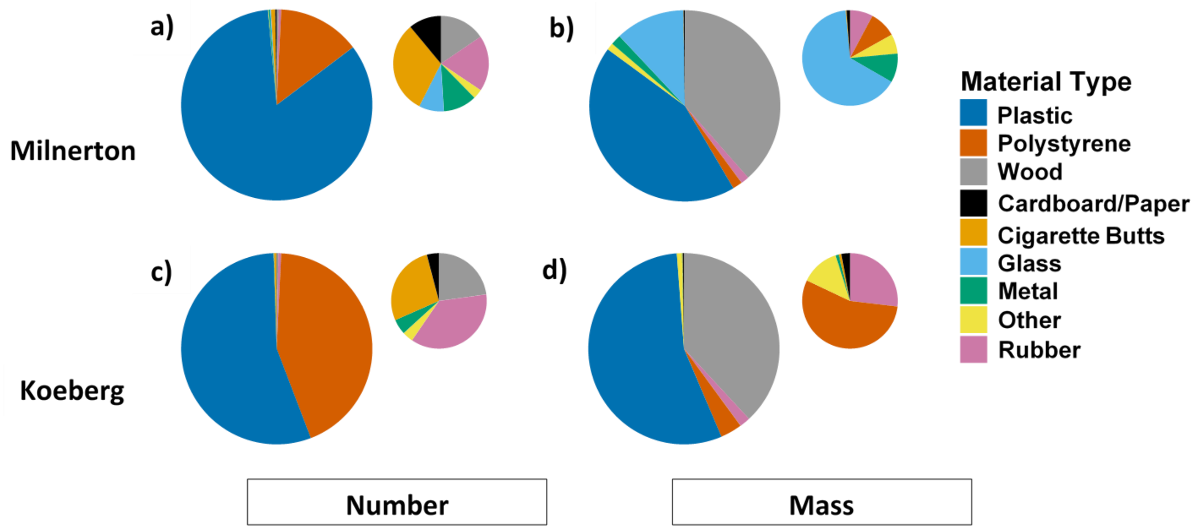

Figure 2.2: Beach litter composition for each site (Milnerton and Koeberg) based on the number (a, c) and mass (b,d). The smaller pie charts show lesser contributing materials.

At Milnerton the total fourth-root transformed accumulation rates differed among months ($F_{2,27}$ = 17.05, p = 1.62x10^{-5}). August had significantly greater accumulation rates than October (p = 5.94x10^{-5}) and December (p = 9.96x10^{-5}), but October and December were not significantly different from each other (Figure 2.3 a). The total accumulation rate and plastic accumulation rates were ~8 times greater in August than in October and December, while the expanded polystyrene accumulation rate was ~11 times greater (Figure 2.3 a). Plastic and expanded polystyrene had the largest mean accumulation rates, while the mean accumulation rates of all other materials combined contributed very little to the total accumulation rates for each month (Figure 2.3 a).

Koeberg did not follow the same monthly pattern as Milnerton (Figure 2.3). At Koeberg the total fourth-root transformed accumulation rates differed among months ($F_{2,27}$ = 9.589, p = 7.14x10^{-4}), with October having significantly larger values than August (p = 0.0035) and December (p = 0.0014), which had similar total transformed accumulation rates (Figure 2.3 b). The large increase in total accumulation rate seen at Koeberg in October was attributed to undercutting and the exhumation of buried debris. This debris was predominantly plastic and expanded polystyrene. The total accumulation rate of all materials was ~4 times greater in October than in August and December, with the mean and plastic accumulation rates respectively being ~3 and 5 times greater in October. For polystyrene, the accumulation rate in October was ~3 and ~26 times greater than in December and August, respectively (Figure 2.3 b).

Comparing the two sites, in August and December Milnerton had a greater accumulation rate than Koeberg, but in October the accumulation rate at Koeberg was approximately twice that at Milnerton (Figure 2.3 a and b). Undercutting at Koeberg during the October sample period led to the site having a greater accumulation rate than Milnerton.

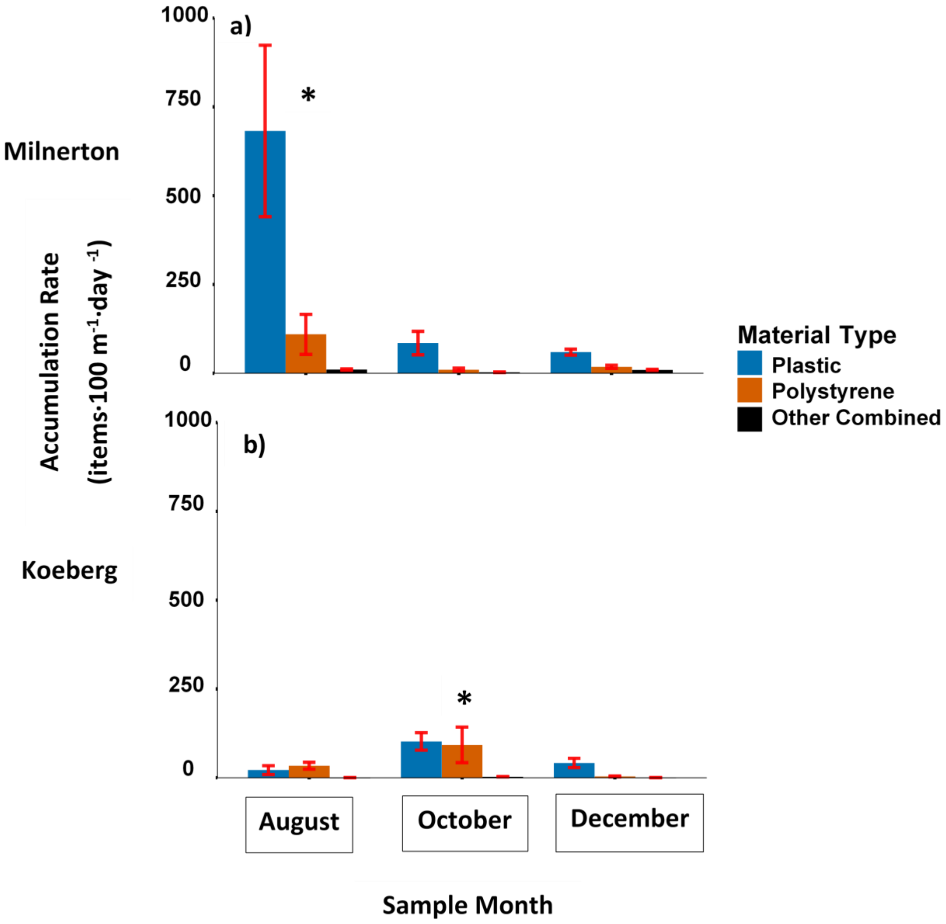

Figure 2.3: Beach litter accumulation rates (items·100 m^{-1}·day^{-1}) for each sample month in 2019 for a) Milnerton, and b) Koeberg. "Other combined" shows the combined mean accumulation rates of all non-plastic items. Accumulation rates are averaged across all sample days for each site and month. The red bars show the standard error of each mean. The asterisk indicates months in which total fourth-root transformed accumulation rates are significantly different from other months.

There were predominantly southerly winds (5 to 15 knots) at both sites across all sample periods (Figure 2.4). There was a decrease in daily rainfall from winter (23.7 mm) to spring (4.7 mm) and summer (0 mm). Each site and sample period showed variability in daily accumulation rates. Wind, rainfall and their combination appeared to affect the daily accumulation rates on an event basis. It was apparent that a storm event occurred at Milnerton in August (Figure 2.4 a), shown by the change in wind direction from a south-easterly to a north-westerly between days 2 and 3 and the increased daily rainfall in the subsequent days (Figure 2.4 a). The largest accumulation rates were recorded at Milnerton on days when there was high rainfall and winds were relatively strong onshore/cross-shore (days 5 and 6) (Figure 2.4 a). It appeared that rainfall had more of an influence at Milnerton than at Koeberg, likely due to Milnerton being near the mouth of the Black and Diep rivers (Figure 2.1). The GLM’s showed that there were no correlations between the fourth-root transformed accumulation rates and the maximum tidal height (m), wind speed (m.s^{-1}) or rainfall (mm).

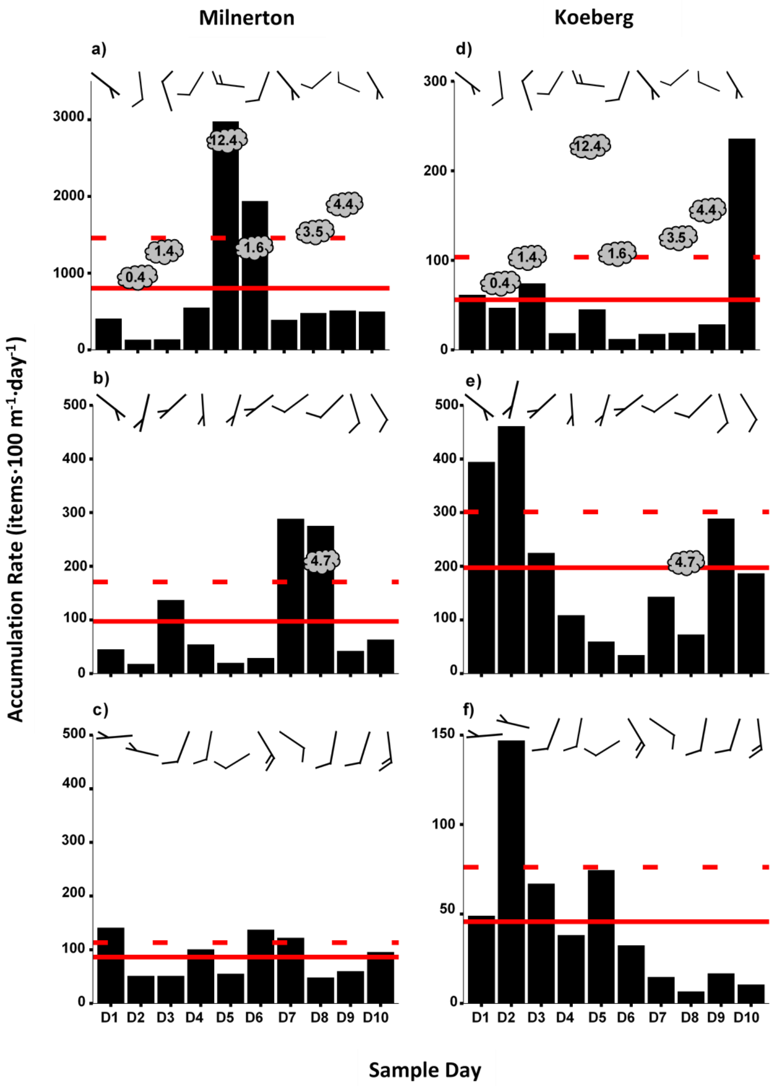

Figure 2.4: Daily accumulation rates for each site (left panel: Milnerton, right panel: Koeberg) and month: (a, d) August, (b, e) October, (c, f) December. The solid red lines indicate the mean accumulation rates, and the dashed red lines show the +95% confidence interval of the mean. Wind vectors above each plot show the average wind speed (knots) and wind direction for each day. Clouds show daily rainfall (mm). Note, y axes are on different scales.

