Cape Peninsula University of Technology

Environmental concentrations, characteristics and risk assessment of microplastics in the Olifants and Breede Catchments, Estuaries and Coastal Areas, Western Cape, South Africa

by

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Declaration

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

22/01/2026

Signed **Date**

Abstract

Microplastic (< 5 mm) contamination is increasingly being reported from South African aquatic environments but few studies have been done from catchment-to-coast. Thus, the aim of this study was to determine the concentrations, characteristics and risk assessment of microplastics in the Olifants and Breede River catchments, estuaries and coastal areas in the Western Cape, South Africa. Surface water and sediment were collected and analysed for microplastics in the wet and the dry season in relation to disturbances acting on these systems. Microplastics were extracted and identified using microscopy and Fourier-transform infrared spectroscopy (FTIR) analyses. Average microplastic concentrations ranged from 0.24 ± 0.01 particles/L to 0.26 ± 0.02 particles/L in water and 48.30 ± 3.95 particles/kg dry weight to 43.65 ± 2.71 particles/kg dry weight in sediment of the Olifants and Breede systems, respectively. Microplastics were mainly black/grey fibres, 500 – 1000 µm in size and polyethylene terephthalate was the dominant polymer recorded for both systems. Pollution load indices indicated that pollution was present (< 1) across the different regions and seasons of each system for water and sediment. Polymer risk indices in water ranged from low (7.50) to very high (1658.20) and low (4.00) to high (942.20) in the Olifants and Breede systems, respectively, while in sediment, indices ranged from low (6.60) to moderate (47.30) in the Olifants system and low (4.00) to moderate (57.70) in the Breede system. Spatially, in the Olifants system, pollution risk indices in water was categorised as dangerous in the catchment (3190.50), estuary (5748.60) and coast (6943.30) during the wet season, while moderate in sediment along the coast (198.50) during the dry season. In the Breede system, pollution risk indices in water was categorised as dangerous in the catchment (6790.5) during the wet season and along the coast during the wet (2746.40) and the dry season (3136.10), while high in sediment in the estuary (421.80) during the wet season. Seasonally, in the Olifants system, pollution risk indices in water was categorised as dangerous during the wet season (– 63 µm: 11864.3 & 250 µm: 9278.20) and very high during the dry season (63 µm: 1095.20 & 250 µm: 1102.01), while moderate in sediment during the wet (197.30) and the dry (251.30) season. In the Breede system, pollution risk indices in water was categorised as dangerous during the wet season (63 µm: 1223.30 & 250 µm: 9605.10) and the dry season (3273.20), while ranging from high to low in sediment during the wet (703.20) and the dry (104.40) season, respectively. The results from this study serves a baseline for future reaserch and to inform policy makers that govern the protection of these systems so they may be able to develop and implement the necessary mitigation measures to reduce contamination within these systems. The Olifants and Breede systems are ecological important systems. However, the results from the risk assessment indicates that the polymers that accumulate in these system during the

wet season pose a threat to the overall health and functioning of these systems from catchment-to-coast. Thus, regular monitoring of these system are crucial.

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Abbreviations and acronyms

Abbreviation/Acronym		
°C	Degrees Celsius	
µm	Micrometre (millionth of a meter)	
CF	Contamination Factor	
cm	Centimetre	
dw	Dry weight	22/01/2026
et al.	And others	
FTIR-ATR	Fourier Transform Infrared-Attenuated Total Reflectance	
g	Grams	
H	Polymer Risk Index	
kg	Kilogram	
km	Kilometre	
km^2	Square kilometre	
KOH	Potassium Hydroxide	
L	Litre	
m	Metre	
m^3	Cubic metre	
mg/L	Milligrams per Litre	
ml	Millilitre	
mm	Millimetre	
MP	Microplastic/s	
m/s	Meters per second	

n	Number
N	Newton
n/m	Newtons per metre
NaCl	Sodium Chloride
NTU	Nephelometric turbidity units
PLI	Pollution Load Index
PRI	Pollution Risk Index
ppt	Parts per thousand
QGIS	An open-source Geographic Information System
R & R Studio	Free software programming language for statistical analyses
s	Seconds
SEM	Standard error of the mean

Glossary

Term	Definition
Anthropogenic activities	Human related activities.
Bioaccumulation	The process whereby substances such as chemicals gradually accumulate in an organism.
Bioavailability	Refers to the extent to which a material or substance is available to an organism within the environment.
Biodegradation	The processes whereby materials and/or substances are broken down naturally by microorganisms.
Biofilms	A biofilm forms when communities of microorganisms attach themselves and adhere to surfaces.
Biofouling	The process relating to communities of microorganisms colonising surfaces.
Brackish water	A mix of seawater and freshwater.
Bulk water sampling	The sampling method where large volumes of water are collected which then gets reduced in volume.
Catchment	The drainage area that contributes water to a particular point along a network of channels.
Cross-ecosystem subsidies	Subsidies are referred to as nutrients, organisms, matter, energy and/or resources or services that cross boundaries/ecosystems either through physical or biotic vectors. These subsidies may have either positive or negative impacts on the recipient ecosystem depending on the type of subsidy.
Density separation	This process involves the mixing of a sample with a dense solution and leaving it to settle for a certain period of time,

	allowing the less dense solution and /or particles to float at the surface.
Digestion	Adding a chemical, either an acid or strong base, to a sample to breakdown any organic material.
Ecotoxicological	Relates to how contaminants and toxic substances affect the environment.
Endemic	Refers to something that is native to a specific area which cannot be found anywhere else in the world.
Estuary	A partially enclosed permanent water body, which can either be continuously or periodically open to the sea on decadal time scales, extending as far as the upper limit of tidal action, salinity penetration or back-flooding under closed mouth conditions.
Euhaline	Conditions characterised by salinities ranging between 30 - 35 ppt.
Filtration	The process of filtering a sample.
Fluvial	Relating to rivers.
FTIR-ATR	The equipment used to undertake spectroscopy, which provides specific information on the chemical bonds and functional groups of plastic polymers. In addition, the ATR is the specific mode used while conducting FTIR analysis. This is considered the preferred mode as the spectra obtained are usually of a better quality.
Heterogeneous	Diverse in character and/or composition.
Hydrophobicity	Relates to the tendency of a material or substance to repel water and/or preferring non-aquatic environments.
Hypersaline conditions	Conditions characterised by a high level of salinity (> 35 ppt).
In-situ	On site.

Lower reaches	Section located downstream, closest to the coast.
Macro-plastics	Plastic particles ranging between 25 – 1000 mm in size.
Mechanical abrasion	The process of being worn down or weathered.
Meso-plastics	Plastic particles ranging between 5 – 25 mm in size.
Mesohaline conditions	Conditions characterised by a moderate level of salinity (5 – 18 ppt).
Microplastics	Plastic particles ranging between 1µm - 5 mm in size.
Middle reaches	Section located between the upper and lower reaches.
Milli-Q ultrapure water	Deionised water that has been purified.
Oligohaline conditions	Conditions characterised by a low level of salinity (0.5 – 5 ppt).
Physicochemical conditions	Conditions that can influence aquatic environments (e.g. temperature, salinity, pH, turbidity) which can vary spatially and temporally.
Photo-degradation	The alteration of a material or substances by means of light.
Polymers	Formed from the chemical bonding of individual molecules (monomers) to form long chains.
Spectroscopy	Most common method used for the chemical characterisation of microplastic particles.
Thermohaline	Relates to both temperature and salinity.
Tidal prism	Refers to the amount of water that flows in and out of an estuary.
Tributaries	The network of channels that flow into one main river channel.
Upper reaches	Section located upstream, closest to the river.

Chapter 1: General introduction

1.1 Introduction

Reports on the accumulation of plastic in the environment extend as far back as the 1870's (Ryan, 2015; Geyer et al., 2017). Since then, research on plastic in the environment has increased relative to increase in global plastic production rates. Plastic production increased from 1.5 million tonnes in 1950 to 400.3 million tonnes in 2022 (PlasticsEurope, 2023) and is expected to reach 1.1 billion tonnes by 2050 (Geyer et al., 2017; Geyer, 2020). About half of the plastics produced are used to manufacture single-used items such as straws, cups and plastic bags (IUCN, 2021). Thus, many concerns have been raised about the risks of plastic cause if not properly disposed of these plastic items eventually end up in the environment (IUCN, 2021). Although plastic in the environment is generally slow to degrade, plastics can fragment into smaller plastic debris, known as microplastics (Hale et al., 2020; Song et al., 2024).

Microplastics are referred to as synthetic polymer particles ranging between 1 µm to 5 mm (Frias & Nash, 2019; Thompson et al., 2024). Moreover, microplastics can be classified as either primary or secondary microplastics. Primary microplastics are plastic particles that are intentionally produced to retain a microscopic size (≤ 5 mm) (GESAMP, 2019; Thompson et al., 2024). These microplastics include microbeads found in cosmetic products such as moisturisers, facial scrubs, and industrial cleaning products (Napper et al., 2015; Miraj et al., 2021). Additionally, industrial pellets can also be considered primary microplastics as they serve as precursors in the manufacturing of larger plastic products (Cole et al., 2011; Hidalgo-Ruz et al., 2012; Mato et al., 2001; Raju et al., 2023). In contrast, secondary microplastics are derived from the fragmenting of larger plastic products (> 5 mm) and are considered the dominant source of microplastic debris (GESAMP, 2019; Thompson et al., 2024) due to the continued weathering and degradation of larger plastic items (Andrady, 2017; Song et al., 2024).

About 14 million tonnes of plastic enter the ocean each year (IUCN, 2021). Plastic and more specifically microplastics have been discovered in marine environments around the world, with approximately 98% of microplastics in the ocean being land-based (tyres, road markings, plastic pellets, and synthetic textiles) and 2% stemming from activities at sea (plastic pellets and marine coatings) (Boucher & Friot, 2017). In addition to the annual plastic emissions into the ocean, 98.5% of plastic waste remains and accumulates within terrestrial environments before progressively contaminating inland aquatic environments (Meijer et al., 2021). As most plastic waste is generated from land-based sources, the necessary prevention and

mitigation measures can significantly decrease the plastic waste entering the ocean (Meijer et al., 2021). However, reducing plastic waste may prove difficult for many developing countries, like South Africa, where adequate waste management is unfortunately lacking (Jambeck et al., 2015; Verster & Bouwman, 2020).

In South Africa, approximately 25 million tonnes of general waste were generated in 2022, 549 628.38 of which were plastic(Department of Forestry, Fisheries and the Environment, 2024). Of the plastic waste generated, 34.9 % was either recycled, recovered or treated while 357 816.87 tonnes (65.1%) was disposed of (Department of Forestry, Fisheries and the Environment, 2024). Furthermore, it is estimated that the annual plastic emissions in South Africa's marine environment range between 15 000 – 40 000 tonnes (Verster & Bouwman, 2020).

Despite South Africa's substantial contribution to the plastic emissions in the ocean, research on plastic pollution has received limited attention with research on microplastics receiving even less (Naidoo et al., 2015; Govender et al., 2020; Samuels et al., 2024). Research on microplastics in South Africa has only recently gained traction, with research initially focusing on coastal and marine environments (Ryan, 1988; Ryan et al., 2009; Nel & Froneman, 2015; Ryan, 2020a). However, research on freshwater and estuarine environments remains limited despite both these environments being considered as important pathways for the transport of microplastics from land to the ocean (Verster & Bouwman, 2020; Meijer et al., 2021; Malli et al., 2022).

1.2 Research problem

With millions of tonnes of plastic entering the ocean each year, the presence of microplastics has become a major cause for concern (Ryan et al., 2009; PlasticsEurope, 2022). Much of the research on microplastics have been conducted in coastal and marine environments and consider freshwater and estuarine environments as one of the major pathways through which microplastics reach coastal and marine environments. Despite this, research on microplastics has predominantly focused on individual environmental compartments rather than the interconnected nature of freshwater, estuarine and coastal and marine environments (Horton & Dixon, 2018; Verster & Bouwman, 2020). This lack of research on microplastics within the context of catchment-to-coast is thus what hinders the development of appropriate mitigation strategies (Horton & Dixon, 2018). Therefore, it is necessary to consider each environmental compartment to better understand the concentration of microplastics, the risks, transport and fate from freshwater to coastal and marine environments.

In South Africa, limited research has investigated microplastics across interconnected freshwater, estuarine and coastal environments, despite the country's high biodiversity and increasing anthropogenic pressures. Aquatic systems such as the Olifants and Breede systems are ecologically and socio-economically important, supporting fisheries, protected estuaries and biodiverse coastal zones, while simultaneously facing pressures from agriculture, urban development, tourism and recreational activities (Western Cape Government, 2021a; Western Cape Government, 2025). These systems therefore provide representative catchment to coast environments for assessing the distribution, accumulation and potential ecological risks of microplastics. Understanding microplastic dynamics within these systems is essential for informing locally relevant management and mitigation strategies in South Africa, as well as in other regions experiencing similar environmental pressures.

1.3 Research aim and objectives

This study determined the environmental concentrations, characteristics and risk assessment of microplastics in the Olifants and Breede river catchments, estuaries and coastal areas in the Western Cape of South Africa.

The following objectives were used to address this aim:

- To determine the concentration of microplastics in water and sediment within and between the catchment, estuary and coast during the wet and dry season.
- To determine whether environmental parameters (temperature, salinity, turbidity, pH, & grain size analysis) influence the concentration of microplastics within and between the catchment, estuary, and coast during the wet and the dry season.
- To determine the level of disturbance associated with surrounding anthropogenic activities which may influence the concentration of microplastics within and between the catchment, estuary and coast during the wet and the dry season.
- To determine the potential risks posed by microplastics within and between the catchment, estuary and coast during the wet and the dry season.

1.3 Delineation and limitations of the research

The research was conducted in the Olifants and Breede systems of the Western Cape Province of South Africa. For both systems, sampling was conducted along the catchment, estuary and coastal area.

Sampling was conducted during the wet and the dry season and four replicate samples of water and four replicate samples of sediment was collected. Environmental parameters measured were temperature, salinity, turbidity and pH and three replicate samples of each parameter were recorded at each site and within each system. Grain size analysis was also conducted using a sub-sample of all sediment samples collected with four replicates for each site analysed. A risk assessment as well as a disturbance index was also conducted for each system.

1.4 Thesis outline

Chapter 1 provides a general introduction on plastic and microplastic contamination and South Africa's contribution to plastic in the environment is highlighted. The research problem, aim and objectives are outlined as well as the delineation and limitations of the research.

Chapter 2 provides a literature review on plastic production and the characteristics of microplastics is described and the sources and pathways in which microplastics enter aquatic environments are discussed. Microplastic contamination in riverine (catchment), estuarine and coastal and marine environments, both internationally and within South Africa is discussed as well as the effects of land-use types and risks of microplastics to aquatic organisms. Additionally, the hydrodynamic conditions that can affect the movement and accumulation of microplastics within catchment, estuarine and coastal environments is discussed. Furthermore, a description of both study areas where the research has been conducted is provided.

Chapter 3 provides a detailed account of the methodology used to conduct this research. Field sampling methods for both water and sediment are outlined as well as the laboratory analysis. Microscope and FTIR analyses are outlined. The methods for collecting and analysing of the environmental parameters are outlined as well as the methods used to conduct both the disturbance index and polymer risk assessment. Additionally, the quality controls implemented during both field sampling and laboratory analyses as well as the statistical analyses carried out on the data are outlined.

Chapter 4 & 5 provides an overview of the results for the Olifants and Breede system, respectively. Each of these two content chapters will be submitted as standalone papers for publication, therefore, there might be some overlap in the methodology and context among these chapters.

Chapter 6 provides a general conclusion and recommendations for this research.

Chapter 2: Literature review

2.1 Introduction to plastic production

Polymers are large molecules that are made up of similar or equal subunits that have been bonded together (Geyer, 2020). These polymers are not of human invention, but rather occur naturally in various forms including cellulose, silk, rubber, hair, muscle and even DNA (Geyer, 2020). Plastic, however, is a product of human invention created from synthetic polymers (Ryan, 2015; Geyer, 2020).

In the 1850's, the first man-made polymer, although not fully synthetic, was produced by treating cellulose with nitric acid, thus creating the first thermoplastic (Mark, 1985; Geyer, 2020). Thermoplastics are a group of plastics that when heated, they melt, but when cooled, they harden (PlasticsEurope, 2019). The first truly synthetic polymer was produced by combining phenol with formaldehyde, creating the first synthetic thermoset (Mark, 1985; Geyer, 2020). Unlike thermoplastics, when heated, thermosets undergo a chemical change, forming an irreversible three-dimensional network (PlasticsEurope, 2019). This process means that thermosets cannot be re-melted or reformed once they have been set (PlasticsEurope, 2019).

The first modern plastic was polyvinyl chloride (PVC), which continues to be produced in large quantities ever since its discovery in 1872 (Geyer, 2020). Pure PVC is however too rigid and brittle to be extensively utilised (Geyer, 2020). Therefore, to make the material softer and more flexible, chemical additives that are now known as plasticizers were added to PVC in the 1920's, creating the first modern plastic (Geyer, 2020).

During the 1940s, plastic production began to increase due to growing shortages of other materials but also due to the versatile uses of plastic as a substitute for those materials (Geyer, 2020). This led to an increase in production capacity, with plastic producers seeking new markets (Geyer, 2020). With the demand for plastic fuelled by both economic growth and the emergence of modern consumer society, it led to a rapid increase in global plastic production (Geyer, 2020). Prior to 1950, the cumulative global plastic production ranged between 4 and 8 million tons (Geyer, 2020). By 1950, the annual global plastic production reached a significant 1.5 million tons, marking the beginning of the era of mass plastic production (Boucher & Friot, 2017; Thompson et al., 2024).

On average, pure polymers contribute 94% to global plastic production (Geyer, 2020). This includes polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene-terephthalate (PET),

polystyrene (PS), polyamide (PA), polyester (PY), polyurethane (PUR) and acrylic (Geyer, 2020; PlasticsEurope, 2022). Additives account for the remaining 6% of global plastic production, although the actual additive content of plastic can vary significantly by polymer and application (Geyer, 2020). Other types of additives include impact modifiers, colorants, antioxidants, heat stabilisers and lubricants (Geyer, 2020). All these additives are used to modify and enhance the properties of plastics, making many of them persistent and resistant to degradation (Ryan, 2015; Geyer et al., 2017).

2.2 Introduction to microplastics

Plastic production industries have made considerable efforts to slow the degradation of plastics in many applications (Ryan, 2015; Geyer et al., 2017). Despite these efforts, plastics are still susceptible to degradation over time. As plastics degrade, they can fragment into smaller plastic particles referred to as microplastics. Microplastics are widely defined as plastic particles ranging from 1 µm to 5 mm in size, and are composed of polymers, functional additives as well as chemical additives that have either been intentionally or unintentionally added to them (Frias & Nash, 2019; Hartmann et al., 2019; Thompson et al., 2024). These particles can then be subcategorised as either a primary or secondary microplastic. Primary microplastics are intentionally manufactured to be microscopic in size through processes such as grinding or extrusion (Cole et al., 2011; Browne, 2015; Thompson et al., 2024). They can be directly released into the environment in the form of plastic pellets or powders and are commonly found in cleaning, personal care and cosmetic products (Cole et al., 2011; Andrady, 2011; Boucher & Friot, 2017). Primary microplastics are however also used as the raw materials in the production of larger plastic products (Costa et al., 2010; Browne, 2015; Thompson, 2015; Raju et al., 2023).

Secondary microplastics, on the other hand, form from the fragmentation of larger plastic materials into smaller plastic particles (Ryan et al., 2009; Costa et al., 2010; Thompson et al., 2024). When these larger plastics are released into the environment, they progressively become brittle due to exposure to ultraviolet light, heat, humidity and aerobic conditions, eventually fragmenting into smaller particles (Barnes et al., 2009; Andrady, 2015; Thompson et al., 2024). This fragmentation can occur through processes such as biodegradation, photo-degradation, mechanical abrasion or even during regular use, resulting in the release of microplastics into the environment (Lechner, 2020). As a result, secondary microplastics are considered a significant source of microplastic contamination.

Microplastics come in various shapes, sizes and colours making them highly heterogeneous (GESAMP, 2019; Fu et al., 2020). These properties are crucial for monitoring because they can affect how microplastics behave and how they are distributed in the environment (GESAMP, 2019). Microplastics can be categorised into forms such as fibres, fragments, films, foams and spheres (GESAMP, 2019). Fibres, in particular, may be highly bioavailable due to their size and morphology, as smaller microplastics tend to be more bioavailable (Botterell et al., 2019). Additionally, the colour of microplastics can also influence their bioavailability as their colour can affect how easily they are found and how they interact with their surroundings (Wright et al., 2013; Fu et al., 2020). Certain colours might make microplastics more or less visible and can influence how they behave when exposed to environmental factors like light, weathering, biofilms or other substances (GESAMP, 2019).

The polymer type of microplastics also plays a significant role in their environmental behaviour. Different plastic polymers have varying densities, which determine whether a microplastic can float or sink. For example, low-density polymers such as PE (0.89 – 0.97 g/cm^3) and PP (0.89 0.91 g/cm^3) generally float, while high-density polymers like PS (1.04 – 1.08 g/cm^3) and PVC (1.3 – 1.58 g/cm^3) are more likely to sink (Wright et al., 2013; Botterell et al., 2019; Fu et al., 2020). These differences in microplastic characteristics contribute to their bioavailability and diverse distribution environment.

2.3 Sources and pathways of microplastics

Over the years, research on microplastics has made a considerable amount of effort to identify pathways and sources of contamination and to understand their environmental impact (Costa et al., 2010; Browne, 2015; Thompson, 2015). All plastic originates on land, where the majority of it is extensively utilised before polluting the environment (Horton & Dixon, 2018). Microplastics can enter the environment through various pathways such as wastewater treatment plants (WWTPs), drainage ditches or stormwater outlets and can originate from either point or diffuse (non-point) sources (Skalska et al., 2020). Point sources, such as wastewater effluents, urban and agricultural runoff, serve as direct sources of microplastic contamination (Horton et al., 2017; Skalska et al., 2020). In contrast, non-point sources represent contamination sources that are dispersed over larger areas such as littering, urbanisation and even atmospheric deposition (Horton et al., 2017; Skalska et al., 2020).

2.3.1 Point sources

Several point sources contribute to microplastic contamination in aquatic environments, with WWTPs being among the most well documented. Studies have reported that during wastewater treatment, microplastic concentrations decrease significantly, with removal rates exceeding 98% and 99% after secondary filtration processes (Murphy et al., 2016; Talvitie et al., 2017). However, despite these reductions, a small percentage remains within the effluent due the small size and buoyancy of microplastics (Skalska et al., 2020). Consequently, studies by Murphy et al. (2016) and Nizzetto et al. (2016) highlight that although the percentage may seem small, it can still amount to millions or even trillions of microplastics being released into aquatic environments. For example, McCormick et al. (2016) observed greater microplastic concentrations at sites downstream of WWTPs. Reynolds & Ryan (2018) also recorded significantly higher microplastic concentrations at sites receiving effluent from a sewage treatment facility. Hence, WWTPs are generally inefficient in removing microplastics.