The results of the principal coordinate analysis indicate that the first two axes explain 69.7 % of the variance in the transformed accumulation rate data (Figure 2.5). Overall, there is a large degree of overlap between sites and months. There was no clear separation between sites seen in October and December; however, there was a more distinct site separation seen in August (Figure 2.5).

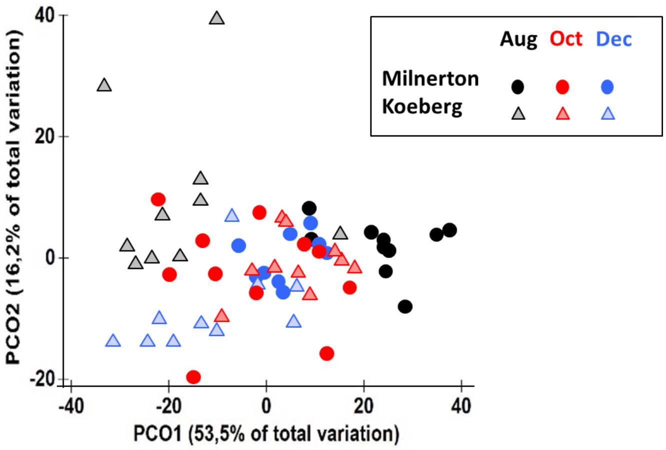

Figure 2.5: Principal Coordinate (PCO) showing variation between sample days for each site (Milnerton and Koeberg) and month based on fourth-root transformed accumulation rate data (items·100 m^{-1}·day^{-1}).

Beach litter composition at Milnerton was relatively constant among months. Plastic and expanded polystyrene were the predominant material types (Figure 2.6 a-c), with all other material types combined contributing < 3% in August and October (Figure 2.6 a and b) and increasing to 10.7% in December (Figure 2.6 c).

At Koeberg the beach litter consisted predominantly of plastic and expanded polystyrene across all three sample months. However, the percentage contribution of plastic and polystyrene varied substantially (Figure 2.6 d-f). The combined contribution of all other materials was relatively low (between 0.9-1.4%). There was greater diversity of material types in October than in August or December (Figure 2.6 e). Not a single glass item was collected at Koeberg. Overall, more material types accumulated at Milnerton than at Koeberg. The PERMANOVA results showed that beach litter composition differed significantly between sites and sample periods (Table 2.3). The pairwise PERMANOVA results showed that beach litter composition differed significantly between each month combination for both sites (Table 2.4).

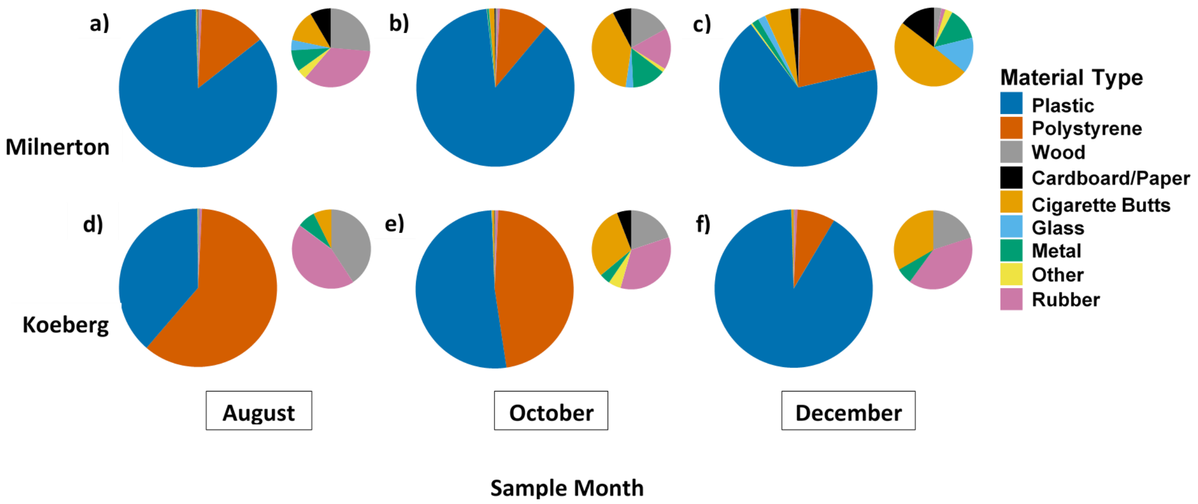

Figure 2.6: Beach litter composition at Milnerton and Koeberg beaches in 2019 for August, October and December, based on numbers, averaged across all sample days for each site and month. The lesser contributing materials are shown in the smaller pie charts.

Table 2.3: PERMANOVA results comparing beach litter composition between sites (Milnerton and Koeberg) and months sampled (August, October, December) in 2019 based on the fourth-root transformed accumulation rates (items·100 m^{-1}·day^{-1}). df = Degrees of freedom, SS = Sum of Squares, MS = Mean squares, Pseudo-F = Pseudo-F test statistic obtained by unique permutations, p(perm) = the probability calculated via permutation, Unique perms = the number of unique permutations run for each factor and interaction term. Significant results are highlighted with an asterisk (p< 0.05 *, p<0.01 **, p<0.001 ***).

Source	df	SS	MS	Pseudo-F	p(perm)	Unique perms
Site	1	3927	3927.4	11.9580	0.0001***	9949
Month	2	2830	1415.2	4.3091	0.0003***	9932
Site x Month	2	7910	3955.0	12.0420	0.0001***	9938
Residual	54	17735	328.4			
Total	59	32403				

Table 2.4: Pairwise-PERMANOVA results comparing beach litter composition among months (August, October and December) sampled in 2019 based on the fourth-root transformed accumulation rates (items·100 m^{-1}·day^{-1}). t = t test statistic obtained by unique permutations, p(perm) = the probability calculated via permutation, Unique perms = the number of unique permutations run for each factor. Significant results are highlighted with an asterisk (p< 0.05 *, p<0.01 **, p<0.001 ***).

Site	Comparison (months)	t	p(perm)	Unique perms
Milnerton	August: October	3.6908	0.0002***	9447
	October: December	1.6480	0.0280*	9421
	August: December	3.9908	0.0002***	9407
Koeberg	August: October	2.9642	0.0001***	9422
	October: December	2.8683	0.0014***	9412
	August: December	2.2118	0.0006***	9444

The greatest dissimilarity in beach litter composition between sites was seen in August (Table 2.5). This dissimilarity is predominantly attributed to food wrapping, lids and lollipop sticks, all of which were more abundant at Milnerton than Koeberg. Accumulation rates were greater at Milnerton in August and December but were greater at Koeberg in October. Expanded polystyrene, food wrapping, and earbuds were the three functional groups that contributed the most to the 25.0% dissimilarity between sites in October (Table 2.5).

Table 2.5: SIMPER results comparing beach litter composition between sites (Milnerton and Koeberg) for each month sampled (August, October and December) in 2019. Comparison = sites being compared, month = sample month, average dissimilarity % = the dissimilarity in beach litter composition between sites, functional group = the three main contributing functional groups to dissimilarity, transformed accumulation rate = the average transformed accumulation rate for each functional group for each site and month, % contribution = each functional group's contribution to the dissimilarity, cumulative % contribution = the summated contribution percentages. Larger average accumulation rates among months are displayed in bold and common functional groups are identified with an asterisk.

				Transformed accumulation rate (items·100 m^{-1}·day^{-1})$^{0.25}$			
Comparison (site)	**Month**	**Average dissimilarity %**	**Functional group**	**Milnerton**	**Koeberg**	**% Contribution**	**Cumulative % contribution**
Milnerton & Koeberg	August	48.4	Food wrapping*	**3.57**	1.13	10.9	10.9
			Lids	**2.84**	1.02	8.4	19.3
			Lollipop sticks	**2.25**	0.47	8.1	27.4
	October	25.0	Polystyrene*	1.57	**2.43**	11.0	11.0
			Food wrapping*	2.24	**2.32**	8.2	19.2
			Earbuds	0.9	**1.45**	7.4	26.6
	December	26.6	Non plastics	**1.42**	0.52	10.2	10.2
			Disposables	**1.48**	0.61	10.0	20.2
			Polystyrene*	**1.9**	1.25	8.1	28.3

At both Milnerton and Koeberg the greatest dissimilarity in beach litter composition between months was between August and October (Table 2.6). At Milnerton this was predominantly attributed to lids, food wrapping and lollipop sticks, which all had greater accumulation rates in August, and at Koeberg it was mostly attributed to food wrapping, tubs and expanded polystyrene, which all had greater accumulation rates in October. Food wrapping and polystyrene were common functional groups causing dissimilarity between months at both sites.

Table 1.6: SIMPER results comparing beach litter composition for Milnerton and Koeberg among months sampled (August, October and December) in 2019. Site = the sample sites, comparison = months being compared, average dissimilarity % = the dissimilarity in beach litter composition between months, functional group = the three main contributing functional groups to dissimilarity, transformed accumulation rate shows the average transformed accumulation rate for each functional group for each month and site, % contribution = each functional group's contribution to the dissimilarity, cumulative % contribution = the summated contribution percentages. Larger average accumulation rates among months are displayed in bold and common functional groups are identified with an asterisk.