In addition to effluents from WWTPs, another recognised point source which contributes to microplastic contamination are stormwater outlets transporting urban runoff into aquatic environments (Shruti et al., 2021). Stormwater outlets are designed to manage large volumes of rainwater, to prevent flooding (Weideman et al., 2020a). However, these outlets often become conduits, transporting contaminants, including microplastics, to aquatic environments during heavy rainfall events (Hitchcock, 2020; Shruti et al., 2021). Lutz et al. (2021) predicted that the estimated microplastic concentration for a representative storm drain is 760 microplastic particles per kg. Additionally, a study by Weideman et al. (2020a) estimated that between 60 – 570 tons of plastic are washed out of Cape Town, South Africa, annually, via stormwater outlets.

Agriculture drainage and runoff constitute another significant source and pathway of microplastic contamination, as sewage sludge, a by-product of WWTPs, is commonly used as fertiliser and applied directly to agricultural lands (Nizzetto et al., 2016). While sewage sludge contains beneficial nutrients and organic matter, it also contains synthetic chemicals and contaminants, including microplastics (McBride, 2003; Zubris & Richards, 2005; Yang et al., 2021). For instance, Horton et al. (2021) reported an average microplastic concentration ranging from 301 - 10 380 microplastics/g within treated sewage sludge. It is also estimated that throughout Europe 125 – 850 tons of microplastics are annually added to agricultural lands through the application of sewage sludge (Nizzetto et al., 2016; Horton & Dixon, 2018). Once applied

to agricultural lands, these microplastics may be retained within the sediment and subsequently enter aquatic environments during high rainfall events (Zubris & Richards, 2005; Horton et al., 2017). Additionally, the use and fragmentation of agricultural plastics, such as mulches, polytunnels, and commonly used fertilisers and pesticides containing various polymers, further contribute to microplastic contamination within the environment (Rillig, 2012; Steinmetz et al., 2016; Horton et al., 2017).

2.3.2 Diffuse (non-point) sources

As secondary microplastic are considered the dominant source of microplastics, plastic litter thus serves as a primary source of microplastic contamination, particularly in urban areas with a high population density (Öborn et al., 2022). As a non-point source, plastic litter is widespread throughout the world, often accumulating near aquatic environments through direct littering or indirect transport from landfill sites through wind advection or surface runoff (Horton & Dixon, 2018; Skalska et al., 2020; Öborn et al., 2022). Serving as a secondary source of microplastics, plastic litter undergoes fragmentation in terrestrial environments, through processes like photo-oxidative degradation and anthropogenic activities, and in aquatic environments due to hydrodynamic conditions (Andrady, 2011; Kataoka et al., 2019). A study by Scheurer & Bigalke (2018) reported that the majority of microplastics originate from the fragmenting of mesoplastics. Similarly, research conducted by Xiong et al. (2019) reported a positive correlation between microplastic concentrations and the abundance of mesoplastics.

Studies have also shown that microplastic concentrations are often elevated due to their proximity to sources of contamination (Grbić et al., 2020; Talbot & Chang, 2022). Serving as a non-point source, urbanisation can influence the accumulation of microplastics through various other sources, including population density, effluent discharge, surface runoff, litter and even atmospheric deposition (Horton et al., 2017; Kataoka et al., 2019). Studies by Yonkos et al. (2014) and Townsend et al. (2019) both reported positive correlations between microplastic concentrations and increased urbanisation and population density. Similarly, Kunz et al. (2023) reported a positive correlation between microplastic concentrations and the size of industrial, residential and traffic areas.

Although the atmospheric deposition of microplastics tends to be overlooked, recent research work now considers it as a significant source and pathway for microplastic contamination. Boucher & Friot (2017) reported that atmospheric deposition account for 7% of the microplastics in the ocean. This is linked to the lightweight nature of many microplastics as these particles can often become suspended in the air and

transported as urban dust (Dris et al., 2016; Dehghani et al., 2017). Airborne microplastics commonly originate from industrial emission, road and tyre wear, landfills, particle re-suspension, waste incineration, sludge and textile shedding (Gasperi et al., 2018; Skalska et al., 2020). Microplastics have been detected in the atmosphere of large urban cities particularly with high population densities (Wright et al., 2020) but also in remote locations (Bergmann et al., 2019; Aves et al., 2022), with wind and air currents facilitating their movements and leading to their deposition either on land or in aquatic environments.

Given that diffuse sources are dispersed over larger areas, it becomes difficult to pin-point their exact origin as opposed to point sources. Therefore, it becomes important to understand the transport mechanisms associated with the distribution of microplastics in the environment. Nonetheless, whether microplastics originate from point or non-point sources and pathways, these studies highlight their significant contribution to microplastic contamination in the environment.

2.4 Disturbance index of microplastics

On a broad scale, research on microplastics in aquatic environments have been linked to anthropogenic disturbances, with higher microplastic concentrations often reported in more urbanised areas where there are higher levels of anthropogenic activities (Kunz et al., 2023). Thus, it has been hypothesised that areas with greater sources of contamination will result in greater microplastic inputs in surrounding aquatic environments (Nel et al., 2016; Zhang et al., 2024).

Kunz et al. (2023) investigated the influence of land use on the concentration of microplastics in two river catchments in central Taiwan along an urban-rural gradient. The results showed a significant increase in the concentration of microplastics at the transition from rural to urban areas, with concentrations ranging between 0 particles/m^3 in rural areas to 230 particles/m^3 in urban areas (Kunz et al., 2023). Reports by Su et al. (2020) and Schell et al. (2021) also reported that microplastic contamination was linked to urban land-use and increasing levels of anthropogenic activities.

Similarly, research on microplastics in South African aquatic environments have also shown a link between the level of anthropogenic disturbances and the concentration of microplastics (Govender et al., 2020), suggesting that microplastic concentrations increases relative to an increase in proximity to anthropogenic disturbances. Naidoo et al. (2015) reported high microplastic concentrations in estuaries located in urban areas with microplastic concentrations decreasing in estuaries located further away from urban areas. Naidoo & Glassom (2019) reported higher microplastic concentrations in the Durban area along the

KwaZulu-Natal coastline in South Africa which was also attributed to high levels of urbanisation in the surrounding area. Additionally, a study by Umlauf (2019) also reported higher microplastic concentrations in urban areas compared to rural areas along the Crocodile River in Gauteng, South Africa.

Given the general trend, Govender et al. (2020) adopted a disturbance index where various forms of disturbances were assessed based on a scoring system by Appalasamy et al. (2020). Some examples of anthropogenic disturbances assessed in the disturbance index include development, agriculture, industries, effluent from urban sources, pollution, maritime and /or fishing activities (Govender et al., 2020). This index was conducted to understand the potential influence that surrounding anthropogenic disturbances may have on the concentration of microplastics in aquatic environments.

Based on the disturbance index, Govender et al. (2020) reported that microplastic concentrations increased with increasing levels of anthropogenic disturbances. Similarly, Johnson et al. (2023) reported that aquatic systems exposed to high levels of anthropogenic disturbances appear to be more at risk to microplastic contamination than systems exposed to moderate and/or low levels of anthropogenic disturbances. The study also found that a greater proportion of aquatic organisms ingested microplastics in systems with high levels of disturbances compared to systems with low or moderate disturbance levels (Johnson et al., 2023). These findings support the notion that microplastic concentrations increases relative to an increase in anthropogenic disturbances, while also indicating that organisms in more disturbed areas are more likely to ingest microplastics. Thus, investigating the spatial distribution of microplastics along South African aquatic environments is needed as it can provide important information on the potential sources and pathways through which these microplastics enter these environments.

2.5 Hydrodynamic conditions affecting the movement and distribution of microplastics

Hydrodynamics refers to the movement of water and the forces that act on it (Ji, 2017). This movement serves as the primary mechanism for transporting and distributing nutrients, sediments and pollutants within aquatic environments (Ji, 2017). Hydrodynamic conditions are integral components of complex aquatic environments, with water of different types, moving at different scales (Ji, 2017).

For example, aquatic environments can be classified into freshwater, brackish water and marine water. Freshwater can be classified as either being lentic or lotic. Lentic refers to standing water bodies (lakes & ponds) whereas lotic refers to flowing water bodies (rivers & streams) (Harvey & Schmadel, 2021). Typical sources of brackish water are estuarine systems, the transitional areas where rivers meet the sea and are

thus derived from the mixing of freshwater and marine water (Sandrin et al., 2009; Whitfield, 2021). Brackish water is thus influenced by both the flow of freshwater and marine water. In coastal and marine environments, marine waters are characterised by high levels of salinity (33 – 35 ppt) and is thus denser than freshwater (Sandrin et al., 2009; Khan & Rajshekhar, 2020). Marine waters are also subjected to considerable mixing and movement caused by the actions of currents and tides, wind and/or upwelling events (Sandrin et al., 2009).

Therefore, the differences in these different types of water does not only affect the distribution of nutrients and the physicochemical conditions of aquatic environments but can also affect the distribution of algae, sediments and contaminants, amongst others (Ji, 2017). Thus, the hydrodynamic conditions of aquatic environments can carry pollutants from their source, causing environmental impacts in areas far removed from the original point of pollution.

2.5.1 Hydrodynamic conditions of river catchments

2.5.1.1 Rainfall

Rainfall over southern Africa is highly variable. The Southern Hemisphere high-pressure systems influence this variability within South Africa (Rouault et al., 2024). Rainfall in southern Africa is characterised by distinct winter and summer rainfall patterns, with the west and southwest coasts constituting the winter rainfall region, while the south coast experiences rainfall throughout the year (Weldon & Reason, 2014; Rouault et al., 2024).

During winter, the rainfall along the west and southwest coasts occurs due to temperate systems such as cold fronts and cut-off low-pressure systems (Landman et al., 2017; Rouault et al., 2024). These systems enhance rainfall during winter, with cut-off low-pressure systems significantly contributing to the rainfall over South Africa (Rouault et al., 2024). Cold fronts also regularly sweep over the southern parts of the country, bringing rain to the south-western and north-western Cape and also extending it to the south coast and eastward (Landman et al., 2017). However, during summer, the South Atlantic high-pressure system is what influences rainfall along the west, as it creates subsidence which prevents rainfall from occurring outside of the winter months (Rouault et al., 2024).

Along the south coast, summer rainfall occurs through convection which is driven by large-scale dynamics (Landman et al., 2017; Rouault et al., 2024). These dynamics include tropical-temperate trough events,

where a tropical trough or low-pressure system combines with a westerly wave, resulting in widespread rainfall that can occur over several consecutive days (Landman et al., 2017). Although, the country is influenced by the Southern Hemisphere high-pressure systems which prevent rain from occurring, a thermal low can occur over the subcontinent during summer. This thermal low can cause a break in the subsidence associated with the high-pressure systems, resulting in summer rainfall (Rouault et al., 2013; Rouault et al., 2024).

The summer rainfall along the south coast is also strongly linked to the El Nino Southern Oscillation (ENSO) (Weldon & Reason, 2014; Rouault et al., 2024). The ENSO is a natural phenomenon involving prolonged warming or cooling of the east-central Pacific Ocean Sea surface temperatures, which affects climate and weather patterns globally (Weldon & Reason, 2014; Landman et al., 2017; Rouault et al., 2024). The ENSO influences the rainfall along the south coast by increasing the number of cut-off low-pressure systems, leading to enhanced rainfall during the summer months (Weldon & Reason, 2014).

The amount of rainfall an area receives can determine the concentration of microplastics in the water column. As rainfall becomes increased, river flow becomes increased resulting greater microplastic inputs, re-suspension and overall accumulation of microplastics within the water column (Cheung et al., 2016; Talbot & Chang, 2022). However, if rainfall becomes reduced, river flow becomes reduced resulting in decreased microplastics concentrations in the water column but allowing for increased settling rates among the sediment (Nel et al., 2018; Faulstich et al., 2022).

2.5.1.2 River flow

River flow is highly variable and is dependent on seasonality. During the wet season, river flow increases relative to an increase in precipitation (Malli et al., 2022). In contrast, during the dry season, river flow decreases relative to a decrease in precipitation (Malli et al., 2022). River flow is therefore increased during the wet season but decreases during the dry season.

River flow can thus influence the movement accumulation of microplastics, although this does vary seasonally. During the dry season when river flows rates are reduced, microplastics can have extended residency times in rivers, leading to their accumulation (Li et al., 2020; Talbot & Chang, 2022). However, during the wet season, increased river flow rates can exacerbate microplastic inputs transporting them from

terrestrial to aquatic environments, while also re-suspending microplastics that have become trapped among the sediment due to the increased turbulence (Hurley et al., 2020; Talbot & Chang, 2022).

2.5.1.3 Flow regime

- Perennial flow

Perennial rivers are characterised by flows that continue throughout the year and thus have a low variability (Uys & O'Keeffe, 1997; Ayers et al., 2024). These flows are predictably higher during the wet season and are often accompanied by floods (Warfe et al., 2014). In contrast, flows are generally lower during the dry season, however, inputs from groundwater are able to maintain base flows (Warfe et al., 2014).

- Intermittent flow

Rivers with intermittent flows may cease and become dry at certain parts along their length (Uys & O'Keeffe, 1997; Busch et al., 2020). This dry phase can occur for a variable period, ranging from annually to two or more years (Uys & O'Keeffe, 1997; Busch et al., 2020). The flow of these rivers, however, may recommence, often occurring seasonally, depending on the climatic conditions and the predictability of rainfall as well as its seasonal connection to groundwaters (Uys & O'Keeffe, 1997; Busch et al., 2020; Brinkerhoff et al., 2024).

- Ephemeral flow

Ephemeral rivers are characterised by being dry for longer periods of time as they are disconnected from groundwater all year round with flows occurring at shorter periods only in response to rainfall events (Uys & O'Keeffe, 1997; Busch et al., 2020; Brinkerhoff et al., 2024). River flows are thus absent for most of the year, however, during extreme rainfall events, sporadic flows and high intensity floods may occur (Uys & O'Keeffe, 1997; Busch et al., 2020; Brinkerhoff et al., 2024). These rivers support a series of pools along certain parts of its river channel (Uys & O'Keeffe, 1997).

- Episodic flow

Rivers with episodic flows refer to river systems with highly variable flows. These rivers are characterised by flows and floods which only occur because of extreme rainfall events (Uys & O'Keeffe, 1997). These rivers may remain dry for more than five years and may only flow once every few years (Uys & O'Keeffe, 1997).

Hence, rivers with perennial flow regimes are likely to accumulate fewer microplastics due to consistent flows experienced by these river systems resulting in increased flushing rates, as opposed to rivers with a more seasonal flow regime. For example, Faulstich et al. (2022) reported lower microplastics concentrations in the sediment of perennial and ephemeral rivers due to the annual and seasonal flows enabling microplastics to become remobilised after having been deposited in the sediment. In contrast, higher microplastic concentrations were observed in river systems characterised by low flow rates, which lead to greater microplastic deposition (Faulstich et al., 2022).

2.5.1.4 Sedimentation

Sedimentation refers to the removal of particulate matter from the water column as it settles to the bottom (Bloesch & Uehlinger, 1986; Ostrovsky et al., 2014). This process often occurs in aquatic environments with low hydrodynamic conditions as the resulting lowered turbulence can lead to an increase in the deposition of particles (Horton & Dixon, 2018; Nel et al., 2018). Sedimentation is thus more likely to occur during the dry season as reduced river flow rates due to the cessation of precipitation can enable the settling of particles, unlike during the wet season when hydrodynamic conditions, such precipitation and river flow, increase, leading to an increase in turbulence (Nel et al., 2018).

Given that sedimentation is more likely to occur during the dry season, it is thus expected that the sedimentation of microplastic particles will also occur during the dry season as opposed to the wet season, due to the reduced hydrodynamic conditions facilitating the settling of particles (Nel et al., 2018; Alves & Figueiredo, 2019; Yuan et al., 2023). The sedimentation of microplastics can however become enhanced as result of high-density particles, as they are more likely to settle and accumulate among the sediment (Horton & Dixon, 2018). Additionally, sedimentation tends to favour environments dominated by fine-grained sediment as these environments are typically characterised by low hydrodynamic conditions (Gillanders & Kingsford, 2002; Biltcliff-Ward et al., 2022). Moreover, environments dominated by fine-grained sediment can further enhance the sedimentation of particles as the fine grains are able to adhere to microplastics, leading to an increase in the density of particles causing them to sink (Andersen et al., 2021).

2.5.2 Microplastic contamination in river catchments

Given that the majority of microplastics in the ocean stem from land-based sources, understanding the pathways of microplastic contamination from inland freshwater environments to the marine environment

becomes a prerequisite in developing and implementing appropriate mitigation strategies (Meijer et al., 2021). Freshwater environments such as river catchments are widely recognised as both a major source and sink for microplastic contamination (Anderson et al., 2016; Nel et al., 2018). Microplastics can enter these environments through various pathways, including being blown or washed into these environments via landfills (Barnes et al., 2009), wastewater (Murphy et al., 2016), storm drains (Preston-Whyte et al., 2021), sewage treatment (Reynolds & Ryan, 2018), or through runoff (Horton et al., 2017).

Numerous studies have provided evidence of microplastics reaching marine environments through rivers. (Lebreton et al., 2017) estimated that between 1.51 and 2.41 million tonnes of plastic waste enters the ocean through rivers, annually. According to another study, Meijer et al. (2021) estimated that more than 1000 rivers account for 80% of the global plastic emissions into the ocean, which ranges between 0.8 and 2.7 million tonnes, annually. However, there are many uncertainties associated with these models, including the lack of data and the lack of comprehension in terms of the sources of plastic and its associated transport mechanisms (Lebreton et al., 2017; Meijer et al., 2021).

The microplastics that enter riverine environments can often become retained and accumulate within these systems, serving as sinks for contamination (Anderson et al., 2016). However, their role as sinks for microplastics is only temporary due to the variable retention time of these lotic systems (Nel et al., 2018). Since rivers are characterised by their flowing water, their retention time is much lower compared to lentic systems, thus allowing for the distribution of microplastics (Soballe & Kimmel, 1987; Nel et al., 2018). Consequently, it is important to consider their roles as sources of contamination, as rivers serve as significant pathways for transporting land-based microplastics to the ocean.

2.5.2.1 Microplastic contamination in South African river catchments

Given South Africa's status as a water-scarce country, the sustainability and protection of its freshwater resources is of critical socio-economic and ecological importance (Verster et al., 2017). Freshwater river catchments represent one of the most complex environments regarding microplastic transport and retention, serving as both a source and a sink (Verster & Bouwman, 2020). While numerous studies have mainly researched and continue to conduct research on microplastic concentrations along different parts of the South African coastline, over the last few years, research on microplastics in South African freshwater environments have increased (Saad et al., 2022; Apetogbor et al., 2023; Saad et al., 2024a; Samuels et al., 2024; Dahms & Greenfield, 2025).

In South Africa, Graham et al. (2024) investigated microplastics in the Orange-Senqu River basin, reporting average microplastic concentrations of 13 ± 27.5 items/L^{-1} in the water and 825 ± 1493 particles/kg^{-1} in the sediment, with low flow rates increasing the sedimentation of microplastics while increased flow rates facilitated the resuspension and flushing of microplastics. In the Zandvlei catchment in Cape Town, South Africa, Samuels et al. (2024) reported average microplastic concentrations of 2.62 ± 0.41 MPs/L in the water and 70.23 ± 7.36 MPs/kg in the sediment with higher concentrations occurring during the wet season which was attributed to an increase in microplastic inputs during the wet season. In contrast, Dahms & Greenfield (2025) reported average microplastic concentrations of 518 ± 2556 particles/m^{-3} in the water and 545 ± 2 740 particles/kg^{-1} in the sediment in three different rivers in Limpopo, South Africa, with higher microplastic concentrations occurring during the dry season suggesting that microplastics become trapped in rivers during periods of low flow.

2.5.3 Hydrodynamic conditions of estuarine environments

According to South Africa's National Biodiversity Assessment of 2018, an estuary is defined as a partially enclosed permanent water body, which can either be continuously or periodically open to the sea on decadal time scales, extending as far as the upper limit of tidal action, salinity penetration or back-flooding under closed mouth conditions (Van Niekerk et al., 2019).

2.5.3.1 Estuary dynamics (mouth state)

In South Africa there are 290 estuaries, all of which were classified based on their key features and dominant physical processes such as their size, connection to the sea, geomorphology, maximum water level, average tidal amplitudes and level of salinity, mixing process, sediment stability as well as their mean annual runoff (van Niekerk et al., 2020). Moreover, these estuarine ecosystems were further classified based on their biogeographical region (tropical, sub-tropical, warm- and/or cool temperate), resulting in 22 estuarine ecosystems and nine estuary types (van Niekerk et al., 2020). As the present study focuses specifically on the Olifants and the Breede systems, only predominantly open estuaries are described here.

- Predominantly open estuaries

Predominantly open estuaries are linear systems (10 – 7 500 ha) with restricted inlets that are open to the sea at least 90 % of the time (van Niekerk et al., 2020). Some systems can however be permanently open to the sea either due to perennial river flow or the presence of large tidal prisms (van Niekerk et al., 2020).

Tidal amplitudes within these systems range between 0.75 – 1.5 m with mixing processes dominated by both fluvial inputs and tidal action, resulting in both vertical and horizontal salinity gradients (van Niekerk et al., 2020). Salinity levels in these systems range between 0 – 40 ppt, with low river flows and high evaporation rates facilitating hyper-salinity at the upper reaches of these systems (van Niekerk et al., 2020). Mean annual runoff within these systems varies considerably ranging between 10 – 1 790 × 10^6 m^3 with regular flooding conditions resulting in relatively mobile sediments (van Niekerk et al., 2020).

2.5.3.2 Freshwater input

In South Africa, freshwater inflow is highly variable and unpredictable, with freshwater inflows fluctuating between floods, being extremely low to zero (Van Niekerk et al., 2019). Many of the estuaries in South Africa are thus dependent on groundwater (Van Niekerk et al., 2019; van Niekerk et al., 2020). However, during periods of floods, estuaries can become river mouths with no seawater entering the system (Van Niekerk et al., 2019). In contrast, when there is little or no freshwater inflow, estuaries often become cut off from the sea by the formation of a sandbar and can become either fresh or hypersaline (Van Niekerk et al., 2019; van Niekerk et al., 2020).

In estuarine systems, freshwater inflow is determined by the size and shape of the catchment, which is what controls the magnitude and flow distribution, as well as by the climatic conditions as freshwater inflow can vary seasonally. During the wet season, high precipitation leads to increased freshwater input from the river catchment into the estuary (Whitfield et al., 2008; Malli et al., 2022). In contrast, during the dry season, decreased precipitation results in low to no freshwater input (Whitfield et al., 2008; Malli et al., 2022).

Freshwater inflow can thus influence the concentration of microplastics in the estuary. Freshwater inflow has been linked to the re-suspension and flushing of contaminants, such as microplastics. Studies have reported greater microplastic concentrations in estuaries during the wet season due to increased freshwater inflow facilitating greater microplastic inputs into the estuary (Lima et al., 2015; Cheung et al., 2016; Zhao et al., 2019). Conversely, other studies have reported greater microplastics concentrations in estuaries during the dry season, due to the reduced freshwater inflow enhancing microplastic deposition (Costa et al., 2011; Han et al., 2020; Govender et al., 2020).

2.5.3.3 Tidal input

The tidal input within an estuary occurs on both a daily and monthly time scale. On a daily scale, the estuary is influenced by the ebb and flood tides. During ebb tides, the water gets flushed out of the estuary toward the sea, creating a low water level (Malli et al., 2022). In contrast, during flood tides, water enters the estuary, flowing in an upstream direction, creating a high-water level (Malli et al., 2022). Additionally, on a monthly time scale, the estuary is influenced by the spring and neap tides (Malli et al., 2022) (These monthly tides will be expanded on in section 2.5.5.3).

As a result of the daily tides experienced by estuaries, it can influence the distribution and accumulation of microplastics. During ebb tides, microplastics will be flushed out of the estuary toward the coast, while during flood tides, microplastics will enter the estuary. Thus, estuaries dominated by flood tides will likely accumulate more microplastics as opposed to estuaries dominated by ebb tides (Gallagher et al., 2016; Peller et al., 2022).

2.5.3.4 Tidal regime

- Macro-tidal regime

In estuaries with a macro-tidal regime, the exchange of freshwater and seawater during tidal cycles is of a much greater volume than the water exchanged in estuaries with a meso- or micro-tidal regime (Pinheiro et al., 2021). Macro-tidal estuaries have large tidal ranges, often greater than 4 meters (Monbet, 1992; Whitfield & Elliott, 2012; Whitfield et al., 2023). As a result, they experience higher hydrodynamic energy, leading to greater mixing and movement of water compared to meso-tidal and micro-tidal estuaries (Vermeiren et al., 2016).

- Meso-tidal regime

Meso-tidal estuaries have intermediate tidal ranges, averaging between 2 and 4 meters (Monbet, 1992; Whitfield & Elliott, 2012). With this tidal range, estuaries can display varying characteristics. For example, these estuaries may become stratified, in which a dense layer of seawater forms at the bottom of the water column, with a less dense layer of freshwater forming at the surface of the water (Pritchard, 1952; Boothroyd, 1978). Alternatively, the water column may be well mixed, resulting in more stable conditions throughout the estuary (Pritchard, 1952; Boothroyd, 1978).

- Micro-tidal regime

In estuaries with a micro-tidal regime, the combined effects of wind, wave action and freshwater input determines their overall circulation and mixing patterns due to the relatively small tidal input experienced by these estuaries (Monbet, 1992; Postacchini et al., 2023). Micro-tidal estuaries have small tidal ranges, averaging less than 2 meters (Monbet, 1992; Whitfield & Elliott, 2012; Whitfield et al., 2023). Thus, micro-tidal estuaries typically have lower hydrodynamic energies compared to meso- and macro-tidal estuaries.

Tidal regimes play a critical role in controlling the distribution and accumulation of microplastics within estuaries due to influencing hydrodynamic environmental conditions. Estuaries with a meso- and macro-tidal regime are thus more likely to accumulate fewer microplastics compared to estuaries with a micro-tidal regime as increased tidal ranges enhance circulation, sediment resuspension and flushing, facilitating the distribution of microplastics out the estuary into adjacent coastal waters (McLusky et al., 1993; Vermeiren et al., 2016). In contrast, micro-tidal estuaries which experience lower hydrodynamic conditions and reduced flushing rates, may result in longer residency times for microplastics, leading to greater microplastic accumulation within estuaries. As a result, tidal regime is an important physical driver influencing microplastic distribution and accumulation in estuarine environments.

2.5.3.5 Salinity gradient

The salinity gradient in an estuary varies depending on the relative balance between outflowing freshwater and incoming seawater (McLusky et al., 1993; Vermeiren et al., 2016). These variations can affect the turbulence within estuaries, subsequently affecting the mixing, transport and concentration of particles within these environments (Zhang, 2017; Zhao et al., 2019). Salinity gradients are commonly classified into three categories: highly stratified, moderately stratified and vertically homogeneous.

- Highly stratified (salt-wedge) estuaries

Highly stratified estuaries are formed at the interface of the estuary, where freshwater and seawater meet (Malli et al., 2022). In these estuaries, freshwater enters at the upper reaches and is the dominant source of flow (Kowalewska-kalkowska & Marks, 2014). At the lower reaches, seawater enters, however its flow within the estuary is relatively weak and thus vertical mixing is negligible (Kowalewska-kalkowska & Marks, 2014). As a result, two distinct layers are formed within these estuaries, a dense layer of seawater at the bottom (salt-wedge) and a less dense layer of freshwater at the surface (McLusky et al., 1993; Kennish,

2016; Vermeiren et al., 2016). The vertical salinity found in these estuaries are thus higher than those found in partially and well-mixed estuaries.

- Moderately stratified (partially mixed) estuaries

Moderately stratified estuaries are formed as a result of its moderate to strong tidal input and weak to moderate freshwater input, resulting in the partially mixing of water, which occur at different depths (McLusky et al., 1993; Kowalewska-kalkowska & Marks, 2014; Kennish, 2016; Vermeiren et al., 2016). In these estuaries, the vertical mixing of freshwater and seawater are facilitated by both river flow and tidal dynamics (Kennish, 2016). As a result, the salinity in these estuaries increase toward the lower reaches of the estuary, in both the bottom and surface layers of the water, as well as with increasing depth (Kennish, 2016). Thus, the vertical salinity gradient found within moderately stratified estuaries is lower than the salinity gradient found within highly stratified estuaries.

- Vertically homogenous (well-mixed) estuaries

Vertically homogenous estuaries are formed as a result of strong tidal flow and weak freshwater input (Kowalewska-kalkowska & Marks, 2014). The strong tidal input in these estuaries is what contributes to the complete vertical mixing of the estuary (Kennish, 2016). These estuaries are dominated by freshwater at the upper reaches, brackish water at the middle reaches and seawater at the lower reaches of the estuary (Kennish, 2016). As a result of its complete vertical mixing, the salinity gradients within these estuaries are practically uniform (Kowalewska-kalkowska & Marks, 2014).

Salinity gradients and the mixing of freshwater and seawater entering estuarine environments are important factors that can affect the movement of microplastics within these environments (Zhang, 2017). Highly stratified estuaries may accumulate more microplastics as they receive greater inputs from freshwater sources and they have longer retention times than partially and well-mixed estuaries (McLusky et al., 1993; Vermeiren et al., 2016). However, the accumulation of microplastics in highly stratified estuaries does vary seasonally. During the dry season when river flow becomes reduced, the formation of the salt-wedge in highly stratified estuaries allows microplastics originating from the river to be trapped at the upper reaches, while microplastics originating from marine origin are trapped at the lower reaches of the estuary (Lima et al., 2015). Then during the wet season when river flow becomes increased and the salt-wedge becomes diminished, this increases microplastic concentrations downstream due to the increased flushing rates

(Lima et al., 2014). Thus, highly stratified estuaries are considered temporary sinks for microplastic contamination during the dry season.

Conversely, partially and well-mixed estuaries receive greater microplastic inputs from coastal and marine environments. These estuaries may thus also accumulate microplastics as the degree of mixing that takes place in these estuaries can generate turbidity currents, resulting in a turbidity maximum zone (TMZ) (McLusky et al., 1993; Vermeiren et al., 2016; Malli et al., 2022). Thus, during high tides, any suspended particles that enter the estuary can settle and become deposited in the sediment due to the increased turbulence (McLusky et al., 1993; Vermeiren et al., 2016; Malli et al., 2022). These estuaries can thus also accumulate microplastics. However, given that these estuaries have high flushing rates identifying these estuaries as either a source or sink for microplastics has yet to be determined (McLusky et al., 1993; Vermeiren et al., 2016).

2.5.4 Microplastic contamination in estuarine environments

Estuaries, as the interface between terrestrial and marine environments, receive a wide range of both land-based and sea-based sources of microplastics (Sadri & Thompson, 2014; Govender et al., 2020). They also serve as major conduits, transporting microplastics from rivers into coastal and marine environments (Sadri & Thompson, 2014; Naidoo et al., 2015). Estuarine environments are among the most valuable ecosystems in the world (Lamberth & Turpie, 2003; Vermeiren et al., 2016) though they have however also become the most impacted, with the proliferation of microplastics posing a major threat to marine life (Naidoo et al., 2016; Naidoo et al., 2019).

Research on the occurrence of microplastics has been reported on in estuaries worldwide, across different environmental mediums. Research on microplastics in estuaries has been reported in surface water (Zhao et al., 2014; Yan et al., 2019), estuarine sediment (Xu et al., 2020), the sea surface microlayer (Gray et al., 2018) as well as in estuarine biota (Naidoo et al., 2016; Lima et al., 2014). With the research that has been conducted, it is relatively clear that estuaries are sinks for microplastics, however, just like freshwater environments, their variable retention time allows for these sinks to become sources, transporting microplastics from rivers to coastal and marine environments (Nel et al., 2018; Vermeiren et al., 2016).

According to Vermeiren et al. (2016), the role of estuaries in transporting microplastics to coastal and marine environments is significantly influenced by their hydrodynamic conditions. For example, Browne et

al. (2010) reported on microplastic concentrations in the Tamar Estuary and found that wind direction can influence the distribution of microplastics, with greater microplastic concentrations accumulating at sites downwind, along the estuarine shoreline. Zhao et al. (2014) reported high microplastic concentrations in the Yangtze Estuary in China (4137.3 ± 2461.5 n/m^3) with freshwater input from rivers confirmed as being a major source of microplastic contamination in the marine environment. Similarly, Cheung et al. (2016) found that during increased freshwater input, the Pearl River Estuary was a major source of microplastics to beaches along the west coast of Hong Kong.

2.5.4.1 Microplastic contamination in South African estuarine environments

Estuaries are among the most productive systems due to their high nutrient input and provision of sheltered habitats and nursery grounds for aquatic organisms (Van Niekerk et al., 2019). In South Africa, estuaries play an important role in serving as a nursery area for many fish and invertebrate species to complete their life cycle with an estimated nursery value of R 695 million per annum (Van Niekerk et al., 2019). Additionally, these estuaries also significantly contribute toward human livelihoods given the wide range of resources that are harvested for nutritional and health purposes as well as for energy and raw materials (Van Niekerk et al., 2019).

Despite their ecological and socio-economic importance, estuaries are faced with increasing pressures from anthropogenic activities, which impact on estuarine productivity and the provision of ecosystem services (Van Niekerk et al., 2019). In South Africa, estuaries constitute one of the most threatened ecosystems in the country (Turpie et al., 2002; Van Niekerk et al., 2019). Major pressures faced by South African estuaries include, flow modifications, pollution, exploitation of resources, land-use and development, estuary mouth manipulation as well as biological invasions (Van Niekerk et al., 2019). All these pressures faced by estuaries are known to significantly contribute toward their decline and may even lead to additional pressures (Van Niekerk et al., 2019), such as the introduction of contaminants like microplastics, into these systems.

Research on microplastics in South African estuarine systems have increased and often focus on abundance estimates. For example, Boshoff et al. (2023) reported an average microplastic concentration of 91 microplastics kg^{-1} in the sediment of the Knysna Estuary along the south coast of South Africa. Johnson et al. (2023) reported average microplastic concentrations of 177 MP particles/L and 76 MP particles/L in the water and 99 MP particles/kg and 82 MP particles/kg in the sediment of the Durban and Mngazana

Estuary, respectively. Boshoff et al. (2025) also reported microplastic concentrations ranging between 1.7 ± 1.6 and 2.5 ± 1.4 MPs/m^3 in the water and 23.5 ± 24.9 and 30.1 ± 22.1 MP/kg in sediment of four cool-temperate estuaries located along the South African coastline.

2.5.5 Hydrodynamic conditions of coastal environments

2.5.5.1 Seasonality

Seasonally, there are distinct wet and dry seasons. During the wet season, precipitation is high leading to high river flows and freshwater discharge (Malli et al., 2022). In contrast, during the dry season, precipitation is decreased, leading to low river flows (Malli et al., 2022). South Africa experiences distinct wet and dry seasons. On the west and southwest coasts, the wet season occurs during the winter months (June to August), while the dry season occurs during the summer months (December to February) (Landman et al., 2017; Rouault et al., 2024). In contrast, the south coast experiences a permanent wet season due to consistent annual rainfall, which is particularly dominant during the summer months (Rutherford et al., 2006; Weldon & Reason, 2014; Rouault et al., 2024). However, in some areas of the south coast, such as those falling within the bimodal rainfall transition zone, two rainfall patterns are experienced, with most rainfall occurring during the winter months (Rutherford et al., 2006; Weldon & Reason, 2014).

The fluctuation between the wet and the dry seasons can determine the concentration of microplastics. During the wet season when rainfall and river flow is high, it can result in higher microplastic concentrations within the water column due to increased inputs from surface runoff, stormwater and tributaries (Zhao et al., 2020; Piehl et al., 2021; Ariefdien et al., 2024). Additionally, the turbulence from increased rainfall and river flow during the wet season, can allow microplastics to become re-suspended in the water column (Lima et al., 2015; Dahms et al., 2020). However, during the dry season, higher microplastic concentrations is likely to occur in sediment as the low rainfall and river flow rates enhance microplastic deposition (Costa et al., 2011; Nel et al., 2018). Hence, microplastic concentrations increase in the water column during the wet season and increases in sediment during the dry season.

2.5.5.2 Currents

South Africa is uniquely situated between two major boundary currents, the Benguela and the Agulhas Current (Hutchings et al., 2002; South African National Biodiversity Institute, 2019). The west coast of

South Africa is influenced by the Benguela Current which extends from Cape Agulhas at the southern tip of Africa to Cape Frio in northern Namibia (Hutchings et al., 2009; James et al., 2013; South African National Biodiversity Institute, 2019). Whereas the south coast of South Africa is influenced by the Agulhas Current which flows southward along the south-east coast of Mozambique (Lutjeharms, 2006b; South African National Biodiversity Institute, 2019).

- Benguela Current

The Benguela Current is a significant ocean current, just off the southwestern coast of Africa along the Atlantic Ocean (Fennel, 1999; Harris et al., 2019). It is a northward flowing current that is part of one of the ocean's large-scale circulation patterns, the subtropical gyre (Fennel, 1999; Branch et al., 2010; Harris et al., 2019). The Benguela Current is primarily driven by large-scale wind patterns and thermohaline forcing, which involves variations in the temperatures and salinities affecting the ocean (Garzoli & Gordon, 1996; Fennel, 1999; Harris et al., 2019). As for the currents closer to the coast, it is referred to as the Benguela Upwelling System and is driven by local wind patterns (Nelson & Hutchings, 1983; Fennel, 1999; Bordbar et al., 2021).

In the Benguela Upwelling System, distinct characteristics are exhibited among its northern and southern regions. In the northern region, upwelling is continuous throughout the year (Shannon & Pillar, 1986; Bordbar et al., 2021). However, in the southern region, upwelling varies as a result of seasonal variations (Shannon & Pillar, 1986; Bordbar et al., 2021). The force of upwelling is controlled by ocean dynamics. When the wind blows parallel to the coastline, in a direction toward the equator, it pushes surface coastal waters offshore, a process known as Ekman transport (Schumann et al., 1982; Bordbar et al., 2021). These surface waters are then replaced by deeper waters upwelled near the coast. Originating from the ocean depths, these upwelled waters are cold and nutrient rich (Branch et al., 2010; Harris et al., 2019). As they reach the sunlit euphotic zone of the ocean, the nutrients they provide help to sustain phytoplankton populations, leading to a high primary productivity (Schumann et al., 1982; Branch et al., 2010; South African National Biodiversity Institute, 2019).

- Agulhas Current

The Agulhas Current is a major western boundary current that is part of the Agulhas Current System (Harris et al., 2019). Flowing southward, the current transports warm, nutrient-poor waters from the western

Indian Ocean along the east and south coasts of South Africa (Branch et al., 2010; James et al., 2013; Harris et al., 2019). The Agulhas Current is swift, and as a western boundary current, it closely follows the continental slope until it reaches the southern tip of the Agulhas Bank (Roberts et al., 2010; James et al., 2013; Harris et al., 2019). At this point, the Agulhas Current separates from the continental slope where it undergoes retroflection (Roberts et al., 2010; Biastoch et al., 2024).

During the retroflection process, the Agulhas Current changes its direction by turning back on itself (Lutjeharms, 2006a; Harris et al., 2019). As a result, it releases warm core rings or large, swirling masses of warm water, commonly referred to as eddies, into the South Atlantic Ocean (Holloway, 1985; Roberts et al., 2010; James et al., 2013; Harris et al., 2019). However, the majority of its water remain contained within its swift re-curvature before flowing back into the Indian Ocean as the Agulhas Return Current (Lutjeharms & Ansorge, 2001; Lutjeharms, 2006a; Fadida et al., 2021).

These ocean currents play a significant role in the movement and accumulation of microplastics. The Benguela Current, can drive floating microplastics offshore during upwelling events, while also potentially redistributing high density microplastics back into the water column after having settled (Collins & Hermes, 2019; Ryan, 2020a; Ryan et al., 2021). In contrast, the Agulhas Current can drive floating microplastics from the east coast southward into the Atlantic Ocean (Collins & Hermes, 2019; Ryan, 2020a). Meanwhile, high density microplastics are more likely to become entrained by the Agulhas Current as they become redistributed by the circulation of deeper waters linked to the Agulhas Retroflection (Collins & Hermes, 2019; Ryan, 2020a).

2.5.5.3 Tides

Every day, twice a day, the tide rises and falls (Branch et al., 2010; Harris et al., 2019). Tides vary based on changes in positions and alignments of the sun and moon relative to the earth (Kennish, 2016; Unnikrishnan, 2022). Thus, when the positioning of the sun and moon change, the tides change. When the sun is closest to the earth at perihelion and similarly when the moon is closest to the earth at perigee, the gravitational force it exerts is stronger, resulting in a greater tidal range (Kennish, 2016; Unnikrishnan, 2022). In contrast, when the sun is furthest away from Earth at aphelion and when the moon is furthest away from Earth at apogee, the gravitational force it exerts is much weaker, resulting in smaller tidal ranges (Kennish, 2016; Unnikrishnan, 2022).

- Diurnal/semidiurnal tides
    - Low tide

Low tides are referred to as the minimum height that is reached by a falling tide (National Oceanic and Atmospheric Administration, 2001; Ji, 2017). During each tidal day, two low tides occur (South African National Biodiversity Institute, 2019). These tides should be approximately equal in height for each tidal day (National Oceanic and Atmospheric Administration, 2001).

    - High tide

High tides are referred to as the maximum height that is reached by a rising tide (National Oceanic and Atmospheric Administration, 2001; Ji, 2017). Like that of low tides, two high tides occur during each tidal day (South African National Biodiversity Institute, 2019). These tides should be approximately equal in height for each tidal day (National Oceanic and Atmospheric Administration, 2001).

- Monthly tides
    - Spring tide

The greater tidal ranges occur during spring tides when the sun and moon are in alignment (Kennish, 2016; Unnikrishnan, 2022). This occurs during new and full moons as the combined gravitational forces of the sun and moon work together to produce large tidal ranges (Branch et al., 2010; Kennish, 2016; Unnikrishnan, 2022). Thus, during spring tide, the tides are at their highest during high tide and at their lowest during low tide.

    - Neap tide

The smaller tidal ranges occur during neap tides when the sun and moon are no longer in alignment (Kennish, 2016; Unnikrishnan, 2022). This occurs during the first and third quarter moons when gravitational forces of the sun and moon counteract one another, producing smaller tidal ranges (Branch et al., 2010; Kennish, 2016; Unnikrishnan, 2022). Thus, during neap tide, the tides are at their lowest during high tide and at their highest during low tide.

Thus, during spring high tides, the water column will retain greater microplastic concentrations due to the highest high tides associated with spring tides allowing microplastics to become suspended and/or resuspended in the water column due to the turbulent flows (Sadri & Thompson, 2014). In contrast, during

neap tides, sediment will retain greater microplastic concentrations due to low tides associated with neap tides, which result in increased microplastic deposition (Wu et al., 2020a).

2.5.5.4 Wind

Seasonal variations in wind movement across South Africa are heavily influenced by subtropical high-pressure systems (Lennard, 2019). Specifically, two subtropical high-pressure systems, the South Atlantic high-pressure system and the South Indian high-pressure system, dominate the weather in the country (Schumann, 1992; Dyson & Van Heerden, 2002; Rouault et al., 2024). However, their effects vary across different regions of the country during different seasons.

During winter, the South Atlantic high-pressure system dominates the interior weather of the country, driving the formation of the north-westerly wind (Schumann, 1992; Lennard, 2019). These winds carry dry air from the South Atlantic Ocean and the cool Benguela Current, resulting in mild, sunny days and cold, clear nights (Jury, 2013; Lennard, 2019). Early morning frost may occur, and temperature inversions lead to a cold surface layer of air that traps air pollution (Lennard, 2019). During summer, the South Indian high-pressure system dominates the weather interior weather across most of the country, driving the formation of the easterly winds (Kruger et al., 2010; Bakker, 2021). However, in the south-western and southern regions of the country, the weather is mainly dominated by the eastern extremity of the South Atlantic high-pressure system which drives the formation of the south-easterly wind along the west coast (Schumann, 1992; Lennard, 2019). This wind can often be gale-force and is the cause of the coastal upwelling that occurs along the west coast (Lennard, 2019).

Wind can affect the transport, suspension and deposition of microplastics (Pazos et al., 2021). Several studies have reported wind as an essential transport mechanism for microplastics with wind direction and intensity affecting both the spatial and temporal distribution of microplastics (Browne et al., 2010; Yonkos et al., 2014). For example, Ghayebzadeh et al. (2021) observed greater microplastic concentrations as one moves from west to east along the southern coast of the Caspian Sea. This was linked to both water flow and wind direction travelling from the northwest to the southeast (Ghayebzadeh et al., 2021). Browne et al. (2010) also observed greater microplastic concentrations at sites downwind. Additionally, turbulent mixing induced by wind can allow buoyant microplastics to become redistributed into the water after having settled (Vermeiren et al., 2016). However, intense winds can also allow microplastic deposition as microplastics become submerged in the wind mixing layer leading to their subsequent settling (Kobayashi et al., 2021).

2.5.5.5 Freshwater input

Freshwater inputs into coastal environments vary seasonally and are primarily governed by precipitation (Gillanders & Kingsford, 2002; Malli et al., 2022). Freshwater can enter coastal environments through fluvially dominated estuaries, agricultural run-off, wastewater effluents and urban stormwater (Horton & Dixon, 2018). Once these inputs reach coastal environments, there influence will depend on the hydrodynamic conditions (e.g. wind, currents, tidal regimes) of those environments (Gillanders & Kingsford, 2002). However, given that freshwater inputs are able to transport particulate matter, dissolved organic material, nutrients and pollutants (microplastics), it may affect the physicochemical conditions (e.g. salinity, temperature, turbidity) of the receiving environment (Gillanders & Kingsford, 2002). For example, freshwater input can generate turbidity currents and can either decrease or increase the temperature or salinity of the environment (Gillanders & Kingsford, 2002; Seers & Shears, 2015). Such changes to the physicochemical conditions of coastal environments can in turn significantly influence the distribution of microplastics (Zhou et al., 2021; Simantiris et al., 2022). Hence, not only are freshwater inputs able to transport microplastics to coastal environments but can also influence their distribution within those environments.