				Transformed accumulation rate (items·100 m^{-1}·day^{-1}) $^{0.25}$				
Site	**Comparison (month)**	**Average dissimilarity %**	**Functional group**	**August**	**October**	**December**	**% Contribution**	**Cumulative % contribution**
Milnerton	August & October	36.0	Lids	**2.84**	1.32		8.6	8.6
			Food wrapping*	**3.57**	2.24		8.5	17.1
			Lollipop sticks	**2.25**	0.75		8.2	25.3
	October & December	24.5	Bottles		0.31	**0.89**	8.2	8.2
			Earbuds		0.9	**1.49**	7.9	16.1
			Non plastics		0.87	**1.42**	7.3	23.3
	August & December	25.7	Food wrapping*	**3.57**		2.06	10.6	10.6
			Lids	**2.84**		1.51	9.3	19.9
			Polystyrene*	**2.61**		1.9	8.2	28.1
Koeberg	August & October	36.2	Food wrapping*	1.13	**2.32**		10.3	10.3
			Tubs	0.21	**1.16**		8.3	18.6
			Polystyrene*	2.22	**2.43**		7.6	26.2
	October & December	26.9	Polystyrene*		**2.43**	1.25	12.6	12.6
			Miscellaneous pieces		**1.7**	0.93	8.4	21.0
			Food wrapping*		**2.32**	2.03	7.4	28.4
	August & December	35.9	Polystyrene*	**2.22**		1.25	10.8	10.8
			Food wrapping*	1.13		**2.03**	10.3	21.1
			Tubs	0.21		**0.76**	7.3	28.4

2.5 Discussion

Plastics predominate marine debris at both beaches across all three sample periods in 2019. This mirrors the findings of most published literature pertaining to marine debris (Barnes et al., 2009; Chitaka and von Blottnitz, 2019; Derraik, 2002; Gall and Thompson, 2015; Jambeck et al., 2015; Thompson et al., 2009) and both previous Table Bay studies (Lamprecht, 2013; Swanepoel, 1995). This is expected, as plastics are resistant to decay and are used for a wide range of applications, resulting in many of the items being single-use disposable items (Derraik, 2002; Ryan et al., 2009; Thompson et al., 2009). Expanded polystyrene is also a major contributor to marine debris, but the amounts sampled vary substantially over short sample periods. This is likely due to its tendency to break down into numerous smaller pieces and its lightweight, buoyant nature, which leads to expanded polystyrene having high turnover rates (Ryan et al., 2020a, 2014; Smith and Markic, 2013).

At Milnerton there was a significant decrease in the total accumulation rate from August to October. Several factors likely contributed to this decrease. The first is the decrease in rainfall, which serves as a means by which to flush accumulated debris into the ocean (Armitage and Rooseboom, 2000; Marais et al., 2004; Rech et al., 2014; Silva et al., 2016; Weideman et al., 2020). With the change of season from winter (August) to spring (October) there is less rainfall in the area, and reduced flushing capacity for rivers and storm water systems. The second likely reason for this substantial decrease is the commencement of daily municipal cleaning efforts along the adjacent beach areas and the implementation of river nets in the Black and Diep rivers. The implementation of the nets and commencement of the cleaning efforts only occurred post winter; previously, the area had been cleaned sporadically. Peer reviewed studies have shown that changes in seasonal rainfall and seasonal cleaning efforts affect the amount and composition of debris collected (Martinez-Ribes et al., 2007; Silva et al., 2016). It is important to note the Diep estuary, which connects the Black and Diep rivers to the ocean, was open for the duration of the study. This meant that there was a constant link between the rivers and the ocean.

It is evident that storm events influence the accumulation of marine debris at Milnerton beach. On sample day 5 of the August 2019 sample period there was a large storm event, which led to the flushing of the river and storm water systems and resulted in the large increase in the accumulation rate at Milnerton. It is likely that some of the debris expelled during this event drifted north to Koeberg, stranding several days later, possibly accounting for the marked increase in the accumulation rate at Koeberg on day 10 (Figure 2.4 a and d). This highlights the importance of daily sampling, because episodic events can be recorded and used to explain large and sudden changes in accumulation rates.

There were no statistical relationships between the environmental variables and the accumulation rates recorded for each site. However, this is likely due to the statistical tests looking for continuous relationships, when the relationships are more likely event based (such as the arrival of a storm). It is evident that environmental variables such as wind speed, wind direction and rainfall play an important role in beach litter accumulation rates at Milnerton. On days 5 and 6 of the August sample period there was high rainfall which led to the increased flushing of the Black and Diep rivers. The onshore/cross-shore winds on these days would have facilitated the transport and deposition of debris, which had already entered the bay on prior days.

It is possible that the quality of the weather data may not have sufficed for statistical relationships to be detected at the scale of this study. The composition of marine debris at Milnerton remained relatively constant across all sample periods, predominated by plastics and expanded polystyrene. Although the total accumulation rate in December was significantly less than that in August, the composition of marine debris attributed to materials other than plastic and polystyrene increased. The increased contribution of other material types in December was likely due to the increase in numbers of beach goers in the 'holiday season', serving as an increased source of debris to the site. A study by Silva et al. (2016) assessed the influence of intensity of use, rainfall and location on the amount of marine debris collected at four Brazilian beaches. Their results showed distinct seasonal differences. They found that the largest amounts of debris were recorded in the tourist season, which happened to be their rainy season, and the increase in tourism (during the holiday/tourist season) was a major factor influencing the amount and composition of debris recorded.

The higher accumulation rate at Koeberg during October than in August and December was unexpected and is most explained by undercutting of the back-beach and the resultant exhumation of buried debris. The accumulation rates were generally greater at Milnerton than Koeberg for all sample periods, bar the unusual October sample period. It was expected that Milnerton would consistently have greater average accumulation rates than Koeberg as there are many more sources of debris at Milnerton than Koeberg. The proximity of Milnerton to the urban centre of Cape Town is likely a contributing factor. The two rivers which enter Table Bay near the Milnerton sample site likely are major sources of debris to this beach. The material types at Koeberg appeared to consist of more buoyant materials, which are capable of being transported long distances and deposited ashore.

Beach litter compositions differed significantly between sample sites and sample months, but the extent to which they differed varied. The dissimilarity in beach litter composition between sites was relatively low for October and December but was almost 50 % in August. This dissimilarity was predominantly driven by food wrapping, lids and lollipop sticks, all of which have much greater accumulation rates at Milnerton. These items are all commonly found in storm water systems and rivers (Armitage and Rooseboom, 2000; Marais et al., 2004; Weideman et al., 2020). This highlights the importance of rivers and storm water systems as significant sources of debris to the marine environment. Food wrapping and expanded polystyrene are items that commonly lead to dissimilarity between sample sites and this is likely due to their high turnover rates and differential transport. This further supports the importance of having daily sampling for accumulation studies, as changes in the accumulation rate of rapidly turned over items can be recorded.

The cleaning of buffer zones on either side of the study sites were conducted to try control for undercutting, which was an issue, particularly at Koeberg. The dissimilarity in beach litter composition between sample periods for each site were relatively low, which suggests that the composition of marine debris at each site remained consistent and that it was the amount of marine debris that changed. It is apparent that fewer material types were recorded at the Koeberg sample site, where not a single glass item was recorded. This suggests that buoyant items get transported long distances and are deposited along Koeberg beach. Although no glass items were recorded in the Koeberg sample area, items such as glass light bulbs were seen in the adjacent beach areas which shows that buoyant items such as these also get transported vast distances.

A recent study by Chitaka and Blottnitz (2019) assessed daily accumulation rates of marine debris along five beaches in Cape Town, South Africa. They counted, weighed and classified items based on use. They found that plastic items accounted for 94.5-98.8% of the total count (Chitaka and von Blottnitz, 2019). Most of the plastic category consisted of a few, predominantly single use/disposable plastic items such as; expanded polystyrene packaging, food wrappers and straws. The top ten most frequently found plastic items accounted for 40-57% of the plastics category. The results of Chitaka and Blottnitz (2019) mirror the results of this study in that they show that single use plastics predominate marine debris and that most of the debris is of local-land based origin.

Eriksson et al. (2013) assessed the daily accumulation of marine macro-debris at two sub-Antarctic island beaches. Note, it is hard to make direct inter-study comparisons as different protocols are utilized; however, parallels can be drawn. At both sub-Antarctic islands, plastics dominated (95 % and 94%) and discarded fishing gear comprised the greatest percentage of those plastic items (22 %). It was unsurprising that most of the items sampled in the study were of foreign origin because of the locality of the sample sites; however, in contrast in this study, most of the marine debris sampled was of local, predominantly land based origin. This highlights that the plastics pollution problem is far reaching. Eriksson et al. (2013) found that the accumulation rate of debris was influenced by tide and onshore winds. As mentioned, no statistically significant relationships between weather conditions and accumulation rates were found in this study. However, it was evident that weather events influenced the daily accumulation rates, particularly at Milnerton. The daily accumulation rate of plastic on one of the islands was an order of magnitude higher than that of monthly surveys, further supporting the utilization of daily sampling as the preferred frequency of beach sampling (Eriksson et al., 2013).

Prevenios et al. (2018) assessed marine debris accumulation rates at four Mediterranean beaches on Corfu Island (Greece), located in the North Ionian-Southern Adriatic Sea. Over a period of 16 months, beach macro-litter was sampled twice a month. It was found that sea transport was the dominant pathway affecting the amount and variability of beach litter loadings. However, it was also shown that in situ litter from beach goers (littering) and wind and/or runoff transport from land were important sources of debris. On average, the sampled areas suffered mostly from mis-managed land waste. Prevenios et al.'s (2018) results showed that a few categories comprised most of the total item counts recorded at each beach, and that plastic drink bottles, chip packets, cups and cup lids, straws and stirrers were the most abundant items recorded at the two more frequently visited beaches. The findings of this study mirrored those of Prevenios et al. (2018) in that they highlight the importance of land run-off as a predominant source of debris to the marine environment and the mis-management of land waste as being a predominant contributing factor. Their results also showed that a few plastic categories, mostly single-use items, predominated all the areas sampled and this is mirrored in this study.