2.5.5.6 Anthropogenic influence on the distribution of microplastics

All plastic production occurs on land, where the majority of it is used in consumer products (Horton & Dixon, 2018). After its use, the waste from these consumer products can be released into aquatic environments through direct littering and improper waste management either through a loss of waste during disposal, industrial spillages or through the release of waste from landfills (Sadri & Thompson, 2014; Lechner & Ramler, 2015; Verster & Bouwman, 2020). Additionally, coastal and marine environments also become subjected to plastic waste utilised during recreational fishing and maritime activities such as abandoned fishing gear, accidental loss of cargo and illegal dumping (Horton & Dixon, 2018). Most of this plastic waste will enter these environments in the form of macroplastics which will eventually break down into microplastics through fragmentation (Horton & Dixon, 2018). Whether plastic waste originates on land or at sea, once it reaches coastal and marine environments, hydrodynamic conditions such as currents, winds and waves can disperse it over vast distances, often far from its point of origin (van Sebille et al., 2012).

2.5.6 Microplastic contamination in coastal environments

It is widely considered that coastal and marine environments represent the final sink for microplastics with rivers and estuaries serving as important pathways for transporting microplastics to the ocean (Horton & Dixon, 2018; Nel et al., 2018). Microplastics have become widespread in marine environments with reports of microplastics found along beaches (Wessel et al., 2016; de Villiers, 2018), coastal and harbour environments (Nel et al., 2016; Sparks & Awe, 2022), the open ocean (Law et al., 2010; Law et al., 2014) as well as in ocean depths (Jamieson et al., 2019).

Several studies provide evidence of microplastic particles entering the ocean via river systems. For instance, Moore et al. (2011) estimated that over 72 hours, 2.3 billion plastic particles, 81% of which were less than 5 mm in size, flow into the coastal waters of Southern California via the Los Angeles and San Gabriel Rivers. Mai et al. (2019) estimated that 39 billion microplastic particles are discharged from the Pearl River Delta into the South China Sea. Furthermore, Silburn et al. (2023) reported on microplastics in the sediment of the Belize River basin and recorded an average concentration ranging between 200 to 6500 ± 1273 particles/kg, with concentrations increasing as you move from the river catchment towards the coast.

2.5.6.1 Microplastic contamination in South African coastal environments

Several studies have assessed the concentration of microplastics along various parts of the South African coastline. Among the research conducted, Ryan (1988) and Ryan & Moloney (1990) provided one of the first accounts of microplastics around South Africa's coastline, reporting findings in 1977 - 1978 in 1984 and again in 1989, respectively. The South African coastline extends approximately 3,000 km from the Orange River along the west coast to Kosi Bay along the east coast (Harrison, 1999), supporting over 13 000 species, many of which are endemic (Sink et al., 2019; Naidoo et al., 2020). This rich biodiversity is thus what drives the need for continued research on microplastics in South Africa's coastal and marine environments (Naidoo et al., 2020).

Research on microplastics in South Africa's coastal and marine environments has continued to increase since the first account. Julius et al. (2023) investigated microplastics along the Western Cape coastline, reporting average concentrations of 185.07 ± 15.25 MPs/kg in sediment and 1.33 ± 0.15 MPs/L in surface water. Ferguson et al. (2024) reported average microplastic concentrations of 0.37 ± 0.06 MP/L in the

water and 38 ± 2 MP/kg in the sediment along the rocky shore in Simons Town in Cape Town, South Africa. Ariefdien et al. (2024) reported average microplastic concentrations of 0.15 ± 0.01 MPs/L in water and 52.11 ± 3.51 MPs/kg along three coastal zones in Cape Town, South Africa.

While it is well understood that the majority of microplastics in coastal and marine environments originate from land-based sources, subsequently transported through river systems (Lebreton et al., 2017; Meijer et al., 2021), research on microplastics has primarily focused on individual environmental compartments, rather than within the context of cross-ecosystem subsidies. Rivers, estuaries and coastal environments are closely interlinked compartments (Horton & Dixon, 2018). Thus, considering them separately may hinder the implementation of appropriate mitigation strategies as the processes that influence microplastics within one compartment, can also influence its fate within another compartment (Horton & Dixon, 2018).

Although research is limited, the presence of microplastics in South African aquatic environments is evident, with studies highlighting the role of rivers and estuarine environments as sinks but also as potentially significant sources of microplastic contamination. Therefore, to gain a better understanding of the concentrations, risks, transport and fate of microplastics from river catchments to coastal and marine environments, future research should focus on the hydrodynamic conditions and transport fluxes that govern the movement of microplastics as riverine and estuarine environments may shift from sink to sources, transporting microplastics to adjacent coastal and marine environments.

2.6 Risk assessment of microplastics

In aquatic environments microplastics have the potential to cause significant harm to aquatic organisms. When they enter aquatic environments, microplastics become widely distributed throughout the water column, increasing their bioavailability to organisms at different trophic levels (Thompson et al., 2009; Cole et al., 2011; Athey et al., 2020). Due to their small size, aquatic organisms often mistake microplastic particles for prey, leading to major environmental concerns because of the ecotoxicological risks they pose (Wright et al., 2013; Kim et al., 2024).

Microplastics have been ingested by various aquatic organisms, including invertebrates such as molluscs (Browne et al., 2008; von Moos et al., 2012; Sussarellu et al., 2016), crustaceans (Hara et al., 2020), echinoderms (Plee, 2018) and zooplankton (Cole et al., 2013; Costa et al., 2020) as well as vertebrates such as fish (Neves et al., 2015; Reinold et al., 2021), seabirds (Derraik, 2002; Reynolds & Ryan, 2018),

sea turtles (Bugoni et al., 2001) and mammals (Denuncio et al., 2011). Ingesting microplastics can lead to physical, biological and chemical impacts. The physical impacts of microplastic ingestion include internal abrasion, ulcerations, rupturing of the digestive tract, impaired feeding capacity, deceptive satiation and starvation (Derraik, 2002; Thompson, 2006; Tourinho et al., 2010; Prokić et al., 2019).

The biological impacts of microplastics involve the transfer of microorganisms (Oberbeckmann et al., 2015). Due to their large surface area to volume ratio, microplastics provide an ideal substrate for microorganisms to colonize (Oberbeckmann et al., 2015). The formation of biofilms on microplastic surfaces can alter their physical properties, such as decreasing their hydrophobicity or increasing their density, causing low-density particles to sink deeper and become more bioavailable to benthic organisms (Li et al., 2018; Prokić et al., 2019). These interactions have raised concerns that microplastics could act as vectors for microorganisms, potentially causing a range of harmful biological effects (Oberbeckmann et al., 2015). These effects include oxidative damage, alteration of metabolic and anti-oxidative systems as well as immunological, neurological and histological damage (Prokić et al., 2019).

The chemical impacts of microplastics are directly linked to chemical additives such as plasticizers, stabilizers and colourants, which are commonly used during plastic production to enhance product performance (Li et al., 2018; Fu et al., 2020). Despite microplastics being biologically inert, these chemical additives can leach either directly into the organism or the environment, entering the food chain and bioaccumulating in organisms (Teuten et al., 2009; Li et al., 2018). The leaching of these chemicals can lead to harmful chemical effects like those causing carcinogenesis and endocrine disruption (Teuten et al., 2009; Barnes et al., 2009). Additionally, chemical contaminants can also stem from the environment (Talsness et al., 2009; Horton et al., 2017). Due to their large surface area, microplastics can adsorb these chemicals (Cole et al., 2011; Gall & Thompson, 2015), enabling them to act as carriers that transport contaminants to aquatic organisms.

The ecotoxicological risks posed by microplastics can lead to acute or chronic effects, depending on the duration of exposure to microplastics and their associated contaminants (Lithner et al., 2011). Therefore, it is crucial to assess the extent to which microplastics and their contaminants affect aquatic organisms. Lithner et al. (2011) developed a hazard-ranking model to identify hazardous chemical contaminants used in plastic production. In the model, 55 of the most commonly produced synthetic polymers were studied and information on the chemical substances used to produce each polymer as well as information on the

hazards (e.g. carcinogenicity, reproductive toxicity and germ cell mutagenicity etc.) of those chemical substances were collected (Lithner et al., 2011).

Based on this, Lithner et al. (2011) developed the hazard ranking model by categorising hazardous chemical substances and by comparing different polymers. This was done by assigning each hazard with a hazard level (I – V) and each hazard level was assigned a hazard grade (1 – 10 000) using a multiplier of 10 to be able to clearly distinguish between to the different hazard levels (Lithner et al., 2011). The assigned hazard levels and hazard grades were then used to calculate the hazard score of each polymer, making up the hazard-ranking model (Lithner et al., 2011). The ranking of each polymer indicates that the polymer has been made from a hazardous substance which can be released either during product production, use or at the end-of-life phase (Lithner et al., 2011).

Since the hazardous substances used in polymer production are capable of being released into the environment, there is thus a hazard associated with the ranked polymers. For example, Julius et al. (2023) reported dangerous rankings (2 909) at sites along the Western Cape coastline for water and sediment combined. Samuels et al. (2024) also reported dangerous rankings in the Zandvlei Catchment (water: 6 213) and Estuary (water: 5 469 & sediment: 10 572) in the Western Cape, South Africa. Additionally, Ferguson et al. (2024) reported dangerous rankings for the microplastics in water, sediment and biota combined (> 1200) in Simons Town in the Western Cape, South Africa. These dangerous rankings were attributed to the presence of polymers with high hazard scores, such as polyurethane (PUR) and acrylonitrile butadiene styrene (ABS) (Julius et al., 2023; Samuels et al., 2024; Ferguson et al., 2024). According to Lithner et al. (2011), the high hazard scores of these polymers are due to them being made up of monomers classified as either carcinogenic and/or mutagenic.

The findings from these studies highlight the value of the hazard-ranking model as a useful tool for evaluating environmental risks posed by synthetic polymers and their associated hazardous chemical substances. Thus, understanding the chemical composition and potential risks of microplastics to aquatic organisms is important in terms of developing and implementing the necessary risk reduction measures in order to enhance the protection of aquatic organisms (Lithner et al., 2011).

Chapter 3: Research methods

3.1 Study area

3.1.1 West Coast – Olifants system

3.1.1.1 Physical description

The Olifants catchment is located within the Northern and Western Cape Provinces and falls within the Matzikama municipal area, with a population density of 72 759 in 2021 (Western Cape Government, 2021a; Western Cape Government, 2021b). The Olifants catchments has a perennial flow regime and is the second largest catchment within South Africa, covering a total surface area of 49,000 km^2 (Lamberth et al., 2008; Western Cape Government, 2021a). Despite its large size, the Olifants catchment only contributes 2% to South Africa's mean annual runoff (Lamberth et al., 2008). This is due to the catchment being located within an arid region where most of the precipitation occurs during the winter months with extremely dry conditions during the summer months (Rutherford et al., 2006; Department of Water & Sanitation, 2006). The catchment's main river, the Olifants River, is approximately 250 km in length and serves as the main source of flow into the Olifants Estuary (Western Cape Government, 2021a). Whereas the rivers major tributary, the Doring River, which is approximately 310 km in length, is intermittently dry (Western Cape Government, 2021a).

The Olifants Estuary is located approximately 250 km north of Cape Town (31°42' S 18°11.34' E - 31°33.8'S 18°19.78'E) along the West Coast of South Africa (Western Cape Government, 2021a). It is one of the largest estuaries in South Africa covering a total surface area of 720 hectares (Western Cape Government, 2021a). The estuary extends from its estuary mouth to the extent of the tidal influence, which is about 36 km upstream to the low water causeway in Lutzville (Lamberth et al., 2008; Western Cape Government, 2021a). The depth of the estuary ranges between 2 - 3 m and it has a varying width of 20 m at the head of the estuary to 550 m at the estuary mouth (Western Cape Government, 2021a). This estuary is classified as being a predominately open estuary that enters the Atlantic Ocean (Whitfield, 2000; Lamberth et al., 2008).

The West Coast of South Africa is influenced by the Benguela Current, which extends from Cape Frio in Northern Namibia (18°30'S) to Cape Agulhas (34°80'S) (Hutchings et al., 2009; James et al., 2013). The waters along the West Coast are characterised by their cold temperatures and nutrient richness due to

upwelling from the ocean depths (Branch et al., 2010; Harris et al., 2019). This upwelling makes the waters of the West Coast more productive than those along the South and East coasts of South Africa. This high productivity includes an abundance of phytoplankton and seaweeds, which support more productive food chains, leading to greater populations of fish along the West Coast (Branch et al., 2010; South African National Biodiversity Institute, 2019).

3.1.1.2 Climate

The Olifants System is located along the west coast of South Africa, within the cool-temperate region (Lamberth et al., 2008; James et al., 2013). Given its location, the Olifants system experiences a Mediterranean climate along the southern section of the west coast (Rutherford et al., 2006; James et al., 2013). As for the northern section, it experiences more arid conditions (James et al., 2013). Minimum temperatures range from -3ºC to 3ºC during the wet season and maximum temperatures range from 39ºC to 44ºC during the dry season (Department of Water & Sanitation, 2005). Rainfall within the Olifants System ranges from 300 mm in the north to 1 500 mm in the south (Western Cape Government, 2021a).

3.1.1.3 Topography

West of the Olifants system, along the coastal strip, the topography is characterised by rolling hills and sand dunes (Department of Water & Sanitation, 2005). In the southern area of the Olifants system, the topography is characterised by rugged mountains with peaks rising to about 2 000 m above sea level (Department of Water & Sanitation, 2005). In the north-eastern area of the Olifants system, the topography is characterised by plains and rocky hills (Department of Water & Sanitation, 2005). The topography of the Olifants system itself is characterised as being a deep narrow valley which widens and flattens downstream until the system flows through a wide floodplain (Department of Water & Sanitation, 2005).

3.1.1.4 Geology

The geology of the Olifants area consists mainly of sedimentary rock which forms part of the Cape Supergroup and subsequently the Table Mountain Group (Department of Water & Sanitation, 2005). Along the valley floor of the Olifants system, rocks from the Karoo Supergroup overlie the sedimentary rock (Department of Water & Sanitation, 2005). In the northern section of the Olifants system, layers of sedimentary rocks from the Vanrhynsdorp Group occurs along with exposed pre-Cape metamorphic rock in the north-western and north-eastern corners of the area (Department of Water & Sanitation, 2005). Along

the coastal plain, underlain metamorphosed shales of the Malmesbury Formation and sandstone of the Table Mountain Group occurs and are overlain by semi to unconsolidated sediments of both alluvial and marine origin as well as deposits of calcrete and ferricrete (Department of Water & Sanitation, 2005).

3.1.1.5 Vegetation

The area surrounding the Olifants system is largely arid, dominated by succulent karoo and fynbos vegetation occurring in the south, with Nama karoo vegetation occurring in the north (Western Cape Government, 2021a). Within the estuary itself, the vegetation is divided into four community types. The first type is macroalgae, which is mainly include seaweeds that are found at the lower reaches of the estuary as well as duckweed (*Lemna minor*), a floating macrophyte that occurs at the upper reaches of the estuary (Western Cape Government, 2021a). The second type is submerged macrophytes, which mainly include pondweed (*Stuckenia*) found at the upper reaches of the estuary as well as Cape eelgrass (*Zostera capensis*) found at the lower reaches of the estuary (Bornman et al., 2008; Western Cape Government, 2021a). The third type consists of reeds and sedges, which mainly occur at the upper reaches as they cannot tolerate high levels of salinity (Bornman et al., 2008; Western Cape Government, 2021a). Finally, the floodplain saltmarsh, which is the dominant community type, covering 791 hectares (Bornman et al., 2008). This saltmarsh contributes to the estuary's high productivity and biodiversity by providing habitat and shelter for numerous species of birds and invertebrates (Anchor Environmental Consultants, 2007; Western Cape Government, 2021a).

3.1.1.6 Biota

The invertebrate community of the Olifants system includes zooplankton and the benthic communities (Western Cape Government, 2021a). The dominant invertebrate species are the copepods, *Pseudodiaptomus hessei* and *Acartia longipatella* (Montoya-Maya & Strydom, 2009). Zooplankton and hyperbenthos are most abundant at the middle reaches of the estuary, while subtidal benthos are most abundant at the upper reaches of the estuary (Western Cape Government, 2021a). These invertebrate communities are important for sustaining both bird and fish populations (Western Cape Government, 2021a).

In the Olifants system, a total of 38 fish species from 30 different families have been recorded, 18 of which are either partially or completely dependent on the Olifants Estuary (Lamberth et al., 2008). These species

include the highly valuable white steenbras and mullet species (Lamberth et al., 2008; Western Cape Government, 2021a). These species occur mostly in the upper and middle reaches of the estuary, about 5-20 km from the estuary mouth, where salinities range between 0 - 20 ppt and where water clarity is less than 100 cm (Western Cape Government, 2021a). The species of mullet and estuarine round herring are the dominant fish species within the estuary, along with the elf species, which also make up a significant proportion of the overall fish population (Western Cape Government, 2021a).

The Olifants system also supports a diverse number of bird species due to its extensive size and diverse habitats found along the system (Western Cape Government, 2021a). Approximately 72 water bird species have been recorded at the Olifants estuary, 21 of which are migrants (Department of Water & Sanitation, 2006). Average bird numbers range from 3,200 in winter to 5,900 in summer (Western Cape Government, 2021a). The estuary mouth supports 80% of the bird species, with 90% found within 9 km of the estuary mouth, as the lower reaches provide important roosting sites for species of terns and gulls (Western Cape Government, 2021a). In contrast, the upper reaches of the estuary provide a home to waterfowl, which tend to prefer fresh and/or brackish habitats (Western Cape Government, 2021a). Apart from marine cormorants, the bird species within the Olifants system include invertebrate feeders such as waders, piscivorous feeders which are mostly terns as well as herbivores and generalist feeders such as waterfowl and gulls, respectively (Western Cape Government, 2021a).

3.1.1.7 Land-use activities

Approximately 90% of the Olifants River Catchment is untransformed, with much of this land located in nature reserves, while the rest is used for livestock farming (Western Cape Government, 2021a). Dryland farming does occur in small areas along the river catchment, with intensive viticulture and fruit cultivation farms in the south-west (Department of Water & Sanitation, 2006; Western Cape Government, 2021a). Agriculture serves as the foundation of the region's economy, with the Olifants region utilising 65% of the total water needed for the entire water management area, most of which are used agricultural irrigation (Department of Water & Sanitation, 2006).

Small-scale fishing also occurs along the Olifants Estuary, with the Ebenhaeser and Papendorp communities relying on it to maintain their livelihoods (Sowman, 2009; Williams, 2013). Approximately, 120 households within these communities are involved in fishing, either as a form of sustenance or as a primary source of income (Williams, 2013; Western Cape Government, 2021a). Those not involved in fishing are

either involved in small-scale agriculture on adjacent commercial farms, on an ad hoc basis, or they gain short-term employment through government public works or from poverty alleviation initiatives (Western Cape Government, 2021a). Other land-use activities along the Olifants system include mining for gypsum, salt, mineral sands and diamonds as well as tourism and recreational activities such as recreational angling, boating activities and informal camping along the Olifants Estuary (Department of Water & Sanitation, 2006; Western Cape Government, 2021a).

3.1.2 South Coast – Breede system

3.1.2.1 Physical description

The Breede catchment is located within the Western Cape Province and falls within the Breede Valley municipal area with a population density of 194 555 in 2021 (Western Cape Government, 2021c; Western Cape Government, 2025). The Breede catchment has a perennial flow regime and is one of the largest catchments along the South Coast, covering a total surface area of 12 600 km^2 (Lamberth et al., 2008; Western Cape Government, 2025). Currently, the mean annual runoff for the Breede catchment is 1034 × 10^6 m^3 per annum, which, under natural conditions, accounts for approximately only 42% of the river's mean annual runoff (Taljaard, 2003). However, its mean annual run-off is still the fourth highest for South African rivers (Flemming & Martin, 2021). The catchment's main river, the Breede River, is approximately 322 km in length and serves as the main source of flow into the Breede Estuary (Lamberth et al., 2008). The river's major tributary is the Riviersonderend River, which is approximately 140 km in length and significantly contributes to the catchment as it drains sections of the Hottentots Holland Mountains (Carter, 1983; Taljaard, 2003).

The Breede Estuary is located approximately 270 km east of Cape Town (34°24'21.6" S, 20°51'08.2" E - 34°15'00" S 20°30'40" E) along the south coast of South Africa (Taljaard, 2003; James et al., 2018). It is one the largest warm-temperate estuaries along the south coast, covering a total surface area of 455 hectares with a depth of 3-6 m (Turpie et al., 2002; Lamberth et al., 2008; Western Cape Government, 2025). The estuary extends from the mouth at Witsand to the extent of the tidal influence, to about 10 km beyond the town of Malgas and comprises the lower 52 km of the river (Western Cape Government, 2025). The Breede Estuary is classified as a predominately open estuary, entering the Indian Ocean at Sebastian Bay (Whitfield, 2000; Western Cape Government, 2025).

The South Coast of South Africa is influenced by the Agulhas Current, which extends from the East Coast of South Africa to the southern tip of the Agulhas Bank (27°S to 40°S) (Gordon, 1985; James et al., 2013). The waters along the South Coast are characterised by being warm, nutrient-poor, and significantly less productive than those along the West Coast (Branch et al., 2010). Despite this lower productivity, the South Coast supports a greater species diversity compared to the colder, more productive waters along the West Coast (Branch et al., 2010).

3.1.2.2 Climate

The Breede System experiences a warm-temperate climate, characterised by annual precipitation, as the system located is along the south coast of South Africa (Rutherford et al., 2006; James et al., 2013). Despite its location, the Breede System's geographic positioning places most of its catchment area within the bimodal rainfall transition between warm-temperate and cool-temperate regions (Carter, 1983; James et al., 2018). As a result, the systems also experiences a Mediterranean climate, with most of its rainfall occurring during the winter months (Lamberth et al., 2008; James et al., 2013; Flemming & Martin, 2021). Rainfall within the Breede System ranges from 250 mm in the north-east to 3,000 mm in the south-west (Department of Water Affairs & Forestry, 2004). Average temperatures vary annually, ranging from 17ºC to 15ºC, with an average maximum of 37ºC and a minimum of 0ºC (Department of Water Affairs & Forestry, 2004).

3.1.2.3 Topography

The topography of the Breede system is characterised by mountain ranges with peaks which reach an altitude of 1 500 - 2 000 m (Department of Water Affairs & Forestry, 2004). North of the Breede system, the topography is characterised by the Hex Mountains (Department of Water & Sanitation, 2011). To the east and West of the Breede system, the topography is characterised by the Langeberg Mountains and the Franschhoek and Du Toit's mountains, respectively (Department of Water & Sanitation, 2011). To the south of the Breede system, the topography is characterised by the wide Breede River valley and the rolling hills of the Overberg (Department of Water & Sanitation, 2011).

3.1.2.4 Geology

The geology of the Breede system varies from the upper, central and lower areas of the Breede system. In the upper and central areas of the Breede system, the geology consists of Quartzitic Table Mountain

sandstone (metamorphic rock), Bokkeveld and Malmesbury shales as well as formations of enon conglomerate at the upper area of the Breede system (Department of Water & Sanitation, 2011). At the lower are of the Breede system, the geology consists of Table Mountain and Witteberg sandstone, Bokkeveld shales, coastal deposits as well as enon conglomerate formations (Department of Water & Sanitation, 2011).