The annual accumulation rates of beach debris were assessed along the Tyrrhenian coast of central Italy (Poeta et al., 2016a). Three different sites along a beach were sampled seasonally from spring 2014 to winter 2015. The Fiona river terminates near the sample sites, is known to experience varying seasonal discharge rates and is known to be a source of debris to the area. The study found artificial polymers (79.4 % plastic and 15% polystyrene) dominated the materials collected. They found that a few plastic categories accounted for >85 % of the total amount of beach debris sampled and, among the categories, plastic cotton bud sticks accounted for > 30% of the total sampled debris. A distinct seasonal difference in the composition and amounts of debris sampled was seen in this study. The differences in debris composition and quantity between seasons was attributed to local activities and the varying discharge of the river. Thus, earbuds were most frequent during autumn and winter (when there was high rainfall and increased river discharge), expanded polystyrene pieces were more frequent in spring (when local fishing and agricultural activities intensified), and paper items were most frequent in summer (due to an increase in beachgoers and littering). Seasonal differences were also detected in this study, shown by the significantly larger total accumulation rate recorded at Milnerton in the winter sample period and the increase in material types recorded in the summer (December) sample period. Poeta et al. (2016a) attributed the differences in debris between sample sites to differential sizes, shapes and mainly buoyance of each material. They found that buoyant items such as expanded polystyrene were more numerous in the sample site located furthest from the river. The difference in composition between the Milnerton and Koeberg sample site is also likely attributed to the differential transport of materials and was similar to the findings of Protea et al. (2016a), with a greater spatial separation between sites.

This Table Bay study showed that plastics predominate marine debris at both sites and that there were large seasonal differences in total accumulation rates, particularly at Milnerton. These plastics were predominantly single-use plastics, which highlights the need for a societal change in consumer habits. This study further supports the use of daily sampling for beach surveys and highlighted that the rivers which terminate near Milnerton are prominent sources of debris. Important findings of this study are that better waste management and marine debris mitigation measures are needed, particularly in winter and after large storm events.

Chapter 3:

Long-term changes in marine debris within Table Bay, Cape Town, South Africa

3.1 Abstract

To assess the long-term changes in marine debris, daily accumulation rates were recorded at two sites within Table Bay, Cape Town, South Africa. Sample periods were conducted in the winter, spring and summer of 2019. The two sites had previously been sampled in 2012 and in 1994/95 using the same sampling protocols, and results for all three studies were compared. It is noted that the estuary, which the Diep and Black river flow into, was open during the 2019 sample periods and during the two previous studies. Across most sample years and seasons, Milnerton (min winter 1994/95: 286.7 items·100 m^{-1}·day^{-1} to max winter 2019: 801.8 items·100 m^{-1}·day^{-1} ; min summer 2019: 86.4 items·100 m^{-1}·day^{-1} to max summer 2012: 1698.0 items·100 m^{-1}·day^{-1}) had greater accumulation rates than Koeberg (min winter 2019: 55.9 items·100 m^{-1}·day^{-1} to max winter 1994/95: 129.3 items·100 m^{-1}·day^{-1} ; min summer 2019: 45.7 items·100 m^{-1}·day^{-1} to max summer 2012: 151.4 items·100 m^{-1}·day^{-1}). This was attributed to Milnerton having many more sources of debris. Across all years, winter accumulation rates were greater than summer rates; the flushing of the Black and Diep rivers were the main contributing factors. A large decrease in accumulation rates was seen from 2012 to 2019 in the summer months at both sites. At there was approximately a 95 % decrease in total accumulation rates at Milnerton and approximately a 70 % decrease at Koeberg. The commencement of municipal cleaning efforts in the spring was likely a large contributing factor to the decreases. Plastics (predominantly single-use items) dominated the composition of marine debris at both sites, and their proportional contribution has increased since 1994/95 and 2012. It is evident that plastics are still prevalent in the environment but, when implemented, municipal cleaning efforts (particularly river/storm water screening) are reducing marine debris on Table Bay beaches.

3.2 Introduction

There is increasing global concern pertaining to the pollution of the marine environment by debris, particularly plastic debris. With the demand for plastics increasing since their first commercial development in the 1930s and 1940s, increased amounts have entered the marine environment (Jambeck et al., 2015). Plastics dominate marine debris and are ubiquitous throughout the marine environment (Barnes et al., 2009; Derraik, 2002; Gall and Thompson, 2015; Jambeck et al., 2015; Thompson et al., 2009). Plastic debris' presence and dominance in the marine environment has led to many detrimental effects to marine biota, marine habitats, and human health and wellbeing (Chapter 1).

The monitoring of marine debris is important as it allows for mitigation and remediation measures to be assessed. There are multiple methods by which marine debris may be monitored, which include: i) analysing marine debris interactions with wildlife, ii) at-sea surveys, iii) input monitoring, and iv) beach surveys (Ryan et al., 2009). Each of these methods is described in more detail in Chapter 1. Beach surveys are the most frequently used method by which marine debris is monitored. There are two types of beach surveys: standing stock surveys and accumulation rate surveys (Chapter 1). A common problem, which has been mentioned in multiple studies, is the lack of standardization of sampling protocols, which makes it difficult for inter-study comparability. Standardized survey methods and protocols have been and are being developed (Chapter 1).

Beach surveys have been conducted in South Africa since the mid-1980s (Chapter 1). Swanepoel (1995) assessed the accumulation of marine debris within Table Bay, Cape Town, South Africa, in a study that has since become a baseline survey for the area. Daily and weekly accumulation rates were assessed at Milnerton and Koeberg beaches. Plastics were found to predominate marine debris at both sites and most of the marine debris was found to derive from local land-based sources. There was a marked increase in the accumulation of debris at Milnerton beach during the summer (December) ‘holiday season’. A key finding of Swanepoel (1995) was that there was a large difference in the results obtained from daily and weekly sampling. Weekly sampling intervals yielded lower numbers and weights of items than daily intervals, which suggested that weekly sampling may under-sample marine debris. These results supported the used of daily sampling for accumulation studies.

A subsequent accumulation study was conducted in 2012 at both sites by Lamprecht (2013). This study formed the second part of a times series to assess how marine debris had changed over time at both sites. It was found that plastics still dominated marine debris at both sites and that there had been an increase in the abundance and accumulation rate of debris at both sites since the Swanepoel (1995) study. The amounts of plastic litter had increased by two orders of magnitude in the 18 years between the two studies, which indicated the accumulation of plastic debris in marine environments had increased with increased use of plastics. A notable increase in the summer (December) ‘holiday season' was also recorded Lamprecht (2013). Long time series are important as they allow for changes to be detected and for mitigation and remediation measures to be assessed.

In this study, the same stretches of beach were sampled as in the two previous studies, to assess how marine debris had changed in the 18 years between the previous studies and the seven years until the most recent study. It was hypothesized that the accumulation rates of marine debris at both sites should have increased, as the demand for plastics and disposable products has increased. It was also hypothesized that the composition of marine debris should have changed since the two previous studies were conducted, as the demand for certain products would have changed and cleaning efforts may have changed.

3.3 Methods

3.3.1 Data collation and classification

The data in this study were collected and processed as described in Chapter 2. Expanded polystyrene was reported as a category separate from other plastics. Beach litter abundance and weight data from Swanepoel (1995) and Lamprecht (2013) were made available for this study. The raw data from both studies were reclassified by material type and items were assigned a functional group (Tables 2.1 and 2.2).

The sampling durations and areas of beach sampled in Swanepoel (1995) and Lamprecht (2013) differed slightly. A 500-m stretch of beach was sampled daily for 14 days at both Milnerton and Koeberg beaches in October 1994, December 1994 and July 1995 (Swanepoel, 1995), whereas in October, November and December 2012, sampling was restricted to 10 days and only the southern 250 m of beach was sampled at Milnerton (Lamprecht, 2013). The shorter stretch of beach sampled at Milnerton was because of the marked increase in litter, which would have prevented both beaches being sampled on the same days (Lamprecht, 2013).

The abundance and mass data from both previous studies were converted into accumulation rates (items·100 m^{-1}·day^{-1} and g·100 m^{-1}·day^{-1}) to account for differences in the duration of daily sampling and the lengths of beach sampled. Samples were collected in October (spring) and December (summer) in both previous studies and in this study. Therefore, these months were assessed together throughout the study. The July 1995 sample period was assessed in relation to the August 2019 sample period, as both sample periods are in winter.

3.3.2 Multivariate statistical analyses

A data table was created with accumulation rates (items·100 m^{-1}·day^{-1}), with rows representing the 16 functional groups (Table 2.2) and columns representing the samples. The data table contained all the sample data for each site, year, month and day. Each sample was assigned its own unique identifier which stated its site, year, month and day. To reduce the large difference in accumulation rates among functional groups, the data were fourth-root transformed. A resemblance matrix was created using the Bray Curtis similarity measure. Principal coordinate (PCO) plots were created from the resemblance matrix to assess separation between sites, years and months.

Multiple PERMANOVA (Permutational Multivariate Analysis of Variance) and SIMPER (Similarity Percentages - species contributions) analyses were used to assess whether beach litter composition differed between samples, and whether the differences were consistent for the sites, years and months. PERMANOVA analyses used 9999 unique permutations under the reduced model method and the sums of squares were calculated using a type III partial sum of squares. Analyses of the October and December sample periods (spring and summer months) were conducted separately from the July/August sample periods (winter months) as there was no winter sample in 2012.

Subsets of the transformed data were created for sampling periods (October and December, or July/August) for each site (Milnerton and Koeberg) and year (1994, 2012 and 2019, or 1995 and 2019). Bray Curtis resemblance matrices were constructed using the subset data. PERMANOVAs were applied to the resemblance matrices with fixed factors (Site, Year and Month or Site and Year). The PERMANOVAs were used to assess whether beach litter composition differed significantly among sites, years and months.

A pairwise-PERMANOVA was used to assess in which combinations of years the beach litter compositions were significantly different from each other for each site. The pairwise-PERMANOVA was applied to the transformed data using Bray Curtis similarity measures. To assess which functional groups contributed to the dissimilarity between the sites, years and months, one-way combined factor (Site x Year x Month or Site x Year) SIMPER analyses were conducted on the transformed data with Bray Curtis similarities.