3.1.2.5 Vegetation

The vegetation within the Breede system consists of microalgal communities, including phytoplankton and microphytobenthos. Compared to other systems, these communities occur in a much lower biomass due to the low nutrient availability and low retention time of the Breede system (Western Cape Government, 2025). However, the microalgal community is quite diverse at the lower reaches of the system, where nutrients from the marine environment are readily available (Western Cape Government, 2025). Macrophyte communities also occur along the Breede system and are a major source of organic material. About 23 dominant macrophytes are found within the estuary, with *Zostera capensis* (Cape eelgrass) and *Stuckenia pectinata* (Sago pondweed) forming the basis of these communities (Western Cape Government, 2025). Intertidal salt marsh is also present along the Breede Estuary. This salt marsh possesses the highest diversity of plant species along the length of the estuary, receiving an overall score of 350 in botanical importance (Western Cape Government, 2025). This is the fifth-highest score among all South African estuaries (Western Cape Government, 2025).

3.1.2.6 Biota

The invertebrate community of the Breede system consists of zooplankton, hyperbenthic and macrobenthic communities. While zooplankton and hyperbenthic communities are present in a low diversity and abundance, macrobenthic communities are distributed according to the type of substrate found within the system (Western Cape Government, 2025). The highest diversity of macrobenthos occurs within the beds of the Cape eelgrass and saltmarshes, while the lowest diversity occurs in the sand flats (Western Cape Government, 2025). These habitats are critical in maintaining populations of bait organisms such as *Upogebia Africana* (mudprawn), *Arenicola loveni* (blood worm) and *Solen capensis* (pencil bait) (Western Cape Government, 2025).

Similarly, the Breede system supports a diverse community of fish with the highest species diversity and abundance occurring at the lower reaches, near the estuary mouth (Western Cape Government, 2025). In total 59 fish species having been recorded in the estuary, the majority of which are dominated by marine and estuarine-dependent species (Lamberth et al., 2008; Western Cape Government, 2025). Of these 59 species, 65% are endemic to South Africa and 30% are completely dependent on the estuary for their survival (Harrison, 2002; Western Cape Government, 2025).

The ecological diversity of the Breede system further extends to its avian community, with 177 species having been recorded within the estuary (Western Cape Government, 2025). In the winter and summer of 2000, 48 waterbird species were recorded, with 560 individuals recorded in winter and 1,900 individuals recorded in summer (Western Cape Government, 2025). Invertebrate feeders, such as waders, are the most dominant group occurring within the system, comprising 47% of the bird community in winter and 55% in summer (Western Cape Government, 2025).

3.1.2.7 Land-use activities

Most of the land surrounding the Breede system is privately owned and utilised for agricultural activities, with 63% of the Breede catchment within the Swellendam municipal area being cultivated croplands (Western Cape Government, 2025). Agricultural activities include viticulture and fruit cultivation, which dominate the upper and middle reaches of the Breede system, while livestock, grain and canola farming dominate the lower reaches of the system (Department of Water Affairs & Forestry, 2004; Van Tonder, 2022). The remaining 36% consists of natural vegetation, while urban development, forestry and mining, contribute less than 0.3% to the catchment area (Western Cape Government, 2025). Recreational activities along the Breede system include recreational angling, bait collection, skiing and boating activities, (Western Cape Government, 2025). Other land-use activities include light industrial activities, tourism, the use of public slipways and boat launching sites (Western Cape Government, 2025) as well as the use of the ferry stationed at Malgas, which provides residents with a means to cross the Breede River (Department of Water & Sanitation, 2011; Flemming & Martin, 2021).

3.2 Sample collection

Sampling was conducted at Olifants system along the West Coast and the Breede system along the South Coast in the Western Cape, South Africa (See chapter 4 & 5 for a more detailed description of the study sites for each individual system). For both systems, sampling was conducted on two occasions, once

during the wet season and once during the dry season. Each system was divided into three regions: catchment, estuary and coast and all sampling took place from the shoreline. For the catchment and estuarine regions, sampling took place 5 m from the water's edge and for the coastal region sampling took place along the high tide strandline. Samples of water and sediment were collected and analysed for microplastics and 4 replicate samples of each was collected at each site along each system.

3.2.1 Surface water samples

3.2.1.1 Field sampling

The bulk water sampling method was used to collect the surface water samples given its efficiency in capturing microplastics of varying sizes (Razeghi et al., 2021). Although this method is only able to cover a limited surface area, as opposed to trawl and net sampling methods (GESAMP, 2019; Razeghi et al., 2021), this limitation can be combatted by collecting multiple replicate samples at each site (Zhang et al., 2018). This method is thus seen as efficient in sampling microplastics as well as it being cost effective.

Thus, for the field sampling of water, surface water samples were collected at a depth of 45 - 50 cm (Nel & Froneman, 2015). A pre-cleaned 20 L container was used to collect the surface water. The water collected was then filtered in-situ using a 63 µm and a 250 µm sieve. An aperture of 63 µm was used as this is a common mesh size of fine plankton nets used in microplastic sampling (Dikareva & Simon, 2019). The 63 µm was then used in conjunction with the 250 µm sieve given that smaller sieve sizes often capture greater concentrations of microplastics (Ryan et al., 2020c). Thus, the use of the 63 µm and the 250 µm sieve was used to ascertain whether smaller sieve sizes do in fact capture greater microplastic concentrations. After filtering, the particles captured in the sieves were rinsed into pre-cleaned 50 ml centrifuge tubes. Four replicate samples of the surface water were collected at each site. These samples were then stored in a cooler box before being transported to the CPUT microplastics laboratory for further analysis.

3.2.1.2 Laboratory analysis

For samples containing biological material, it first underwent digestion to break down those materials. Digestion was carried out using a potassium hydroxide (KOH) solution. Firstly, a 10% KOH solution was prepared by adding 100 g of KOH to 900 ml of Milli-Q ultrapure water to make a 1 L solution. After preparing the stock solution, it was stored in a pre-cleaned and pre-labelled amber bottle.

When required, the KOH solution was poured into the surface water samples containing the biological material, maintaining a water-to-KOH ratio of 1:2. Once the KOH was added to the water samples, it was placed in the dry oven (model DHG-9070A) for 24 – 48 hours at 50°C to aid in the digestion process. After the 48 hours, the samples were then removed from the oven and left to cool.

After the digestion process and once all the samples had cooled, the samples were prepared for filtration. To prepare for the filtration process, 20 µm nylon mesh filters was cut and all equipment was cleaned and rinsed with Milli-Q ultrapure water (x3). Once all the equipment was prepared, each water sample was filtered through the pre-cut 20 µm nylon mesh using the Buchner funnel filtering system. After filtering each sample, the mesh the sample was filtered on, was placed in a pre-cleaned and pre-labelled petri dish and stored for microscope analysis.

3.2.2 Sediment samples

3.2.2.1 Field sampling

The bulk sampling method was also used to collect sediment samples. This method was utilised due to the scope of the research as this method is efficient in capturing microplastics of varying characteristics. Thus, for the sampling of the sediment, samples were collected using a quadrat measuring 0.25 × 0.25 m in size (Yin et al., 2021). The quadrat was placed at each site, and 5 cm of the top sediment within the entire quadrat was collected in 1 L glass jars using a metal spoon. Surface sediment samples were collected to cover a greater surface area and 4 replicate samples; each 5 m apart was collected (Yin et al., 2021). For samples collected along the catchment and estuary, samples were collected 5 m from the water's edge while samples collected along the coast were collected at the high tide strandline. To remain consistent, sampling was restricted to un-vegetated areas. After sampling had been conducted, the sediment samples were transported to the CPUT microplastics laboratory for further analysis.

3.2.2.2 Laboratory analysis

All sediment samples collected were placed into pre-cleaned and pre-labelled foil containers and placed in the oven to dry for at least 48 hours using the dry oven model DHG-9070A. Once the samples were dry, a sub-sample of the sediment was weighed, and this was then used for density separation. A sub-sample of at least 200 g of dry sediment was weighed and transferred into a pre-cleaned glass beaker for density separation.

To prepare for density separation, stock solution of sodium chloride (NaCl) was prepared. To make up the NaCl solution, 360 g of technical-grade sodium chloride was added to 1 L of Milli-Q ultrapure water. The Milli-Q ultrapure water was then first poured into a glass beaker and placed onto a hot plate stirrer set to 60°C. The pre-weighed NaCl was then added to the water along with a magnetic stirrer to aid in dissolving the NaCl. While the solution dissolved, the glass beaker was covered with aluminium foil to minimise exposure to ambient microplastics. Once the NaCl had dissolved, the solution was then filtered through a 10 µm nylon mesh filter using the Buchner funnel filtering system and was then stored in a pre-cleaned and pre-labelled glass bottle ready for density separation.

Density separation was carried out by adding the NaCl solution to the sediment samples at a volume three times that of the sample. The sample was then hand-mixed for 2-3 minutes and left for at least 15 minutes or until the sediment had settled (Naidoo et al., 2015). Once the sediment had settled, the microplastics could then be extraction by means of filtration. After the sediment samples had settled, the supernatant water in each sample was filtered through a pre-cut 20 µm nylon mesh filter using the Buchner funnel filtering system. This filtering process was repeated three times using the same filtered water to ensure sufficient microplastic extraction (Naidoo et al., 2015). After filtering, the 20 µm mesh filter was then placed into a pre-labelled and pre-cleaned petri dish and stored for microscope analysis.

3.3 Microscope analysis

For the microscope analysis, all samples collected were visually dissected and characterised. Using a Zeiss stereo microscope (x20 magnification) putative microplastics was categorised according to type and colour and size (Table 1), as proposed by GESAMP (2019). Each petri dish containing the filtered samples was placed under the stereo microscope and the type and colour of the microplastics found were recorded (GESAMP, 2019). The actual size of the microplastics was also recorded by measuring the longest length of each microplastic particle and images of microplastics greater than 500 µm – 5 mm were captured with the Moticam 1080 microscope camera. After the categorisation of individual microplastic particles, FTIR-ATR analysis was conducted to determine the polymer composition of each microplastic via spectroscopy using the Perkin Elmer Two FTIR-ATR spectrometer (Sparks et al., 2022).

Table 1: Categories for microplastic characteristics (GESAMP, 2019)

Type	Colour	Size
1. Filament/Fibre	1. White	1. < 0.5 mm
2. Fragment	2. Transparent	2. 0.5 – 1 mm
3. Film	3. Yellow/orange/brown	3. 1 – 2 mm
4. Sphere	4. Red/pink	4. 2 – 5 mm
5. Foam	5. Blue/green	5. > 5 mm
	6. Black/grey	
	7. Other	

3.4 Fourier-transform infrared-attenuated total reflectance (FTIR-ATR) analysis

For the FTIR-ATR analysis, all microplastics greater than 500 µm – 5 mm were scanned for polymer identification which is the threshold limit for the FTIR-ATR while also still falling within the microplastic (1 µm – 5 mm) size range. The microplastics were scanned via spectroscopy following the same procedure as Sparks et al. (2022) with the wave range set to 5000 – 450 cm -1, resolution set at 4 cm -1, data interval set to 1 cm -1 and scans set to 10. Before scanning the microplastics, a background scan was conducted to account for any ambient microplastics. During scanning, each particle was compressed on the ATR crystal with a force gauge of at least 80 N and the ATR crystal was cleaned with propanol between each scan. Of the total microplastics found, 100% were scanned to determine the polymer identification of each particle. After each scan, the spectral output of each particle was compared to the polymer reference database ST Japan as well as the Perkin spectral library, which then provided the polymer identification of each microplastic particle. Spectral outputs with a result of $\geq$ 60% was the threshold set for polymer identification.

3.5 Environmental parameters

To determine if environmental parameters may influence microplastic concentration, measurements of temperature, salinity, turbidity and pH were recorded, and grain size analysis of sediment particles was conducted. These parameters were selected based on studies indicating their influence on microplastic concentrations (Nel et al., 2018; Govender et al., 2020; Pazos et al., 2018; Lima et al., 2014).

3.5.1 Temperature, salinity, turbidity and pH

At each site, surface water measurements of temperature (degrees Celsius - °C), salinity (parts per thousand – ppt), turbidity (nephelometric turbidity units - NTU) and pH were recorded. Measurements were conducted along the shoreline using the YSI Professional Plus water multi-meter and three replicates of each parameter were recorded.

3.5.2 Grain size analysis of sediment samples

For the grain size analysis, 100 g of sub-sampled sediment was sieved using a sediment shaker through sieves with varying mesh sizes (63 µm, 125 µm, 250 µm & 500 µm). First, the sediment was placed into a foil container, weighed, and then dried in an oven for at least 24 hours. Once dried, the sediment was sieved for 5 minutes through the stacked sieves using a sediment shaker. After sieving, the sieves containing the dry sediment were weighed and the data was recorded using the GRADISTAT programme (Version 9.1) to measure the ratio of the respective sediment size categories.

3.6 Disturbance index

To determine the disturbance index, each system was assessed for varying forms of disturbances based on the rating system (Table 2) adapted from Govender et al. (2020) and Kleynhans (1996).

Table 2: Categories for the disturbance index (Kleynhans, 1996; Govender et al., 2020). Categories are colour-coded as follow: absent = blue (0), low = green (1), moderate = yellow (2), high = orange (3) and very high = red (4).

Disturbance	Category	Level of intensity	Disturbance rating
1. Agriculture 2. Industrial activities 3. Development 4. Effluents 5. Residential areas 6. Recreational activities 7. Maritime activities 8. Macroplastic pollution (Litter) 9. Abstraction 10. Erosion 11. Flooding 12. Mining activities	Absent	No discernible impact / disturbance located in such a way that it has no impact.	0
	Low	The disturbance is present at a small number of localities and impact is limited.	1
	Moderate	The disturbance is generally present with a clear detrimental impact.	2
	High	The disturbance is frequently present in almost the whole of the defined area.	3
	Very high	The disturbance is present overall with a high intensity. Almost the whole defined section is influenced detrimentally.	4

At each site, 12 anthropogenic disturbances were assessed based on their absence or presence across each system. This was conducted on two occasions, once during the wet season and once during the dry season, to account for any temporal variations. The following disturbances were assessed: agriculture (formal or informal), industrial activities, development, effluents, residential areas, recreational activities, maritime activities, macroplastic pollution (litter), abstraction, erosion, flooding and mining activities. These disturbances were chosen based on similar land use types present at both systems.

Each disturbance was then given a disturbance rating based on the level of intensity (0 = absent, 1 = low, 2 = moderate, 3 = high and 4 = very high). This was conducted by four independent observers to ensure overall coverage at each site. The ratings awarded by each observer, for each disturbance, on each of the

two days, were then averaged (n = 8) with a potential maximum rating of 4. The scores for each site were then summed (at site level) and expressed as a total disturbance rating (TDR), with a potential maximum of 48. The TDR for each site was then also summed and averaged at a regional level (catchment, estuary and coast) receiving an averaged total disturbance rating (ATDR).

3.7 Risk assessment

To assess the potential polymer and ecological risks posed by microplastics, indices were applied to all microplastics found in the surface water and sediment samples, based on risk categories (Table 3).

Table 3: Risk categories of indices for microplastic contamination (Kabir et al., 2021)

Risk Category	Low (I)	Moderate (II)	High (III)	Very High (IV)	Dangerous (V)
Contamination Factor (CF)	< 1	1 – 3	3 – 6	> 6	
Polymer Risk Index (H)	< 10	10 – 100	101 - 1000	1000 – 10 000	> 10 000
Pollution Risk Index (PRI)	< 150	150 – 300	300 - 600	600 – 1 200	> 1 200
	No Pollution				**Pollution**
Pollution Load Index (PLI)	< 1				> 1

The microplastic contamination factor (MPCF) which assessed the abundance of microplastics compared to background concentrations (C_{MP}) using the following equation:

Equation 1

$$MPCF_i = \left(\frac{C_{MP}}{C_{baseline}}\right)$$

As there are no historical data for these systems, values selected for $C_{baseline}$ included the site with the lowest average microplastic concentrations for water and sediment samples, an approach considered

acceptable (Kabir et al., 2021). Calculated CF values were then used to calculate the microplastic pollution load index (PLI) for the respective microplastic types using the following equation:

Equation 2

$$MPPLI_{site} = \sqrt[2]{MPCFi \times MPCFr}$$

MPCFi and MPCFr were for fibres and fragments, respectively.

Based on the method by Lithner et al. (2011) where hazard scores are assigned to different polymers to assess their risks, the hazard of polymers was analysed using the following equation:

Equation 3

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

The value for H_i was the calculated polymer risk index, where P_n was the ratio of a polymer type recorded at a site and S_n was the polymer hazard score assigned by Lithner et al. (2011). With the calculated polymer risk index (H_i), the pollution ecological risk index (PRI_i) was then be calculated using the following equation:

Equation 4

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

Based on the association between the pollution load index (PLI) and the polymer risk index (H_i), the calculated PRI_i indicates the ecological hazard of polymers.

3.8 Quality control

3.8.1 Field sampling

Quality controls were implemented during both field sampling and laboratory analysis to minimise microplastic contamination from other potential sources. In the field, all samples were collected downwind to minimise contamination from airborne microplastics. Glass and metal equipment was utilised, and use of any plastic equipment was minimised. All equipment used was rinsed at least 3 times with Milli-Q ultrapure water and gloves were worn during sample collection.

Procedural blanks during field sampling and laboratory analysis were also implemented to account for any airborne contamination. During field sampling blanks were taken at each site by placing an empty glass jar at the site during sample collection to account for any airborne contamination. Blanks were included in all sample filtrations with no microplastic contamination reported.

Contamination, was however, observed by certain equipment (sieves) used during field sampling. During field sampling while rinsing the sieve to collect the putative microplastics retaining within the sieve after filtering, the adhesive used to construct the sieve was observed being rinsed into the sample collected. Laboratory analysis was thus conducted on the exact part of the sieve responsible for the contamination. The data was then adjusted accordingly based on the type, colour and polymer identification. Spectral outputs with a result of $\geq$ 95% was the threshold set for polymer identification.

3.8.2 Laboratory analysis

In the laboratory, a cotton lab coast and gloves were through conduct laboratory analysis. All doors and windows were kept closed to prevent contamination from airborne microplastics and all samples were covered with aluminium foil and were only opened when necessary. Before and after processing the samples, workstations were cleaned with ethanol. Glass and metal equipment was utilised, and the use of plastic equipment was minimised. All equipment used was rinsed at least 3 times with Milli-Q ultrapure water. Milli-Q ultrapure was also used to make up all solutions used during the study (KOH & NaCl solution) which was filtered through a 10 µm mesh to prevent cross contamination.

Procedural blanks during laboratory analysis were also implemented to account for any airborne contamination. During laboratory analysis an open petri dish was placed at the workstation containing damp filter paper. Blanks were included in all sample filtrations with no microplastic contamination reported. Extraction efficiencies were also conducted to determine the efficiency of each method used to extract microplastics from the water and sediment for this study. A known number of neon orange fibres, sized between 500 – 5000 µm were added to four replicate samples of water and sediment. Extraction efficiencies for each test were as follows: water – 100% and sediment – 80%.

3.9 Statistical analyses

3.9.1 Microplastic concentrations

All statistical analyses were conducted using R and R Studio (Version 4.4.1). The Shapiro-Wilk test was carried out to assess the microplastic data's normality, revealing that the data did not follow a normal distribution, neither for the Olifants ($W = 0.57$, $p < 0.001$) or the Breede system ($W = 0.6382$, $p < 0.001$). Therefore, non-parametric tests were applied using a significance level of $p < 0.05$ and the data were expressed as the standard error of the mean (SEM).

For comparisons between the two different sampling seasons (Wet & Dry Season) as well as the surface water samples (63 µm & 250 µm), the Mann-Whitney U test (Z-values) was applied. For comparisons among the three different sampling regions (Catchment, Estuary & Coast) as well the different sampling sites (Olifants: site O1 – O11 & Breede: site B1 – B13), the Kruskal Wallis (H-values) test was applied. A subsequent post-hoc test was also conducted based on any significant difference found among the data to determine where those differences lay. Additionally, the Mann-Whitney U test was also applied for comparisons between the two different systems (Olifants & Breede systems).

3.9.2 Environmental parameters

3.9.2.1 Temperature, salinity, turbidity, pH and grain size analysis

Using R and R studio (Version 4.4.1) the correlation analysis was conducted by first plotting the data to assess the relationship between the microplastic concentrations and the environmental parameters. The plots revealed that the data followed a monotonic and non-linear relationship rather than a bivariate normality and linear relationship. Therefore, the non-parametric Spearman's rank correlation coefficient was conducted to determine the strength and significance ($p < 0.05$) of these relationships.

Chapter 4: Environmental concentrations, characteristics and risk assessment of microplastics in the Olifants catchment, estuary and coastal areas, Western Cape, South Africa

Abstract

Microplastic (< 5 mm) contamination is now increasingly being reported in South African aquatic environments but few studies have been done from catchment-to-coast. Therefore, the aim of this study was to determine the concentrations, characteristics and risk assessment of microplastics in the Olifants River catchment, estuary and coastal areas. Surface water and sediment were sampled and analysed along the catchment, estuary and coast in the wet and the dry season in relation to disturbances acting in on the system. Microplastics were extracted and identified using microscopy and Fourier-transform infrared spectroscopy (FTIR) analyses. Seasonally, average microplastic concentrations in water were similar and ranged from 0.27 ± 0.02 particles/L to 0.21 ± 0.01 particles/L during the wet and the dry season, respectively. Average microplastics concentrations in sediment were significantly different ($p < 0.05$) and ranged from 39.31 ± 6.60 particles/kg dry weight to 57.30 ± 4.03 particles/kg dry weight during the wet and the dry season, respectively. Spatially, average microplastic concentrations in water ranged from 0.20 ± 0.02 particles/L in the catchment, 0.24 ± 0.02 particles/L in the estuary and 0.29 ± 0.03 particles/L along the coast and in the sediment microplastic concentrations ranged from 46.45 ± 8.53 particles/kg dw in the catchment, 51.62 ± 5.70 particles/kg dw in the estuary and 46.36 ± 5.17 particles/kg dw along the coast. No significant spatially differences were observed. Microplastics were mainly black/grey fibres, 500 – 1000 µm in size and polyethylene terephthalate (70%) was the most common polymer type recorded. Pollution load indices indicated that pollution was present (> 1) throughout the different regions of the system during both the wet and the dry season for both water and sediment. Polymer risk indices ranged from low (7.50) to very high (1658.20) in water and from low (6.60) to moderate (47.30) in sediment. Spatially, pollution risk indices in water was categorised as dangerous in the catchment (3190.50), estuary (63 µm: 48887.70 & 250 µm: 5748.30) and coast (6943.30) during the wet season, while in sediment indices were low in the catchment (22.63 - 56.86) and estuary (30.11 - 99.90) but ranged from low (40.53) to moderate (198.50) along the coast. Seasonally, pollution risk indices were categorised as dangerous in water during the wet season (63 µm: 11864.30 & 250 µm: 9278.20) and very high during the dry season (63 µm: 1095.20 & 250 µm: 1102.01), while moderate in sediment during the wet (197.30) and the dry season (251.30). The results from this study serves a baseline for future reaserch efforts and to inform policy makers that govern the protection of the Olifants system so they may be able to develop and implement regular monitoring and

the necessary mitigation measures to reduce contamination within the system. The Olifants system is both an ecological and socio-economically important system. The results from the risk assessment does however indicate that the polymers in water during the wet season pose a threat to the overall health and functioning of the Olifants system from catchment-to-coast. Thus, regular monitoring of the system is crucial.

4.1 Introduction

The global increase in plastic production has led to concerns regarding the waste generated from plastic, particularly in developing countries like South Africa, where poor waste management practices combined with increasing plastic pollution contributes to the proliferation of microplastics in the environment (Jambeck et al., 2015; Boucher & Friot, 2017). In 2010, South Africa was ranked 11th globally for poor waste management practices, contributing 90 000 – 250 000 tons of plastic waste in the ocean (Jambeck et al., 2015). Although current estimates have decreased to 15 000 – 40 000 tons, significant waste management issues persist (Verster & Bouwman, 2020). According to the 2024 South African Environment report, South Africa generated 549 628,38 tonnes of plastic in 2022 (Department of Forestry, Fisheries and the Environment, 2024). Of this, 34.9% was either recovered, recycled or treated, while the remaining 357 808,08 tonnes of plastic waste were disposed of (Department of Forestry, Fisheries and the Environment, 2024).

Ryan (1988) and Ryan & Moloney (1990) provided one of the first accounts of microplastics around South Africa's coastline. Since then, research on microplastics in South Africa has gradually increased, mainly focusing on coastal and marine environments (Ryan et al., 2009; de Villiers, 2018; Julius et al., 2023; Ferguson et al., 2024) with relatively fewer studies on freshwater and estuarine environments (Graham et al., 2024; Samuels et al., 2024). Given the limited research on freshwater and estuarine environments and none on microplastics in a catchment-to-coast system, it highlights the current knowledge gap on microplastic research in South Africa.

Research efforts on microplastic contamination have mainly focused on individual environmental compartments, such as either freshwater, estuarine or coastal and marine environments (Horton & Dixon, 2018). Few studies have compared these environments to establish relationships in the movement of microplastics between them (Silburn et al., 2023). However, given the interconnectedness of these environments, they should be considered as a whole to better understand the movement and accumulation

of microplastics between them (Horton & Dixon, 2018; Nel et al., 2018). This understanding is essential for assessing impacts and guiding policies that govern the protection of these environments.

The Olifants system plays an important role in maintaining marine resources, particularly the Olifants Estuary, which is ranked third in conservation importance in South Africa due to its ecological and socio-economic value (Turpie et al., 2002). The estuary sustains approximately 120 households that depend on fishing either as a form of sustenance or as a primary source of income (Western Cape Government, 2021a). Despite its importance, the Olifants system faces numerous environmental pressures attributed to anthropogenic disturbances, including pollution, mining, agricultural and industrial activities, abstraction and irrigation, all of which can contribute to microplastic contamination within the system (Horton & Dixon, 2018; Western Cape Government, 2021a).

Although prior research on microplastics has been conducted in the Olifants Estuary (Boshoff et al., 2025) and along one of the coastal areas of the system (Wessel et al., 2016; de Villiers, 2018), the focus was on investigating microplastic concentrations in individual aquatic environments rather than from catchment to coast. Thus, the aim of this study is to determine the environmental concentrations, characteristics and risk assessment of microplastics in the Olifants River catchment, estuary and coastal areas. This study will serve as a baseline for future investigations and will 1) identify microplastic concentrations within the catchment, estuary and coastal areas of the Olifants system; 2) identify microplastics based on polymer type using spectroscopy; 3) assess the risks posed by microplastics through conducting a risk assessment; 4) evaluate whether environmental parameters influence the concentration of microplastics and 5) assess whether the degree of disturbance associated with surrounding land-use patterns acting on the Olifants system influences the concentrations and characteristics of microplastics found therein.

4.2 Research methods

4.2.1 Study site

Sampling was conducted at the Olifants system along the West Coast in the Western Cape, South Africa (Figure 1) (Refer to chapter 3 for a more detailed description of the study area and for details on the field sampling methodology and laboratory analysis). Sampling took place during both the wet (August 2023) and the dry season (December 2023). The system was divided into three regions (catchment, estuary and coast) and 11 sites were sampled along the system, with four sites located along the catchment (Site O1 – O4), four sites located along the estuary (Site O5 – O8) and three sites located along the coast (Site O9 –

O11) (Table 4). The fourth site along the coastal region of the system was unable to be sampled due to the mining area situated along that section of the system.

Table 4: Location of the sites sampled along the Olifants system in the Western Cape, South Africa

Region	Site	Latitude	Longitude	Urban/Rural
Catchment	O1	32°21'56.5"S	18°57'12.3"E	Rural
Catchment	O2	32°04'57.2"S	18°49'42.8"E	Rural
Catchment	O3	32°03'03.3"S	18°45'14.2"E	Rural
Catchment	O4	31°45'28.9"S	18°33'30.8"E	Rural
Estuary	O5	31°34'44.3"S	18°21'24.7"E	Rural
Estuary	O6	31°31'52.0"S	18°16'56.6"E	Rural
Estuary	O7	31°36'19.6"S	18°13'41.3"E	Rural
Estuary	O8	31°42'18.4"S	18°11'42.5"E	Rural
Coast	O9	31°38'24.6"S	18°08'45.4"E	Rural
Coast	O10	31°43'37.1"S	18°12'33.1"E	Rural
Coast	O11	31°48'54.8"S	18°14'05.9"E	Rural

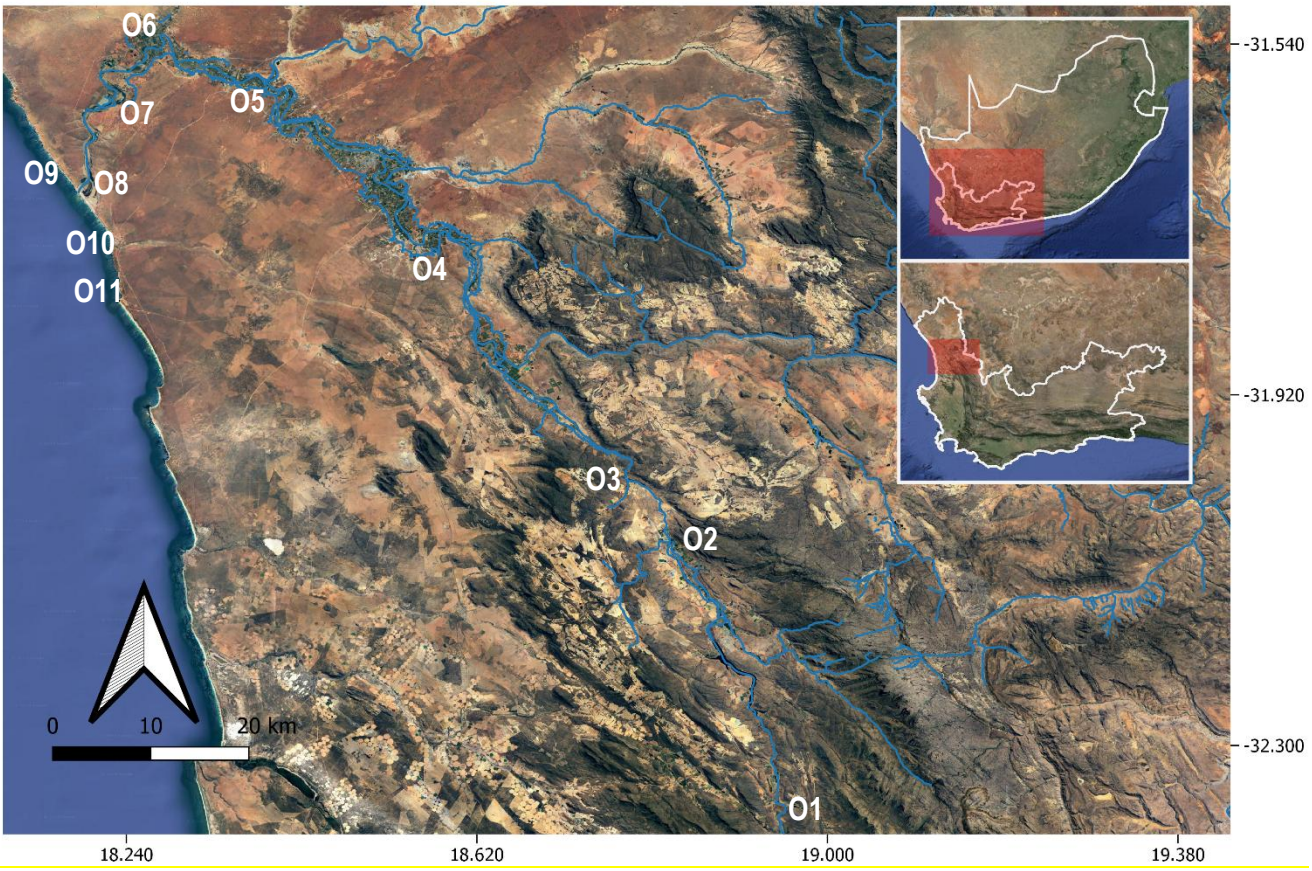

Figure 1: Map of the Olifants system along the West Coast in the Western Cape, South Africa displaying the different sampling sites (Map made with QGIS 3.14)

4.3 Results

4.3.1 Microplastic concentrations and characteristics in the surface water

The average concentration of microplastics within the surface water (63 & 250 µm) samples was 0.24 ± 0.01 particles/L (Figure 2). Microplastic concentrations were similar ($Z = 1.69$, $p = 0.09$) in the wet season (0.27 ± 0.02 particles/L) compared to the dry season (0.21 ± 0.01 particles/L). Across the different regions of the system, microplastic concentrations were similar ($H = 5.45$, $df = 2$, $p = 0.06$) and ranged from 0.20 ± 0.02 particles/L in the catchment, 0.24 ± 0.02 particles/L in the estuary and 0.29 ± 0.03 particles/L at the coast. Across the different sampling sites, microplastic concentrations were significantly different ($H = 25.90$, $df = 10$, $p = 0.004$) and ranged from 0.14 ± 0.02 particles/L at site O5 to 0.43 ± 0.06 particles/L at site O11.

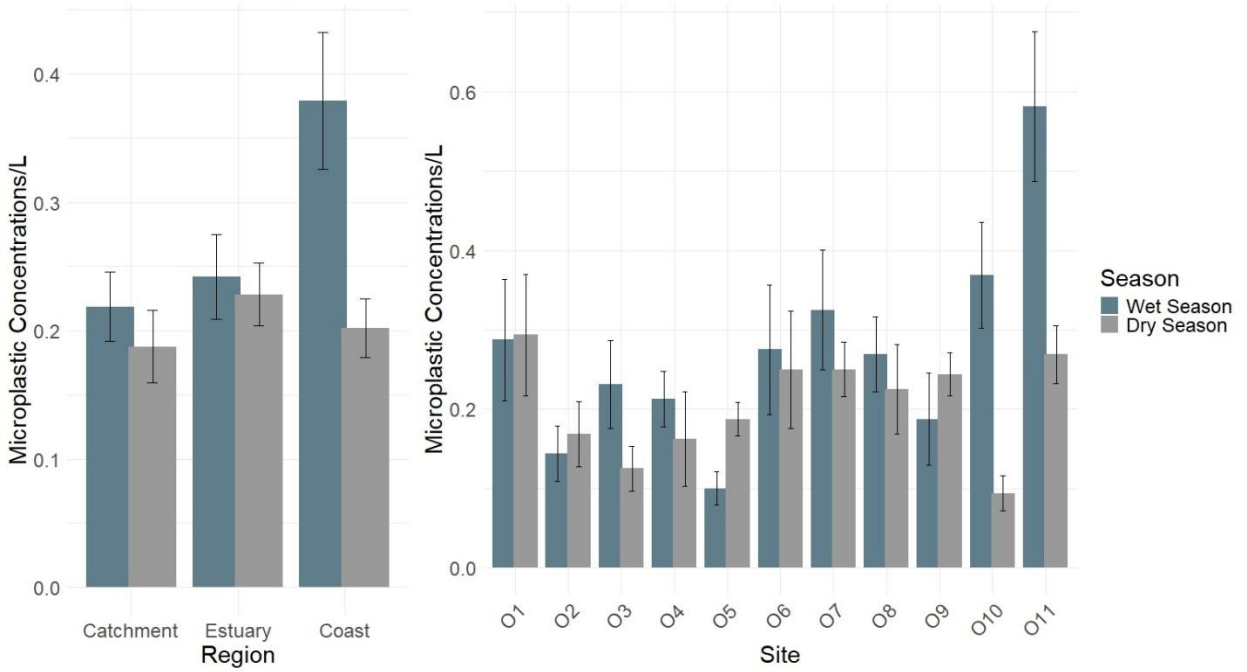

Figure 2: Microplastic concentrations sampled in the surface water (63 & 250 µm) at the different regions (catchment, estuary & coast) and sites (O1 – O11) along the Olifants system during the wet and the dry season (Error bars = SEM)

Microplastic fibres were the most abundant type, constituting 95.5% of the total microplastics recorded, followed by film (2.6%) and fragments (1.9%) (Figure 3). This trend was consistent across both sampling seasons and the different sampling regions of the system. The most abundant microplastic colour was black/grey (51.7%), followed by transparent (27.0%) and blue/green (11.8%) (Figure 4). Regarding size, the most abundant microplastic size class was 500–1000 µm (44.6%), followed by 1000–2000 µm (34.8%) (Figure 5).

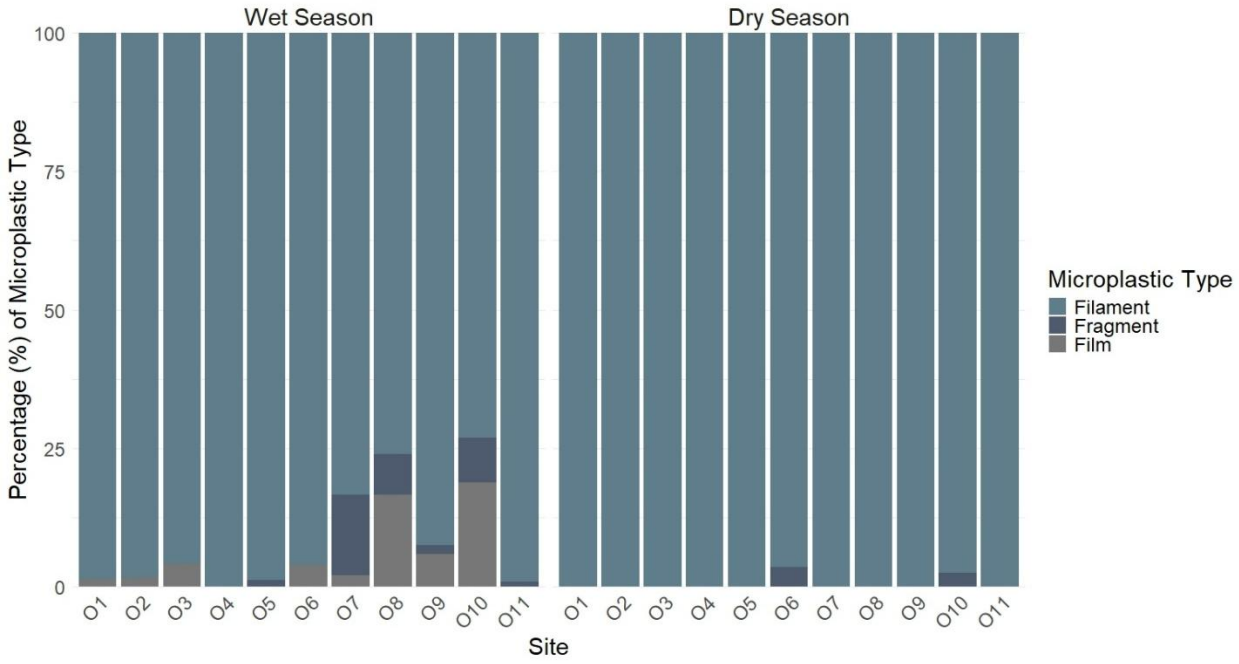

Figure 3: Percentage of microplastic types sampled in the surface water (63 & 250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

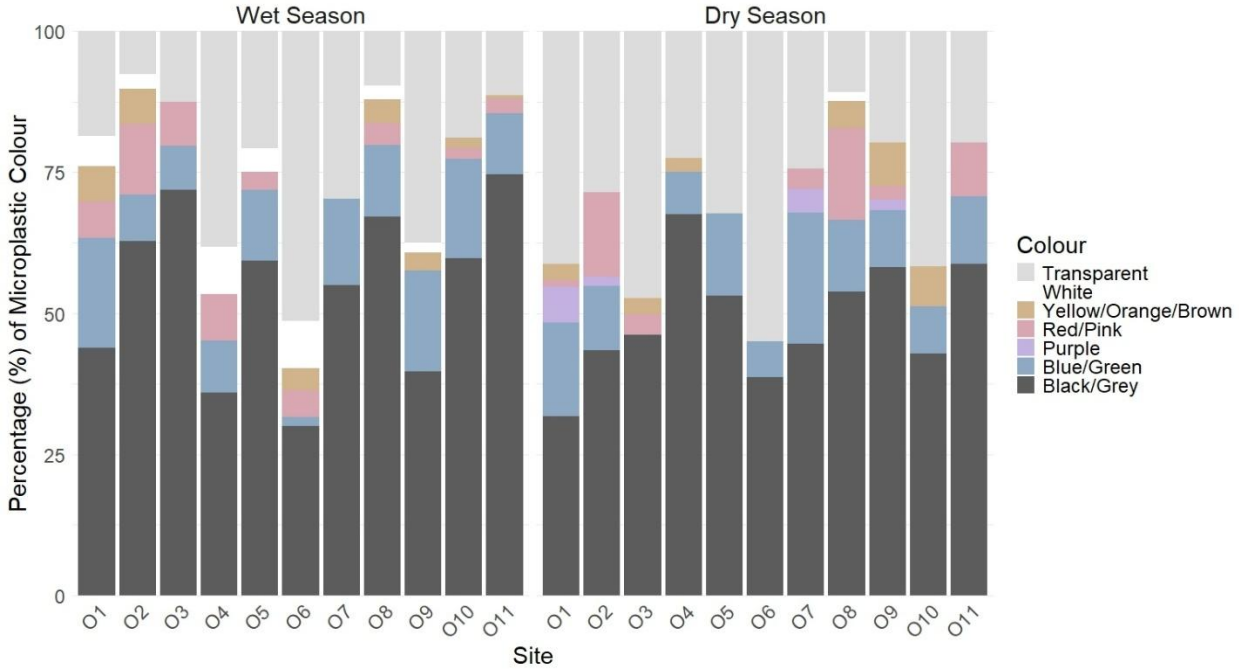

Figure 4: Percentage of microplastic colours sampled in the surface water (63 & 250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

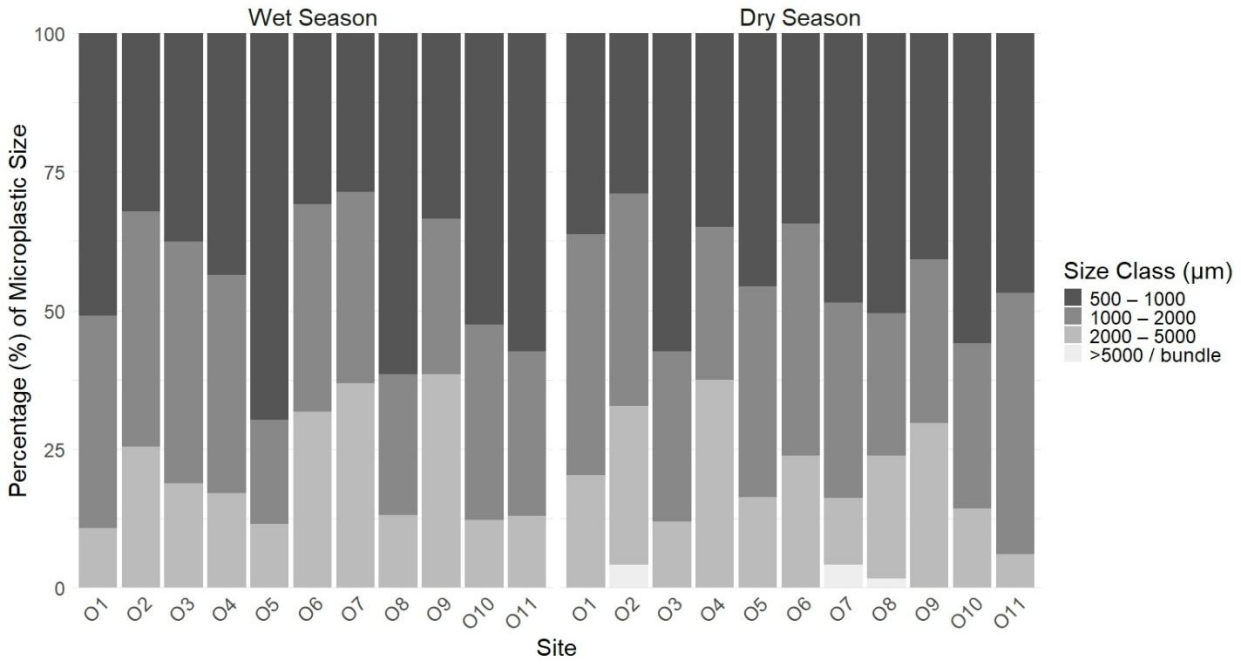

Figure 5: Percentage of microplastic size classes sampled in the surface water (63 & 250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

The average concentration of microplastics within the surface water samples collected through the 63 µm sieve was 0.25 ± 0.02 particles/L (Figure 6). Microplastic concentrations were significantly different ($Z = 2.03$, $p = 0.04$) in the wet season (0.30 ± 0.04 particles/L) compared to the dry season (0.19 ± 0.02 particles/L). Across the different regions of the system, microplastic concentrations were similar ($H = 5.75$, $df = 2$, $p = 0.06$) and ranged from 0.21 ± 0.02 particles/L in the catchment, 0.22 ± 0.03 particles/L in the estuary and 0.34 ± 0.05 particles/L at the coast. Across the different sampling sites, microplastic concentrations were significantly different ($H = 24.19$, $df = 10$, $p = 0.007$) and ranged from 0.12 ± 0.03 particles/L at site O5 to 0.53 ± 0.10 particles/L at site O11.