3.4 Results

The accumulation rates at Milnerton of the three main categories of debris and all debris combined were ~3-4 times greater in winter 2019 than 1995 (Figure 3.1 a). For the summer samples, the average accumulation was much greater in 2012 than the other two years (Figure 3.1 b). This increase was apparent in all three categories of debris but was greatest for the plastics (Figure 3.1 b). In summer 2019, the average accumulation rates were unexpectedly much reduced compared to both 1994 and 2012.

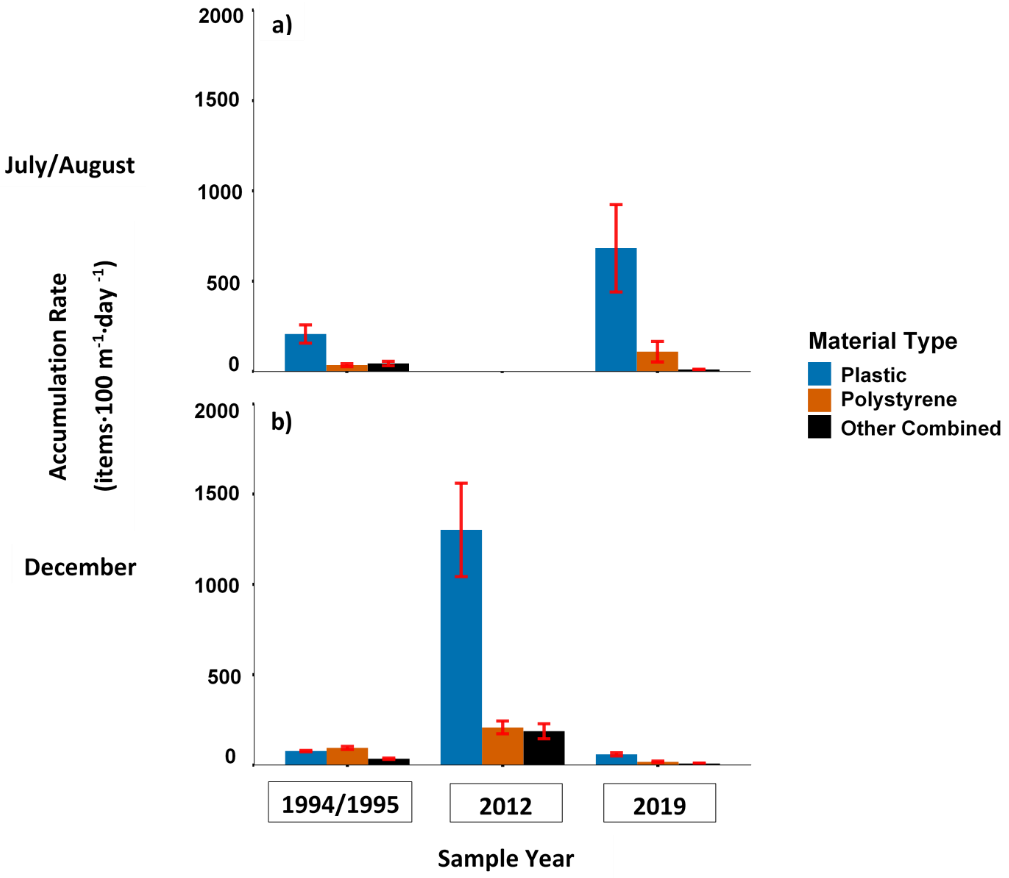

Figure 3.1: Milnerton beach litter accumulation rates (items·100 m^{-1}·day^{-1}) for each year (1994/95, 2012 and 2019) and month (July/August and December). No July/August sample was collected in 2012. "Other combined" shows the combined accumulation rates of all non-plastic items. Accumulation rates are averaged across all sample days for each year and month. The red bars show the standard error of each mean.

At Koeberg, the winter accumulation rates approximately halved between 1995 and 2019 (Figure 3.2 a). In summer there was a similar trend to Milnerton, with a much larger accumulation rate in 2012 than in 1994 and 2019. Like Milnerton, there was an unexpectedly small accumulation rate measured in summer 2019 compared to 2012 (Figure 3.2 b).

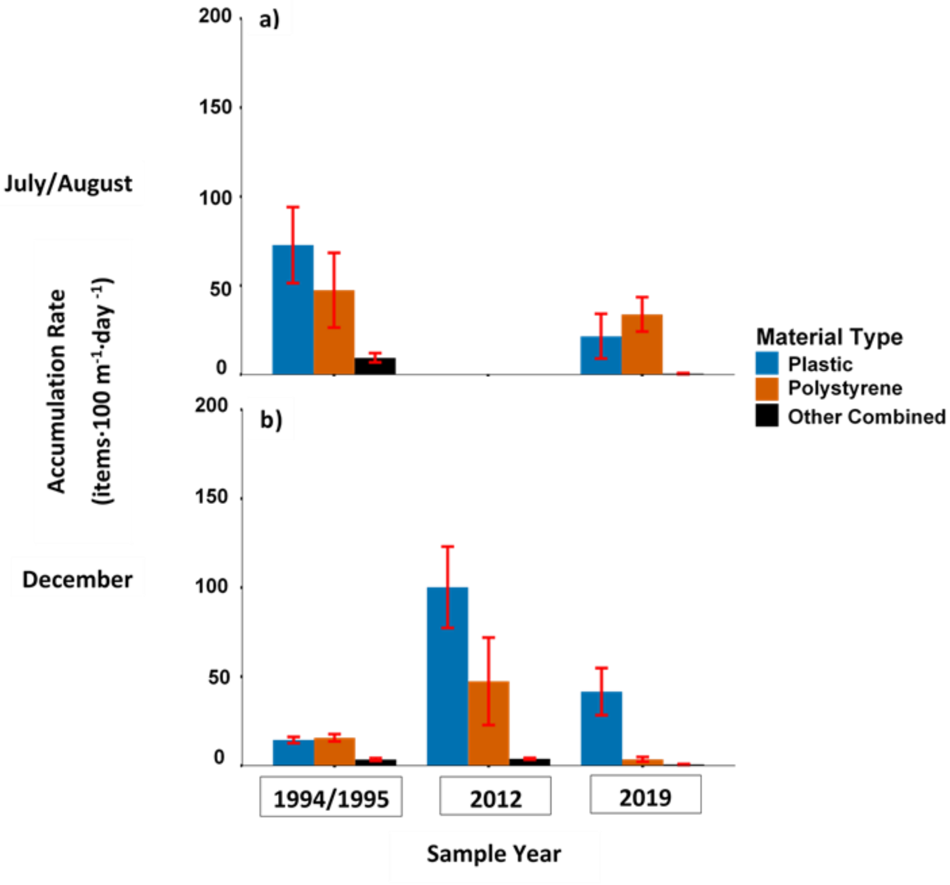

Figure 3.2: Koeberg beach litter accumulation rates (items·100 m^{-1}·day^{-1}) for each year (1994/95, 2012 and 2019) and month (July/August and December). No July/August sample was conducted in 2012. “Other combined” shows the combined accumulation rates of all non-plastic items. Accumulation rates are averaged across all sample days for each year and month. The red bars show the standard error of each mean.

The results of the principal coordinate analysis indicated that the first two axes explained 72.2% of the total variation in the data (Figure 3.3 a-c). There was a slight separation between the sites in terms of litter composition (Figure 3.3 a), but no apparent separation between sample months (Figure 3.3 b). The most obvious separation occurred between years (Figure 3.3 c).

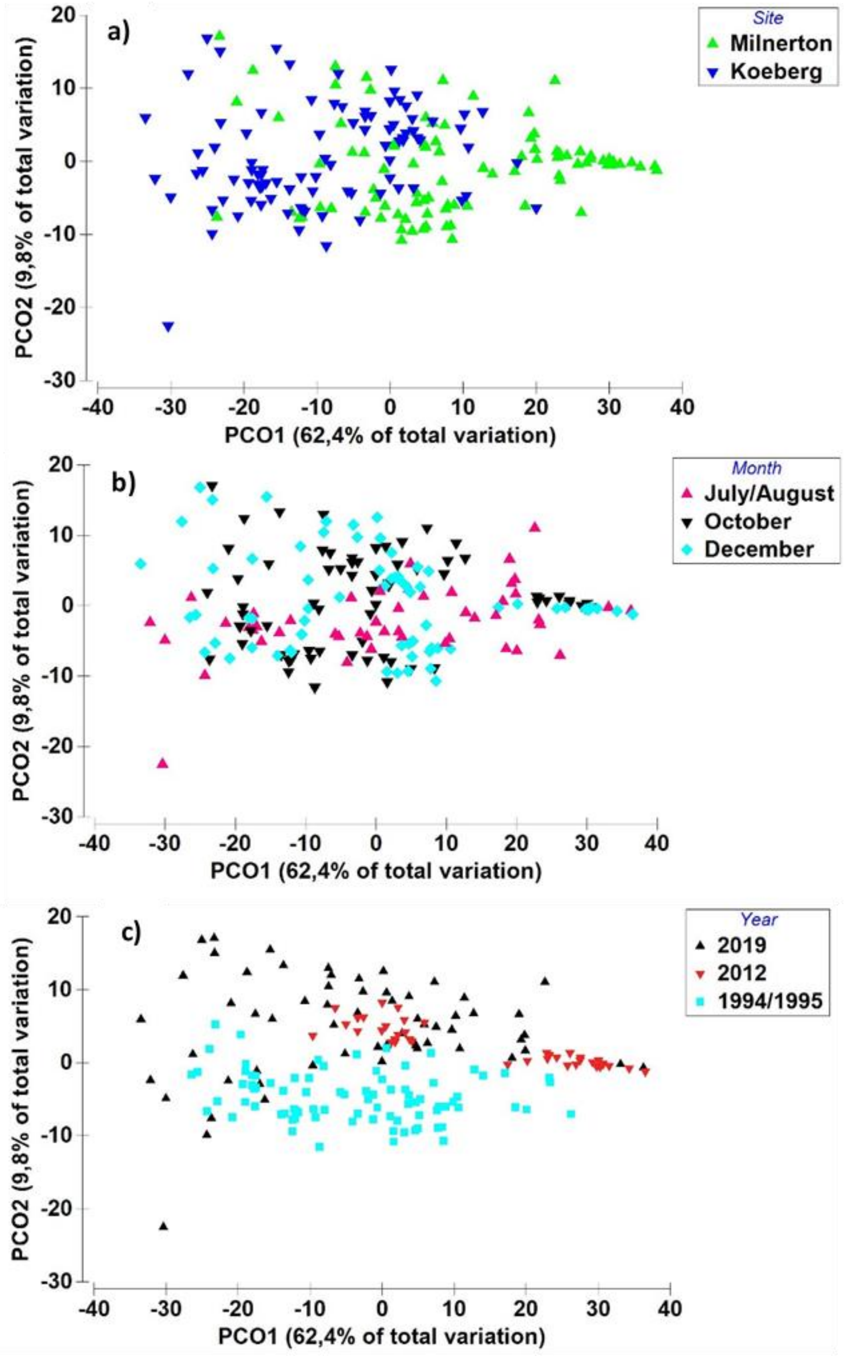

Figure 3.3: Principal Coordinate (PCO) plots showing variation between sample days based on fourth-root transformed accumulation rate data (items·100 m^{-1}·day^{-1}). a) Site overlaid, b) Month overlaid and c) Year overlaid.