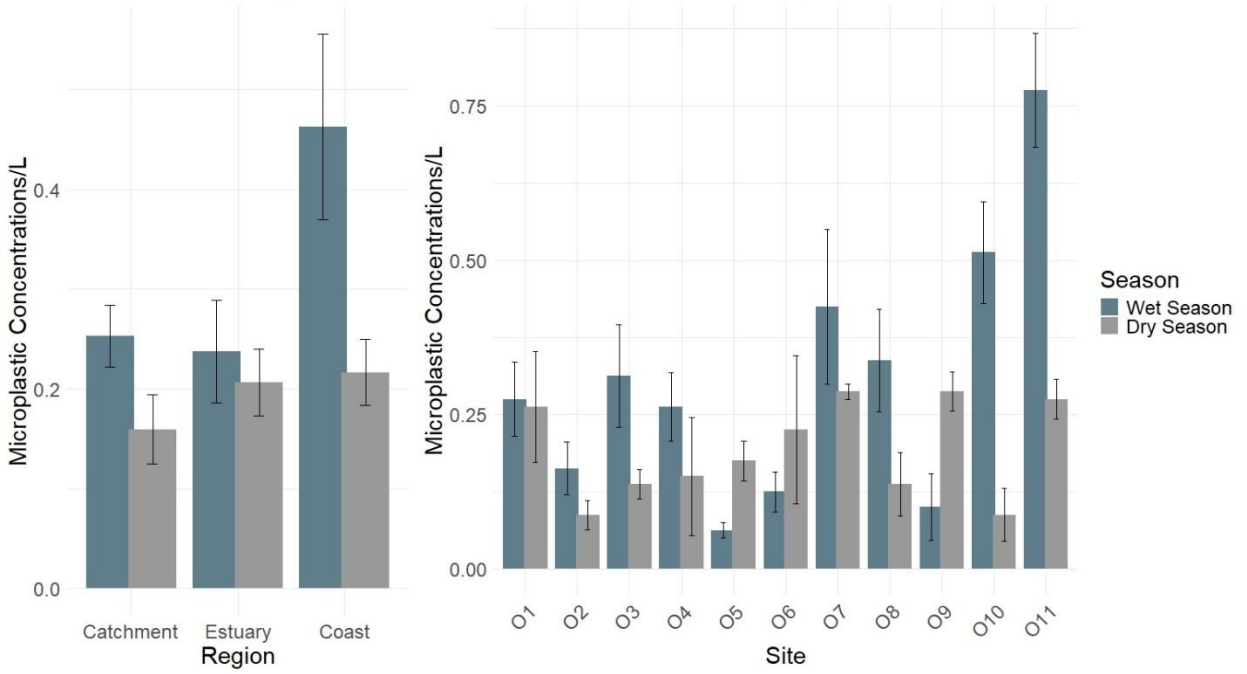

Figure 6: Microplastic concentrations sampled in the surface water (63 µm) along the different regions (catchment, estuary & coast) and sites (O1 - O11) of the Olifants system during the wet and the dry season (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 99.0%, followed by films (0.7%) and fragments (0.3%) (Figure 7). The most dominant microplastic colour was black/grey comprising 51.2%, followed by transparent (27.7%) and blue/green (13.1%) coloured microplastics (Figure 8). The most dominant microplastic size class was 500–1000 µm comprising 50.5%, followed by 1000–2000 µm (33.3%) and 2000-5000 µm (15.8%) in size (Figure 9). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

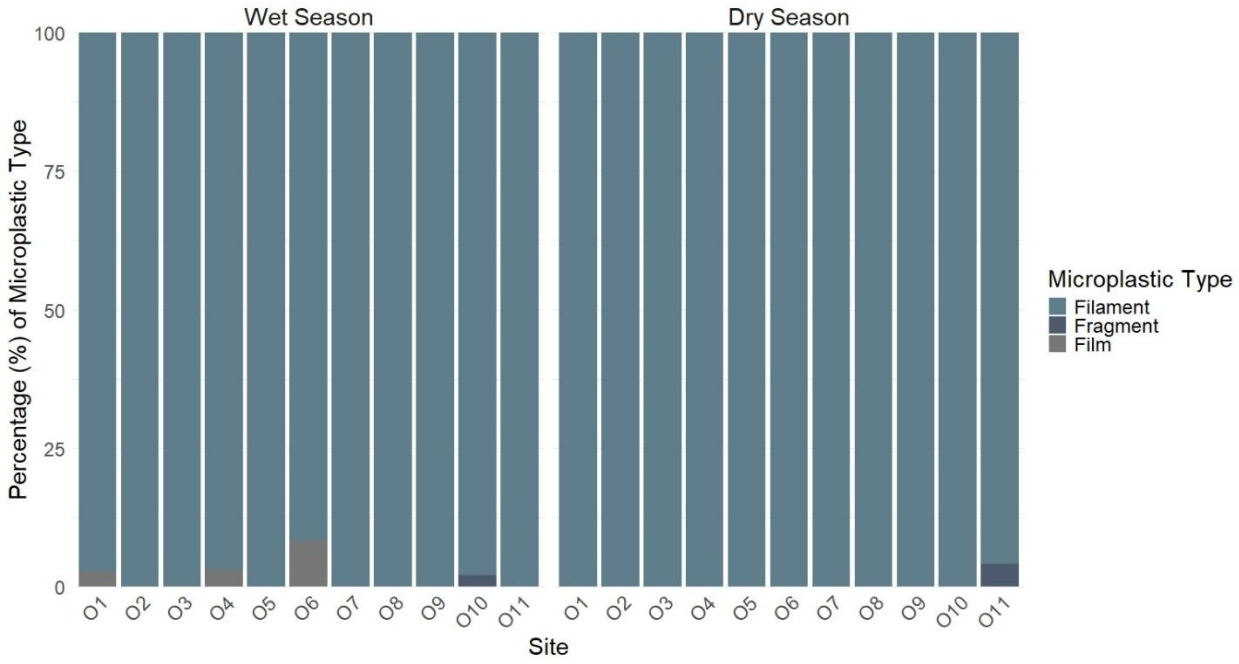

Figure 7: Percentage of microplastic types sampled in the surface water (63 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

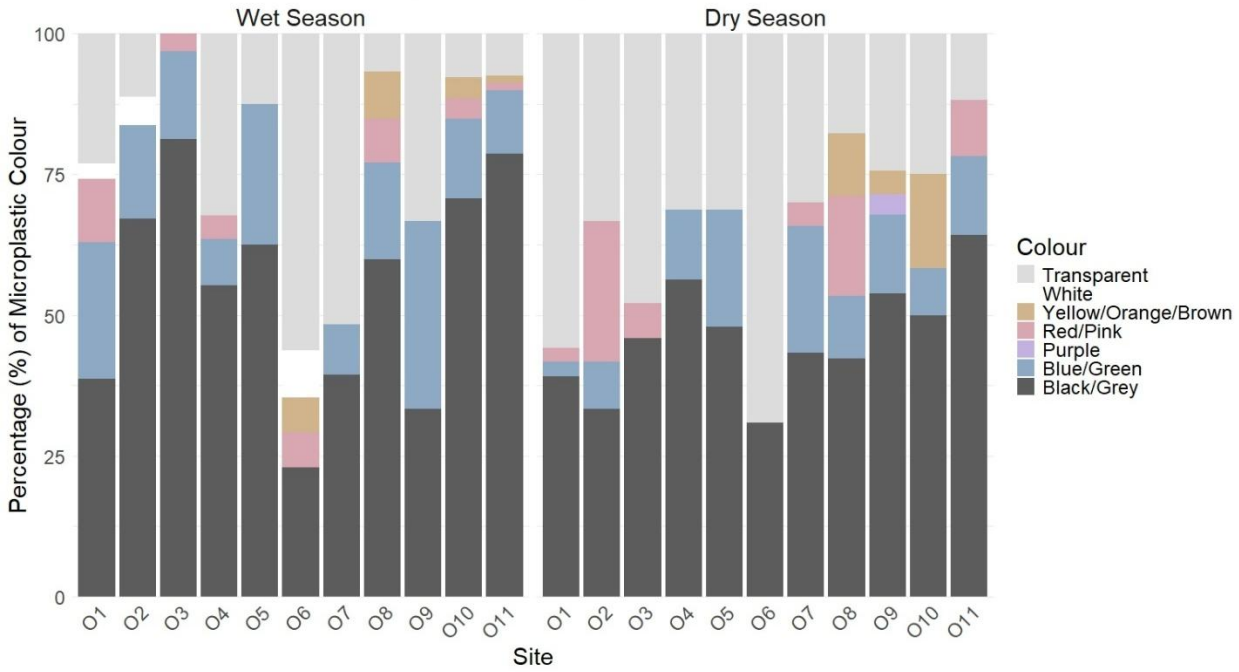

Figure 8: Percentage of microplastic colours sampled in the surface water (63 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

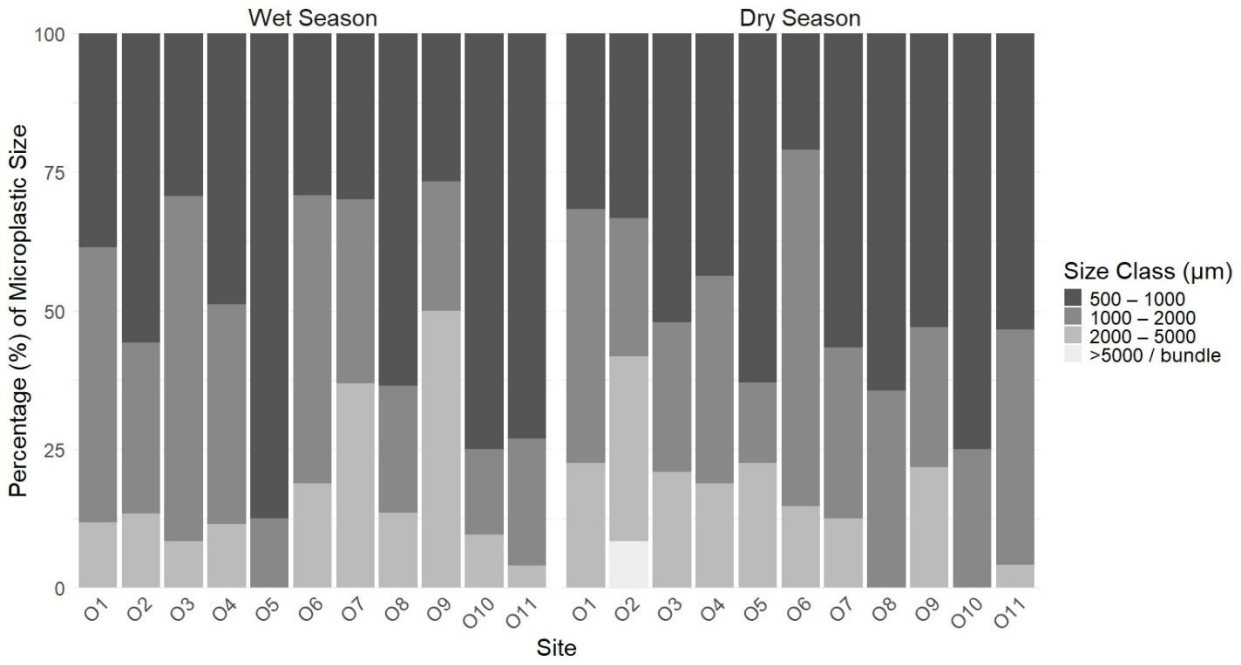

Figure 9: Percentage of microplastic size classes sampled in the surface water (63 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

The average concentration of microplastics within the surface water samples collected through the 250 µm sieve was 0.23 ± 0.02 particles/L (Figure 10). Microplastic concentrations were similar during the wet season (0.24 ± 0.03 particles/L) compared to the dry season (0.22 ± 0.02 particles/L) ($Z = 0.37$, $p = 0.71$). Across the different regions of the system, microplastic concentrations were similar ($H = 5.75$, $df = 2$, $p = 0.06$) and ranged from 0.20 ± 0.03 particles/L in the catchment, 0.25 ± 0.03 particles/L in the estuary and 0.24 ± 0.03 particles/L at the coast. Across the different sampling sites, microplastic concentrations were similar ($H = 11.37$, $df = 10$, $p = 0.33$) and ranged from 0.13 ± 0.04 particles/L at site O3 to 0.35 ± 0.08 particles/L at site O6.

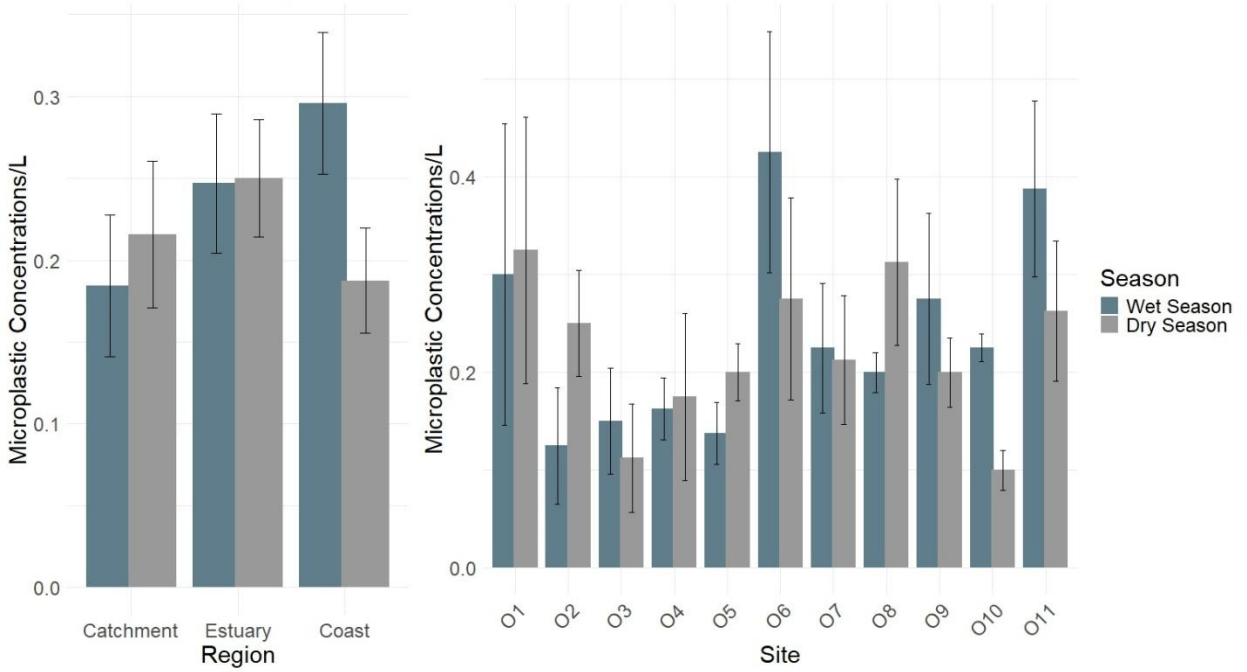

Figure 10: Microplastic concentrations sampled in the surface water (250 µm) along the different regions (catchment, estuary & coast) and sites (O1 – O11) of the Olifants system during the wet and the dry season (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 92.2%, followed by films (4.4%) and fragments (3.4%) (Figure 11). The most dominant microplastic colour was black/grey comprising 52.2%, followed by transparent (26.3%) and blue/green (10.5%) coloured microplastics (Figure 12). The most dominant microplastic size class was 500 – 1000 µm comprising 38.9%, followed by 1000 – 2000 µm (36.2%) and 2000 – 5000 µm (24.3%) in size (Figure 13). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

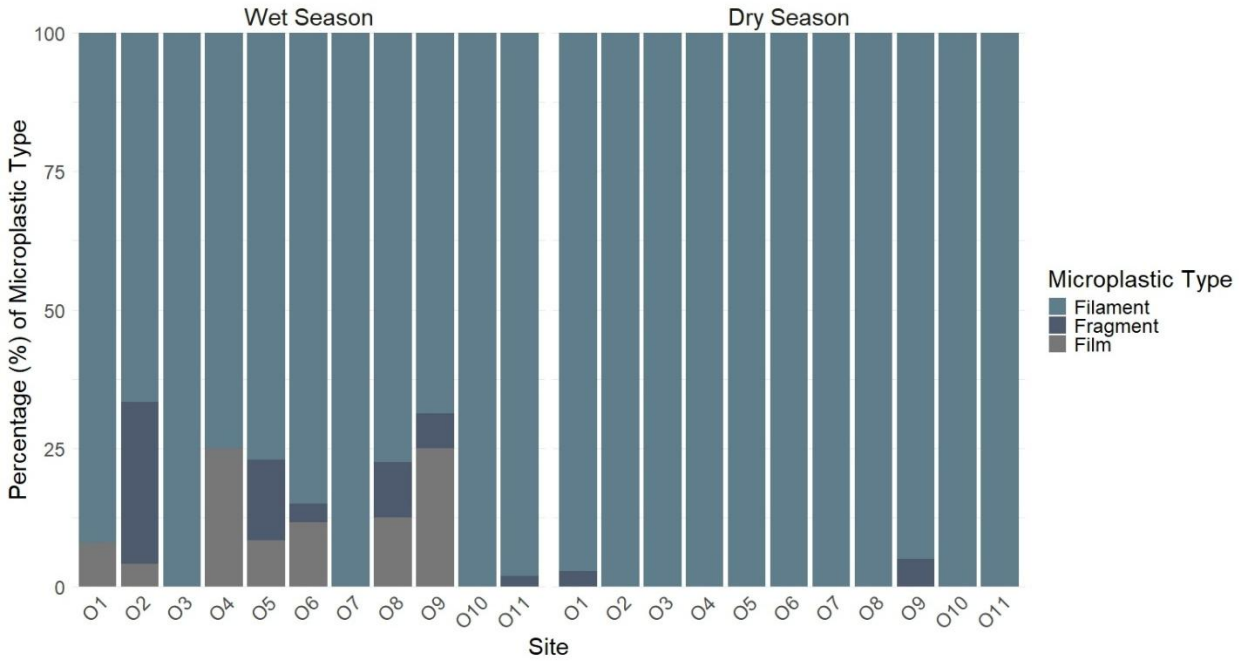

Figure 11: Percentage of microplastic types sampled in the surface water (250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

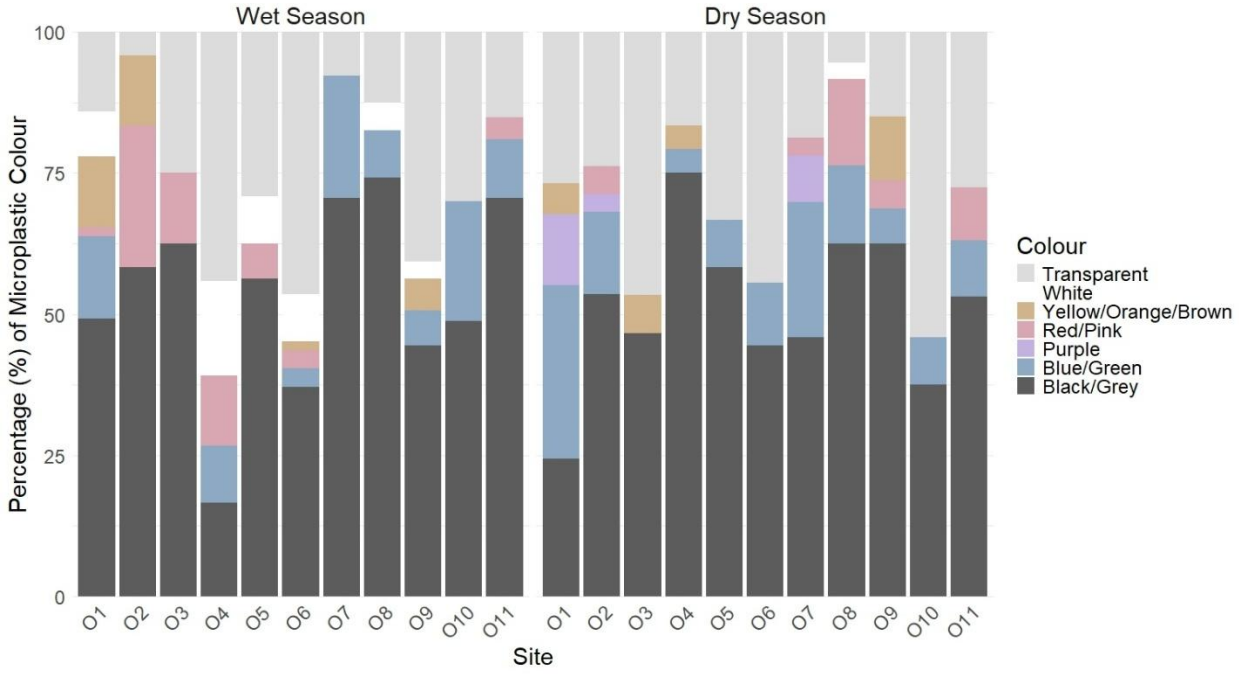

Figure 12: Percentage of microplastic colours sampled in the surface water (250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

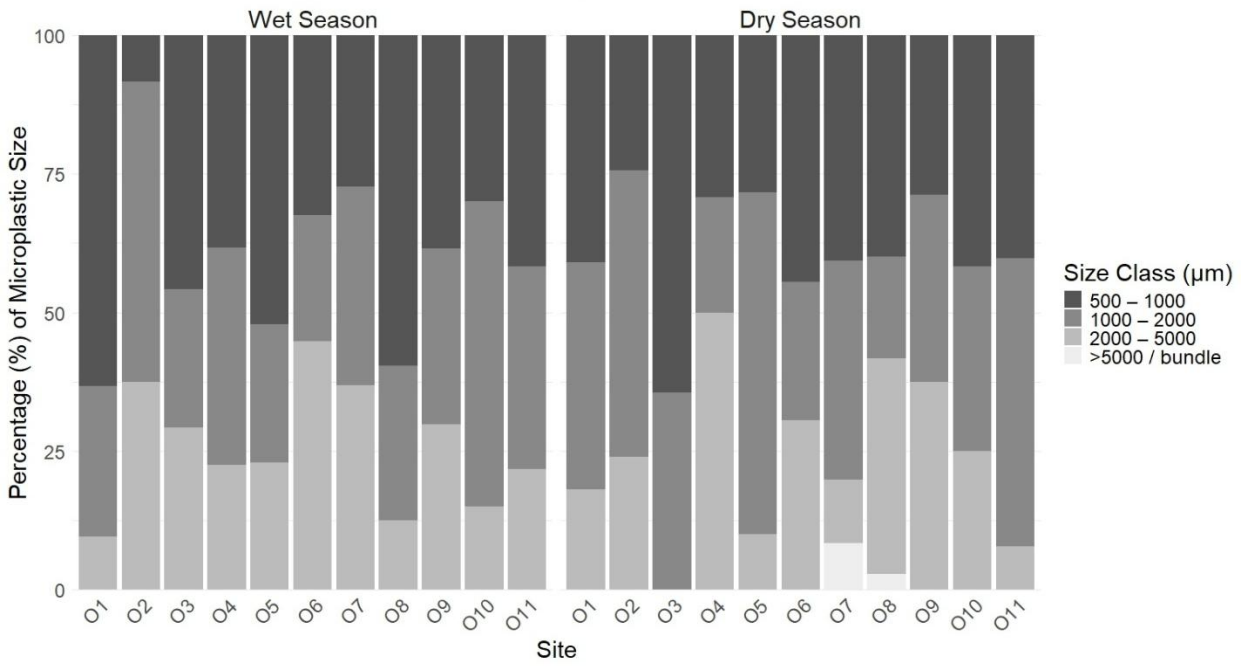

Figure 13: Percentage of microplastic size classes sampled in the surface water (250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

4.3.2 Microplastic concentrations across 63 µm and 250 µm size fractions

For the surface water samples collected through the different sieve sizes, microplastic concentrations were similar in the 63 µm sieve (0.25 ± 0.02 particles/L) compared to the 250 µm sieve (0.23 ± 0.02 particles/L) ($Z = 0.30$, $p = 0.77$) (Figure 14).