Plastic and expanded polystyrene were the main material types at Milnerton for each month and year (Figure 3.4 a-e). Their combined contribution to beach litter composition was greater in 2019 than 2012, which was greater than 1994/95 (Figure 3.4 a-e). The combined contribution of all material types excluding plastic and expanded polystyrene was less in 2019 than 2012, which was less than 1994/95. Cigarette butts comprised most of the lesser materials in 2019 but showed a decreasing trend in relative contributions over time (Figure 3.4 a-e).

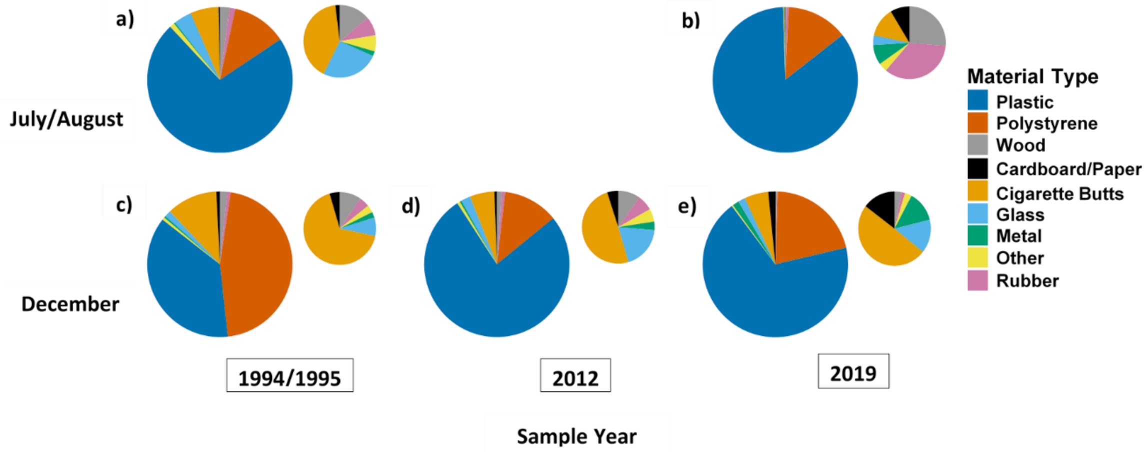

Figure 3.4: Milnerton beach litter composition for each year (1994/95, 2012 and 2019) and month (July/August and December) based on numbers, averaged across all sample days for each year and month. No July/August sample was conducted in 2012. The lesser contributing materials are shown in the smaller pie charts.

At Koeberg, plastic and expanded polystyrene also were the main material types for each month and year (Figure 3.5 a-e) and their combined contribution to beach litter composition increased from 1994 to 2012 and 2019 (Figure 3.5 a-e). More material types were present, and they contributed greater proportions to the beach litter composition, in the earliest samples in December 1994 (Figure 3.5 c) and July 1995 (Figure 3.5 a) compared to other sample months (Figure 3.5 b, d, e). Fewer material types were sampled in August and December 2019 compared to previous years and there were no glass items sampled.

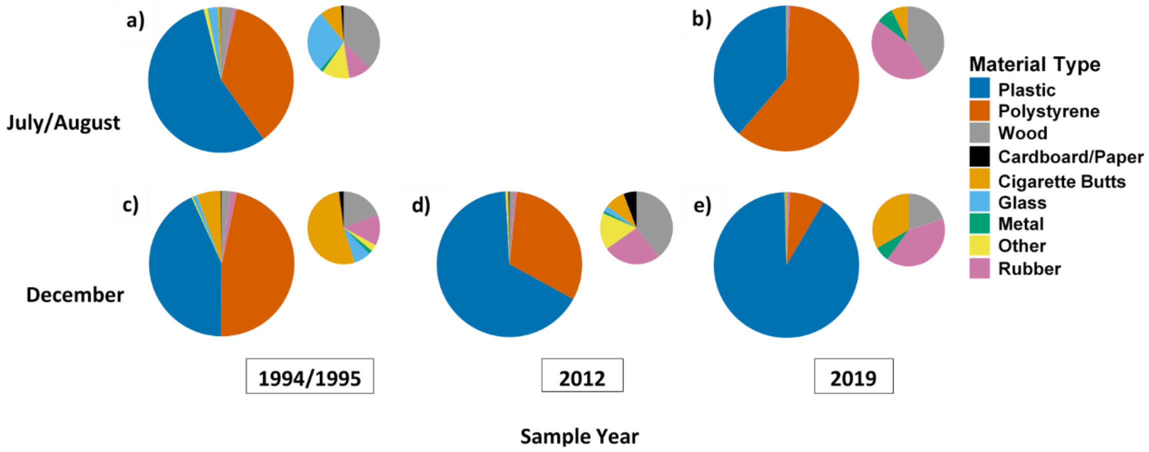

Figure 3.5: Koeberg beach litter composition for each year (1994/95, 2012 and 2019) and month (July/August and December) based on numbers, averaged across all sample days for each year and month. No July/August sample was conducted in 2012. The lesser contributing materials are shown in the smaller pie charts.

PERMANOVA test 1 showed that there was a significant difference in beach litter composition between sites (Milnerton and Koeberg), years (1994, 2012 and 2019) and months (October and December). This test focused on the spring and summer months. Test 2 showed there was a significant difference in beach litter composition between sites (Milnerton and Koeberg) and years (1995 and 2019) (Table 3.1). This test focused on the winter months. The pairwise-PERMANOVA test showed there was a significant difference in beach litter composition among years (1994, 2012 and 2019) for months (October and December) and sites (Milnerton and Koeberg) (Table 3.2).

Table 3.1: PERMANOVA results comparing beach litter composition between sites, years and months based on the fourth-root transformed accumulation rates (items·100 m^{-1}·day^{-1}). Two PERMANOVA tests were conducted. Test 1 compared composition between sites (Milnerton and Koeberg), years (1994, 2012 and 2019) and months (October and December), while test 2 compared between sites (Milnerton and Koeberg) and years (1995 and 2019). df = Degrees of freedom, SS = Sum of Squares, MS = Mean squares, Pseudo-F = Pseudo-F test statistic obtained by unique permutations, p(perm) = the probability calculated via permutation, Unique perms = the number of unique permutations run for each factor and interaction term. Significant results are highlighted with an asterisk (p< 0.05 *, p<0.01 **, p<0.001 ***).

PERMANOVA test	**Source**	**df**	**SS**	**MS**	**Pseudo-F**	**p(perm)**	**Unique perms**
Test 1	Site	1	9441.2	9441.2	72.99	0.0001***	9954
	Year	2	18287	9143.6	70.69	0.0001***	9940
	Month	1	361.69	361.69	2.7962	0.0222*	9951
	Site x Year	2	4186.1	2093.1	16.182	0.0001***	9945
	Site x Month	1	1694.1	1694.1	13.097	0.0001***	9943
	Year x Month	2	1052	525.99	4.0665	0.0002***	9922
	Site x Year x Month	2	1537.4	768.7	5.9429	0.0001***	9938
	Residual	124	16039	129.35			
	Total	135	53183				
Test 2	Site	1	8913.6	8913.6	33.26	0.0001***	9935
	Year	1	1694.5	1694.5	6.3227	0.0004***	9949
	Site x Year	1	2709.1	2709.1	10.109	0.0001***	9953
	Residual	44	11792	268			
	Total	47	23841				

Table 3.2: Pairwise-PERMANOVA results comparing beach litter composition among years (1994, 2012, 2019) for months (October and December) and sites (Milnerton and Koeberg) based on the fourth-root transformed accumulation rates (items·100 m^{-1}·day^{-1}). t = test statistic obtained by unique permutations, p(perm) = the probability calculated via permutation, Unique perms = the number of unique permutations run for each factor. Significant results are highlighted with an asterisk (p< 0.05 *, p<0.01 **, p<0.001 ***).

Site	**Comparison (year)**	**t**	**p(perm)**	**Unique perms**
Milnerton	1994 & 2012	13.826	0.0001***	9936
	2012 & 2019	8.3852	0.0001***	9934
	1994 & 2019	4.264	0.0001***	9960
Koeberg	1994 & 2012	7.462	0.0001***	9958
	2012 & 2019	3.2065	0.0001***	9947
	1994 & 2019	4.2792	0.0001***	9945

The greatest dissimilarity in beach litter composition between sites was in August 2019. Food wrapping, lids and lollipop sticks were the functional groups which contributed most towards this dissimilarity. All of these had greater transformed accumulation rates at Milnerton than Koeberg (Table 3.3). The smallest dissimilarity in beach litter composition between sites was found in October 1994. The transformed accumulation rates of dominant litter items tended to be greater at Milnerton for all months and years sampled, except October 2019, when expanded polystyrene, food wrapping, and earbuds all had greater transformed accumulation rates at Koeberg. Food wrapping, disposables and polystyrene were common functional groups causing dissimilarity between sites (Table 3.3).

The dissimilarity in beach litter composition between months (October and December) for both sample sites (Milnerton and Koeberg) were greater in 2019 than in both 2012 and 1994 (Table 3.4). At Milnerton the greatest dissimilarity was attributed to bottles, earbuds and non-plastics, whereas at Koeberg the greatest dissimilarity was attributed to expanded polystyrene, miscellaneous pieces and food wrapping (Table 3.4). The transformed accumulation rates of dominant items between months for both sites tended to be greater in December for each year sampled. However, the main contributing functional groups at Koeberg in October 2019 had greater transformed accumulation rates than in December 2019. Expanded polystyrene was a common functional group causing dissimilarity between months.

At Milnerton the greatest dissimilarity in beach litter composition among years was between October 2012 and October 2019 (Table 3.5). This was predominantly attributed to miscellaneous pieces, earbuds and food wrapping, which had greater transformed accumulation rates in 2012 than in 2019 (Table 3.5). At Koeberg the greatest dissimilarity in beach litter composition between years was between July 1995 and August 2019 (Table 3.5). This was predominantly attributed to non-plastics, lids and ropes, which had greater transformed accumulation rates in 1995 than in 2019. Miscellaneous pieces were a common functional group causing dissimilarity in beach litter composition between years.

Table 3.3: SIMPER results comparing the beach litter composition between sites, for each month and year. Two SIMPER tests were conducted. Test 1 compared between sites (Milnerton and Koeberg) for months (October and December) and years (1994, 2012 and 2019). Test 2 compared between sites for months (July/August) and years (1995 and 2019). Comparison = sites are compared, month = sample month, year =sample year, average dissimilarity % = the dissimilarity in beach litter composition between sites, functional group = the three main contributing functional groups to dissimilarity, transformed accumulation rate = the average transformed accumulation rate for each functional group for each site, month and year, % contribution = each functional group's contribution to the dissimilarity, cumulative % contribution = the summated contribution percentages. Larger transformed accumulation rates between sites are displayed in bold and common functional groups are identified with an asterisk.

					Transformed accumulation rate (items·100 m^{-1}·day^{-1})$^{0.25}$			
Comparison (site)	**Month**	**Year**	**Average dissimilarity %**	**Functional group**	**Milnerton**	**Koeberg**	**% Contribution**	**Cumulative % contribution**
Milnerton & Koeberg	October	1994	17.9	Disposables*	**1.66**	0.82	13.4	13.4
				Polystyrene*	**2.41**	1.77	12.0	25.4
				Non-plastics	**1.69**	1.15	8.9	34.3
		2012	30.8	Miscellaneous pieces	**4.03**	1.85	12.0	12.0
				Food wrapping *	**4.18**	2.2	10.9	22.9
				Earbuds	**3.21**	1.47	9.6	32.5
		2019	25.0	Polystyrene*	1.57	**2.43**	11.0	11.0
				Food wrapping *	2.24	**2.32**	8.2	19.2
				Earbuds	0.9	**1.45**	7.4	26.6
	December	1994	27.3	Disposables*	**2.17**	0.94	11.9	11.9
				Polystyrene*	**3.08**	1.93	11.1	23.0
				Bottles	**1.08**	0.28	7.9	30.9
		2012	29.9	Miscellaneous pieces	**4.75**	2.32	12.3	12.3
				Disposables*	**2.99**	1.05	9.9	22.2
				Lids	**3.79**	1.89	9.6	31.8
		2019	26.6	Non-plastics	**1.42**	0.52	10.2	10.2
				Disposables*	**1.48**	0.61	10.0	20.2
				Polystyrene*	**1.9**	1.25	8.1	28.3
	July / August	1995	19.9	Food wrapping*	**2.37**	1.51	9.6	9.6
				Disposables *	**1.87**	1.02	8.9	18.5
				Lids	**2.2**	1.82	8.6	27.1
		2019	48.4	Food wrapping*	**3.57**	1.13	10.9	10.9
				Lids	**2.84**	1.02	8.4	19.3
				Lollipop sticks	**2.25**	0.47	8.1	27.4

Table 3.4: SIMPER results comparing beach litter composition between months (October and December), for each site (Milnerton and Koeberg) and year (1994, 2012 and 2019). Conventions as Table 3.3 with months compared.

					Transformed accumulation rate (items·100 m^{-1}·day^{-1})$^{0.25}$			
Comparison (month)	**Site**	**Year**	**Average dissimilarity %**	**Functional group**	**October**	**December**	**% Contribution**	**Cumulative % contribution**
October & December	Milnerton	1994	13.2	Polystyrene*	2.41	**3.08**	12.6	12.6
				Disposables	1.66	**2.17**	9.2	21.8
				Medical/hygiene	0.52	**0.95**	8.4	30.2
		2012	11.9	Tubs	1.67	**2.8**	11.5	11.5
				Food wrapping	**4.18**	3.17	10.5	22.0
				Miscellaneous Pieces	4.03	**4.75**	9.8	31.8
		2019	24.5	Bottles	0.31	**0.89**	8.2	8.2
				Earbuds	0.9	**1.49**	7.9	16.0
				Non-plastics	0.87	**1.42**	7.3	23.4
	Koeberg	1994	15.1	Bottles	**0.65**	0.28	11.7	11.7
				Polystyrene*	1.77	**1.93**	10.3	22.0
				Disposables	0.82	**0.94**	8.0	30.0
		2012	12.4	Tubs	0.6	**1.31**	13.1	13.1
				Polystyrene*	1.66	**2.34**	12.2	25.3
				Miscellaneous pieces	1.85	**2.32**	9.2	34.5
		2019	26.9	Polystyrene*	**2.43**	1.25	12.6	12.6
				Miscellaneous pieces	**1.7**	0.93	8.4	21.0
				Food wrapping	**2.32**	2.03	7.4	28.4

Table 3.5: SIMPER results comparing beach litter composition among years for each month and site. Two SIMPER tests were conducted. Test 1 compared among years (1994, 2012 and 2019) for months (October and December) and sites (Milnerton and Koeberg). Test 2 compared among years (1995 and 2019) for months (July/August) and sites (Milnerton and Koeberg). Conventions as Table 3.3 with years compared.

					Transformed accumulation rate (items·100 m^{-1}·day^{-1})$^{0.25}$				
Site	**Month**	**Comparison (year)**	**Average dissimilarity %**	**Functional group**	**1994/95**	**2012**	**2019**	**% Contribution**	**Cumulative % contribution**
Milnerton	October	1994	32.7	Miscellaneous pieces*	1.24	**4.03**		14.8	14.8
		&		Lollipop sticks	0	**2.46**		12.9	27.7
		2012		Food wrapping	1.89	**4.18**		12.0	39.7
		2012	40.8	Miscellaneous pieces*		**4.03**	1.3	12.4	12.4
		&		Earbuds		**3.21**	0.9	10.5	22.9
		2019		Food wrapping		**4.18**	2.24	9.0	31.9
	December	1994	27.3	Miscellaneous pieces*	1.68	**4.75**		16.6	16.6
		&		Lollipop sticks	0.05	**2.35**		12.7	29.3
		2012		Tubs	0.52	**2.8**		12.4	41.7
		2012	34.6	Miscellaneous pieces*		**4.75**	1.56	14.5	14.5
		&		Lids		**3.79**	1.51	10.4	24.9
		2019		Tubs		**2.8**	0.94	8.5	33.4
	July/August	1995	21.5	Lollipop sticks	0.31		**2.25**	14.7	14.7
		&		Food wrapping	2.37		**3.57**	10.7	25.4
		2019		Polystyrene	2.26		**2.61**	8.0	33.4
Koeberg	October	1994	20.4	Lollipop sticks	0	**1.13**		15.7	15.7
		&		Miscellaneous pieces*	1.07	**1.85**		10.9	26.6
		2012		Food wrapping	1.41	**2.2**		10.8	37.4
		2012	15.1	Polystyrene		1.66	**2.43**	13.3	13.3
		&		Food wrapping		2.2	**2.32**	9.0	22.3
		2019		Tubs		0.6	**1.16**	8.8	31.1
	December	1994	26.6	Miscellaneous pieces*	1.03	**2.32**		13.0	13.0
		&		Tubs	0.1	**1.31**		12.2	25.2
		2012		Lollipop sticks	0	**1.2**		12.1	37.3
		2012	29.2	Miscellaneous pieces*		**2.32**	0.93	13.2	13.2
		&		Polystyrene		**2.34**	1.25	10.1	23.3
		2019		Non-plastics		**1.35**	0.52	8.03	31.3
	July / August	1995	33.6	Non-plastics	**1.59**		0.52	10	10
		&		Lids	**1.82**		1.02	8.2	18.2
		2019		Ropes	**1.46**		0.75	7.3	25.5

3.5 Discussion

In the 18 years between the studies of Swanepoel (1995) and Lamprecht (2013) and the subsequent seven years since the two sites were previously sampled, there have been large changes in the accumulation rates and composition of debris recorded at both the Milnerton and Koeberg sample sites. Across most years and seasons, marine debris accumulation rates tended to be greater at Milnerton than Koeberg.

The accumulation rates at Milnerton were generally an order of magnitude greater at Milnerton than Koeberg. This was expected as there are many more sources of debris to Milnerton than Koeberg. Large differences in accumulation rates were seen until 2019, when the two beaches had relatively similar accumulation rates. This corresponds with the commencement of more frequent river cleaning in 2019. A likely explanation for this is the exhumation of buried debris at Koeberg and because proportionally more debris from ships arrive at Koeberg. It is also likely that the effects of river cleaning are particularly strong close to their mouths, whereas other debris sources into the bay have not been reduced.

The debris composition and accumulation rates showed that both sites were dominated by land-based sources of debris. This parallels what is seen in Ryan (2020), where the transport and fate of marine plastics in Southern Africa and adjacent oceans was assessed. Ryan (2020) reviewed the sampling of 82 beaches along the coast of South Africa and showed that the densities of marine debris were consistently greater close to urban centres than at remote beaches, despite there generally being greater cleaning efforts nearer to the urban centres. This supports the findings of this study, which showed that accumulation rates were greater at Milnerton than Koeberg. Prominent land based sources of debris to the Milnerton sample area include rivers, waste water/stormwater systems, windblown litter and debris left by recreational beach goers (Ryan et al., 2009)

Seasonal differences in accumulation rates were shown at both sites in 1994/95 and in 2019, when both winter (July/August) and summer (December) samples were collected. The winter accumulation rates tended to be greater than the summer accumulation rates. The region is known to receive winter rainfall. The winter rainfall would have facilitated the flushing of debris from the Black and Diep rivers into Table Bay, near the Milnerton sample site, thereby increasing the accumulation rates (Armitage and Rooseboom, 2000; Rech et al., 2014; Ryan et al., 2009; Weideman et al., 2020). A study by Silva et al. (2016), which assessed the influence of intensity of use, rainfall and location on the amount of marine debris collected at four Brazilian beaches showed distinct seasonal differences. They found that the largest amounts of debris recorded in terms of number and weight were collected during the rainy season, which happened to be in the summer and was also the tourist season. They suggested that a major contributing factor to the increased abundances recorded during the rainy season was the flushing of debris from rivers/storm water systems. This supports a conclusion of this study that the Black and Diep rivers are prominent sources of debris to Milnerton beach as well as Table Bay. Other likely contributing factors which would have led to the seasonal differences in accumulation rates are currents, wave activity and winds. The results of this study, however, do not correspond with the findings of Martinez-Ribes et al. (2007), where the accumulation rates of marine debris were monitored on 32 beaches on the Balearic Islands within the Mediterranean Sea. They found that, in summer (the high tourist season), the accumulation rate in terms of abundance was double that of the low season (winter). In both seasons, the marine debris characteristics suggested a strong link with local land-based sources. Beach users were the main source of debris in the summer, whereas rivers/stormwater systems were the main source of debris in the winter season. It is likely that tourism is a factor that has more of an effect on marine debris at the Mediterranean sites than the sites sampled in this study. The results of this study suggested that rivers/stormwater systems had a greater influence than tourism on marine debris at Milnerton.

Milnerton and Koeberg showed similar summer patterns in that their summer accumulation rates increased substantially from 1994 to 2012, and then decreased substantially from 2012 to 2019. The increase in accumulation rates from 1994 to 2012 was expected, as both the population size (World Population Review, 2020) and the production and use of plastics (which predominate marine debris) had increased during that period (Jambeck et al., 2015). However, the decrease in accumulation rates recorded in summer at both sites from 2012 to 2019 was unexpected. A likely localized effect, which would have contributed to the large decrease in summer accumulation rates recorded at Milnerton, was the commencement of municipal cleaning efforts along the adjacent beach areas and rivers, and the deployment of river nets. The cleaning of Milnerton beach has been sporadic over the past few years and the commencement of cleaning efforts only started post winter (August) in 2019. This would have led to less debris being flushed into the bay and, thus, decreased accumulation rates. The implementation of the cleaning efforts coincided with the change in season at the beginning of spring, continuing into the summer ‘holiday season’, which sees more people visit the site. The implementation of cleaning efforts to coincide with the ‘holiday/tourist season’ was also shown to influence the abundance and composition of debris at popular tourist beaches in Brazil (Silva et al., 2016), where cleaning efforts reduced the abundance of debris at popular recreational beaches when their intensity of use was high in the holiday/tourist season. It is likely that the decreased amount of debris that entered Table Bay via the rivers by Milnerton also would have contributed to the decreased accumulation rates recorded at Koeberg, as less debris would have been transported to the site.

When the data were analysed in terms of the 16 functional groups, beach litter compositions were statistically different between each site, year and sample month. However, the extent to which they differed varied substantially. The composition of marine debris at both sites across all sample periods and years was dominated by plastics and expanded polystyrene. This is in agreement with the findings of most published literature on marine debris (Barnes et al., 2009; Derraik, 2002; Gall and Thompson, 2015; Jambeck et al., 2015; Thompson et al., 2009). The proportions attributed to plastics and polystyrene increased since 1994/95 and 2012 at both sites. This could be due to material types other than plastics and polystyrene decreasing in their abundance; however, a more likely explanation is the increasing production and utilization of plastics (Jambeck et al., 2015).

A sample period that stood out among the sites, seasons and sample years was the Koeberg spring (October) 2019 sample period. The relatively large accumulation rates and the increase in material types recorded showed that undercutting had taken place. Items that previously had been deposited and covered were being re-exhumed by increased wave action, which undercut the beach. This highlights the importance of recording change in conditions when conducting accumulation studies, so that unusual results can be interrogated correctly.

At both sites there was little dissimilarity in marine debris composition between seasons (spring and summer) across all sample years. The accumulation rates varied more than the compositions between spring and summer seasons. This is likely due to the sources of debris remaining the same. In Martinez-Ribes et al. (2007) a strong seasonality in accumulation rates and composition was seen. In summer (the high tourist season) cigarette butts were the most abundant item recorded, whereas in winter (the low tourist season) plastics related to personal hygiene/medical items predominated. This highlighted that tourism was an important factor influencing the composition of marine debris at those sites. However, in this study the results suggested that tourism has less of an effect on debris composition.

The greatest dissimilarity in compositions were seen between sites and between sample years. Between sites, the greatest dissimilarity (48.4%) was seen in July 2019, when food wrapping, lids and lollipop sticks all had greater accumulation rates at Milnerton than Koeberg. These are all items commonly found in urban areas and that get washed into rivers and storm water systems (Armitage and Rooseboom, 2000; Jambeck et al., 2015; Leite et al., 2014; Marais et al., 2004; Rech et al., 2014; Ryan et al., 2009; Silva et al., 2016; Weideman et al., 2020). These are also items commonly found on beaches near urban centers across South Africa (Ryan, 2020). This shows that Milnerton is a site that experiences a strong urban influence on the composition of marine debris. It is evident that differential transport was a contributing factor that led to the dissimilarity between sites. Marine debris found at Koeberg tended to consist of buoyant items. Materials such as expanded polystyrene and food wrappers were capable of being transported vast distances away from their sources and deposited at the Koeberg sample site (Ryan et al., 2020a).

At both sites, across all seasons, the composition of marine debris recorded in 2012 stood out. The items recorded were predominantly small plastic items and miscellaneous plastic pieces. It is evident that the accumulation rates of debris in 2012 was what led to the large differences in compositions between years. This highlights that it wasn’t so much the composition of marine debris that changed from year to year but rather the accumulation rates of different debris types that changed. This shows that single-use plastics and expanded polystyrene items still dominate marine debris at both sites and that their accumulation rates have changed over the years. It evident that the small size classes of plastics items are still very prevalent, which brings with it many problems, particularly to marine life.

Plastics (predominantly single-use plastics) dominate marine debris at both sample sites but there has been a large decrease in accumulation rates recorded in the summer months from when the sites were last sampled in 2012. Many factors would have contributed to this decrease. However, the cleaning efforts implemented near the Milnerton sample site, which commenced in the spring to summer months of 2019, probably were having a meaningful impact. They should be implemented throughout the year to decrease the amounts of marine debris entering Table Bay.

Chapter 4: Conclusions

This study aimed to assess marine debris within Table Bay, South Africa, at both a remote and an urban beach. The accumulation rates and compositions of marine debris were assessed so that inter-site, seasonal and long-term comparisons could be made. It was evident that, as with many marine debris studies, both national and international, plastics predominate marine debris within Table Bay. The accumulation rates recorded at Milnerton tended to be much greater than those recorded at Koeberg, which was expected as there were many more sources of debris to Milnerton than Koeberg. There was a strong urban influence on the debris collected at Milnerton, which consisted of predominantly single-use plastic items. The composition of the debris showed that both sites were predominated by land-based sources of debris. This is important to know, as this allows for us as South Africans to take effective measures to reduce the amount of marine debris that we produce.

The Black and Diep Rivers were both important sources of debris to the Milnerton sample site and to Table Bay. It is evident that there was a strong seasonal component in the accumulation rates of debris. At both sites across the years, accumulation rates tended to be greater in the winter. The flushing of debris from the rivers and storm water systems during the rainy winter season likely led to the large increase in accumulation rates. During the 2019 winter sample period it was evident that a storm event occurred and that after large rain events there was a spike in accumulation rates recorded at Milnerton. This supports many published studies which recommend that daily sampling is the best frequency with which to conduct accumulation studies. The undercutting that occurred at Koeberg during the 2019 spring sample period further supports that daily sampling should be implemented and that standardized sampling protocols should be utilized as they allowed for anomalous results to be interrogated and explained. The use of similar sampling protocols allowed for the data collected in 1994/95 and 2012 to be compared to the data collected during this study, highlighting the importance of standardized sampling protocols and long-term time series.

It was noted that cleaning of both sites had been sporadic over the past few decades and it is evident that the implementation of cleaning efforts at the Milnerton sample site post-winter 2019 had a large impact in reducing the amounts of marine debris collected. This shows that remediation and mitigation efforts were having a positive impact in reducing the amounts of marine debris that enter the bay. The cleaning efforts should be implemented throughout the year and not only in the spring and summer (holiday/tourist seasons).

A limitation of the study was the quality of the weather data. For future research as part of this long-term monitoring, it would be useful to acquire improved data on weather and currents in the bay to try gain a more holistic view of marine debris transport within Table Bay. It would be useful if on-site measurements such as wind speed and direction could be taken.

For future research there could be concurrent monitoring of litter loads in rivers/storm water systems as this would provide better understanding of the sources and transport mechanisms of marine debris. This could be run as a parallel research project as it would require significantly more resources and effort to achieve. For future research building on from this study, a tag and release study could be conducted to assess the flow paths of land-based debris, which could be used to highlight potential choking/clogging points. This could then be used to effectively implement marine debris mitigation measures such as river nets and booms and this information could be utilized by the local municipality. It is recommended that accumulation studies continue within the bay so that the effectiveness of mitigation and remediation measures can be assessed. It is also recommended that the accumulation studies are conducted annually if possible as it would allow for a more detailed assessment of the area. For future research building on from this study it is also recommended that similar studies be conducted around the country to assess the marine debris problem not only in Table Bay, Cape Town, but across the nation. In areas where research like this has not yet been conducted, important baseline studies could be run.

From conducting this study, it is promising to see that people are becoming more aware of the ocean pollution problem and that they are actively trying to make a positive difference. The work being conducted by organizations such as the beach co-op and The Cape Town Beach Clean Up is vital as it helps mitigate the problem while educating the public about the ocean pollution problem. It is encouraging to see that, when mitigation and remediation efforts are implemented, they can have a positive effect. However, it is up to us South Africans to make important choices when it comes to reducing our dependence on plastics and waste production.

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