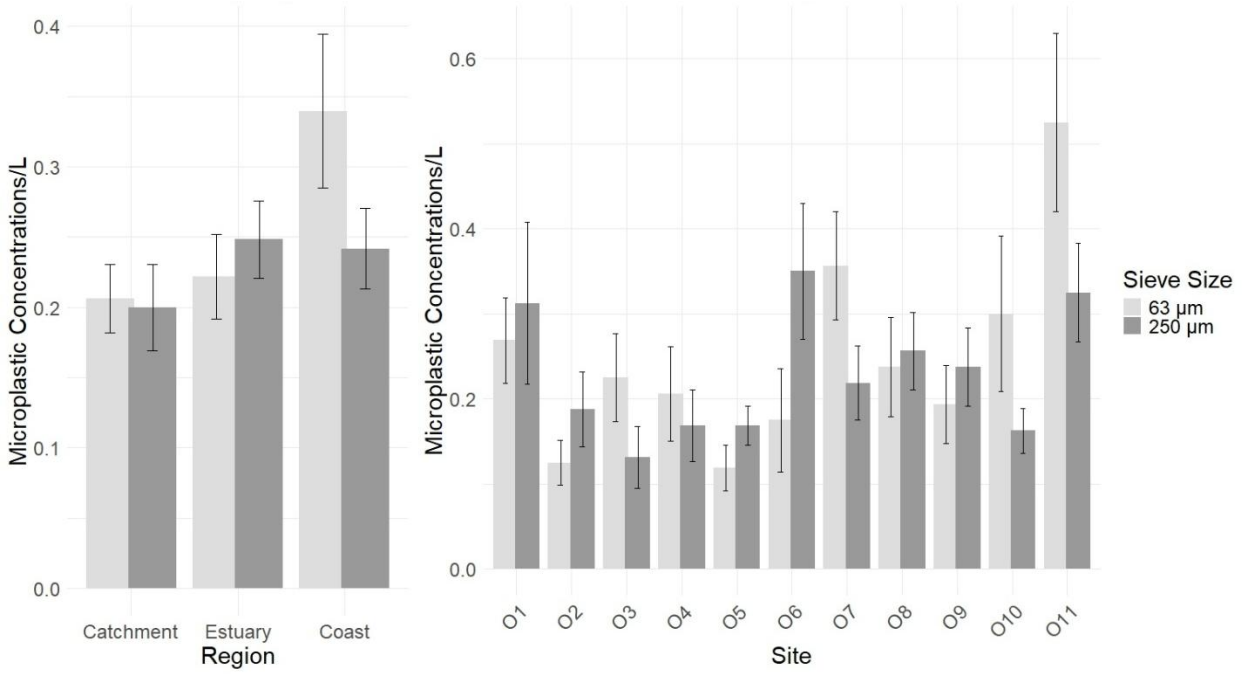

Figure 14: Microplastic concentrations sampled in the surface water using the 63 µm and 250 µm sieve sizes at the different regions (catchment, estuary & coast) and sites (O1 – O11) along the Olifants system (Error bars = SEM)

4.3.3 Microplastic concentrations and characteristics in the sediment

The average concentration of microplastics within the sediment samples was 48.30 ± 3.95 particles/kg dw (Figure 15). Microplastic concentrations were significantly different in the wet season (39.31 ± 6.58 particles/kg dw) compared to the dry season (57.30 ± 4.03 particles/kg dw) ($Z = -4.19$, $p<0.001$). Across the different regions of the system, microplastic concentrations were similar ($H = 0.93$, $df = 2$, $p = 0.63$) and ranged from 46.45 ± 8.53 particles/kg dw in the catchment, 51.62 ± 5.70 particles/kg dw in the estuary and 46.36 ± 5.17 particles/kg dw at the coast. Across the different sampling sites, microplastic concentrations were similar ($H = 13.21$, $df = 10$, $p = 0.21$) and ranged from 24.97 ± 6.61 particles/kg dw at site O2 to 85.43 ± 9.88 particles/kg dw at site O7.

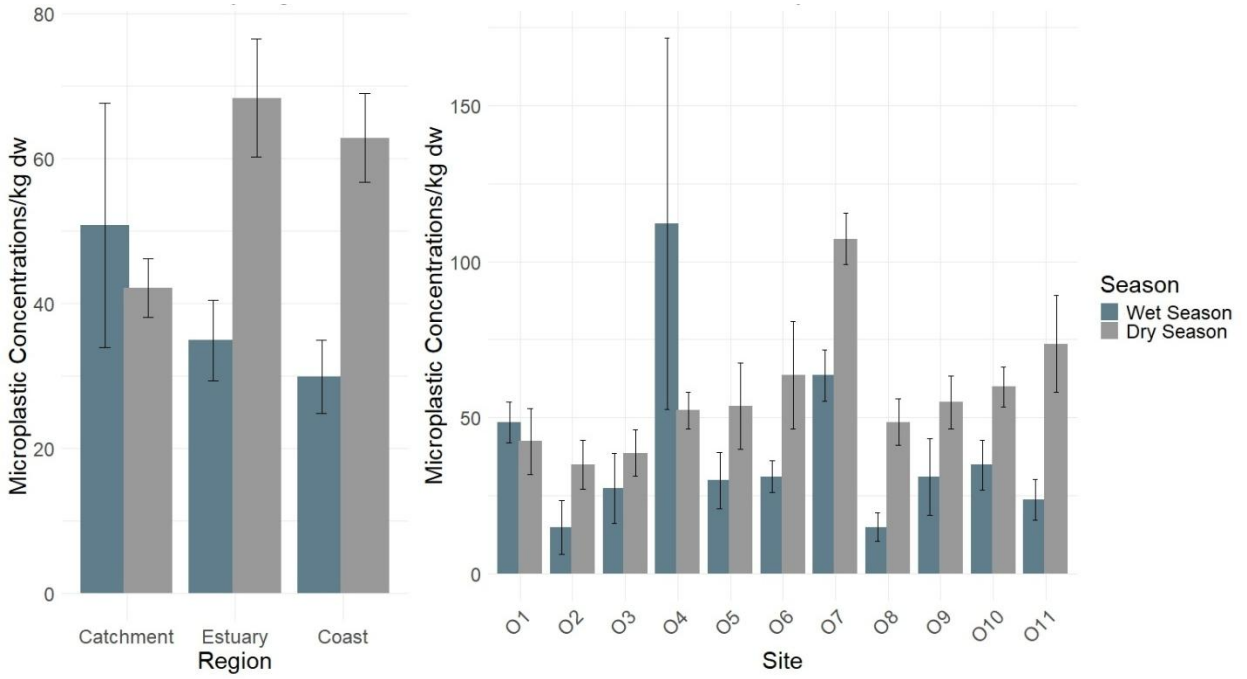

Figure 15: Microplastic concentrations sampled in the sediment along different regions (catchment, estuary & coast) and sites (O1 - O11) of the Olifants system during the wet and the dry season (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 99.5%, followed by foams (0.19%), films (0.16%) and fragments (0.15%) (Figure 16). The most dominant microplastic colour was black/grey comprising 41.7%, followed by transparent (35.6%) and blue/green (15.3%) coloured microplastics (Figure 17). The most dominant microplastic size class was 1000 - 2000 µm comprising 42.7%, followed by 500 - 1000 µm (41.6%) and 2000 - 5000 µm (15.0%) in size (Figure 18). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

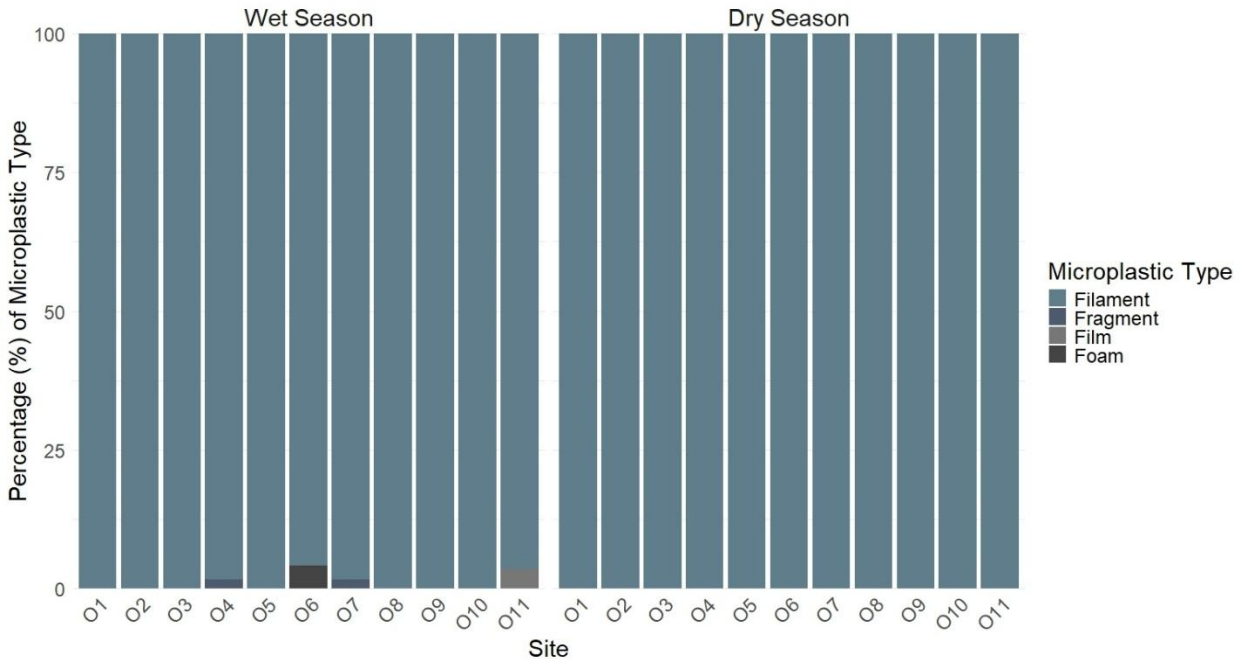

Figure 16: Percentage of microplastic types sampled in the sediment at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

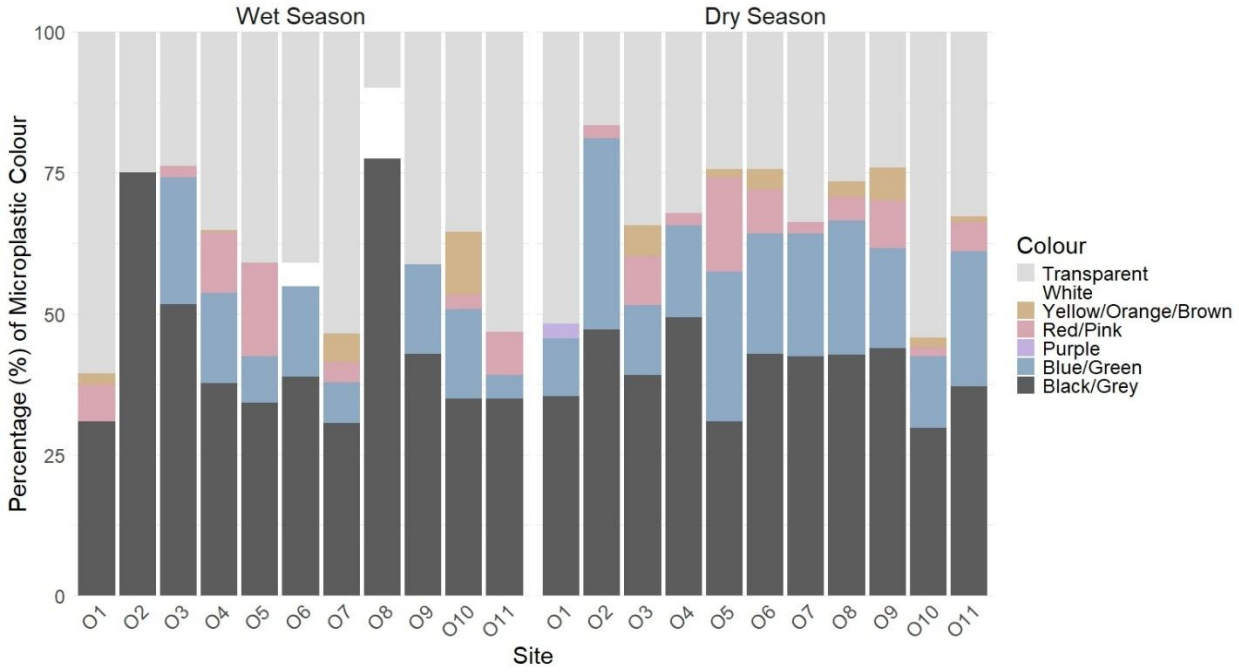

Figure 17: Percentage of microplastic colours sampled in the sediment at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

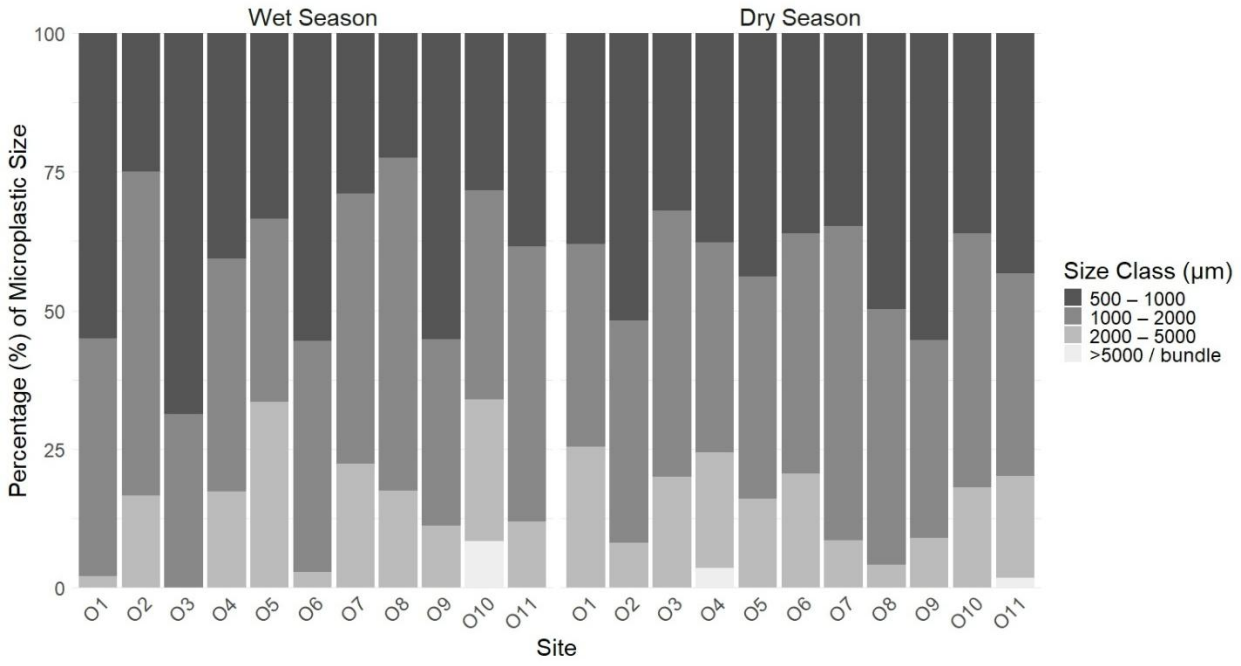

Figure 18: Percentage of microplastic size classes sampled in the surface water (250 µm) at the different sites (O1 – O11) along the Olifants system during the wet and the dry season

4.3.4 Microplastic polymer identification

All microplastic particles ≥ 500 µm were recorded and identified according to their polymer composition using FTIR analyses. Of these, 59% of particles were natural (cotton) and 1% were semi-synthetic, which were excluded from further polymer abundance estimates (Figure 19). Thus, for synthetic (40%) microplastics, polymers recorded in the water samples were mainly PET during both the wet (56.8%) and the dry (59%) season as well as in the catchment (70.6%), estuary (47.9%) and along the coastal region (60%) of the system. Similarly, polymers recorded in the sediment samples were also mainly PET during both the wet (70%) and the dry (88%) season as well as in the catchment (86.7%), estuary (75%) and along the coastal region (80.9%) of the system.

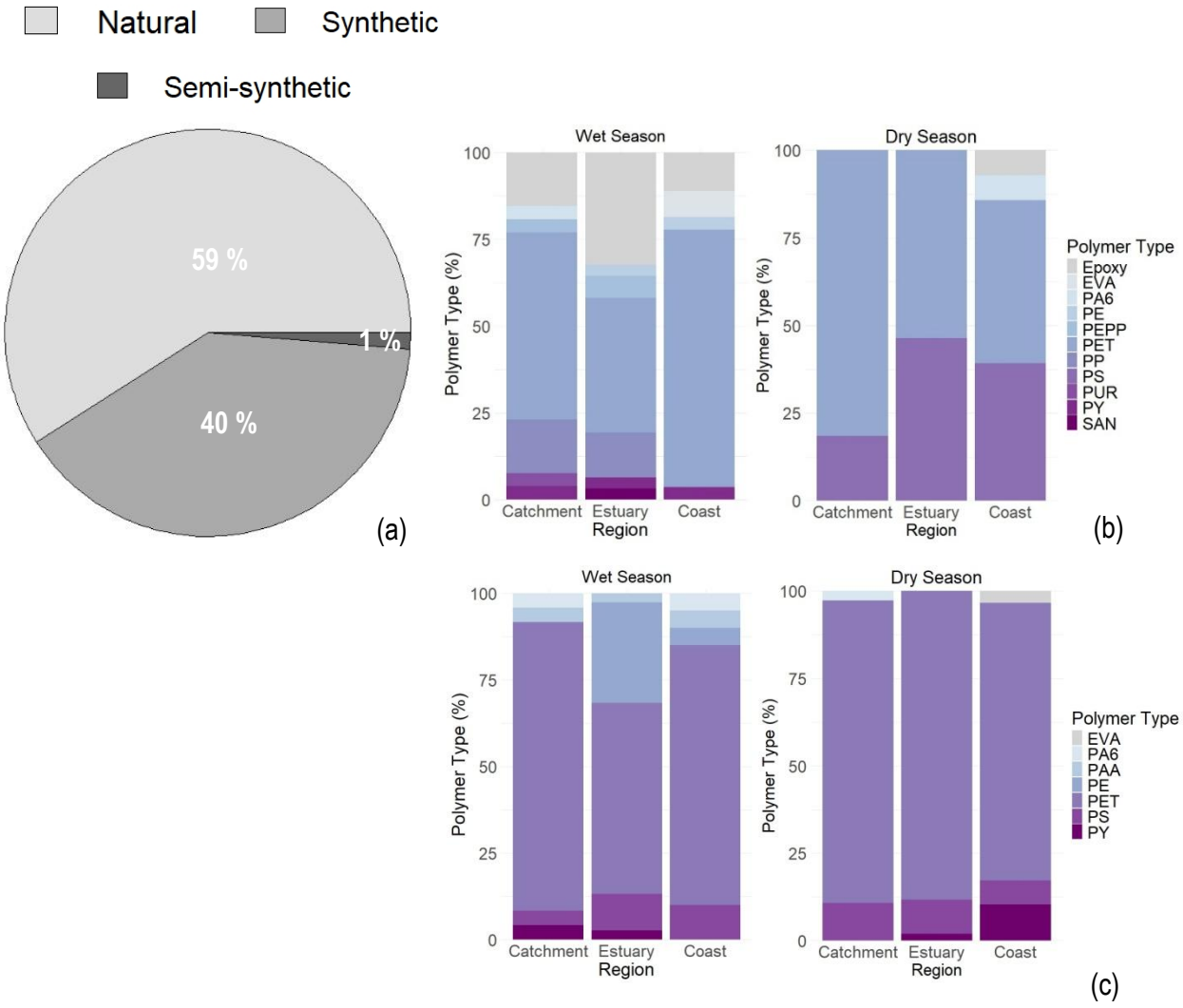

Figure 19: Percentage of microplastic composition in (a) all samples, seasons, regions and sites, microplastic polymer composition in (b) the surface water samples and in (c) the sediment samples collected during the wet and the dry season along the catchment (sites O1 - O4), estuary (sites O5 – O8) and coast (sites O9 – O11) (Epoxy: Epoxy Resin; EVA: Ethylene vinyl acetate; PA6: Polyamide 6 / nylon 6; PAA: Polyacrylic acid; PE: Polyethylene; PEPP; Polyethylene-polypropylene; PET; Polyethylene Terephthalate; PP: Polypropylene; PUR: Polyurethane; PS: Polystyrene; PY: Polyester: SAN: Styrene acrylonitrile).

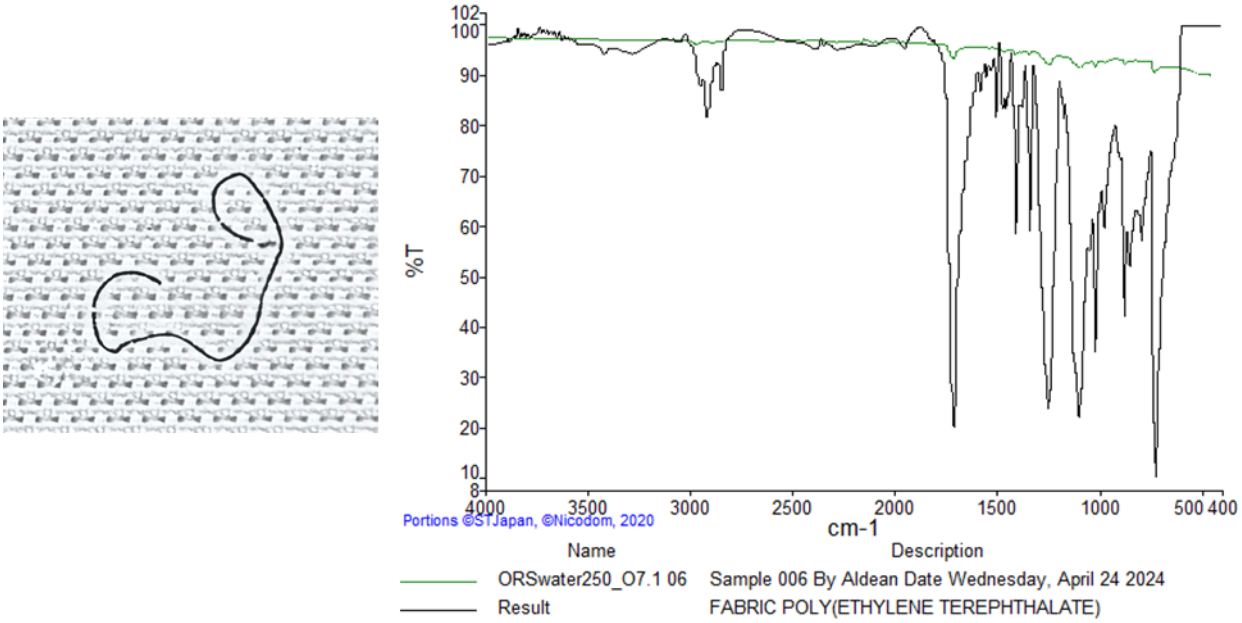

Figure 20: FTIR scan of black/grey PET fibre (1 – 2 mm) sampled in the surface water along the estuarine region of the Olifants system during the dry season

4.3.5 Grain size analysis

All sediment was classified as sand, with coarse (> 500 µm) and medium (250 - 500 µm) sized grain sediment being the most dominant followed by fine (125 - 250 µm) and very-fine (63 – 125 µm) sediment (Figure 21).

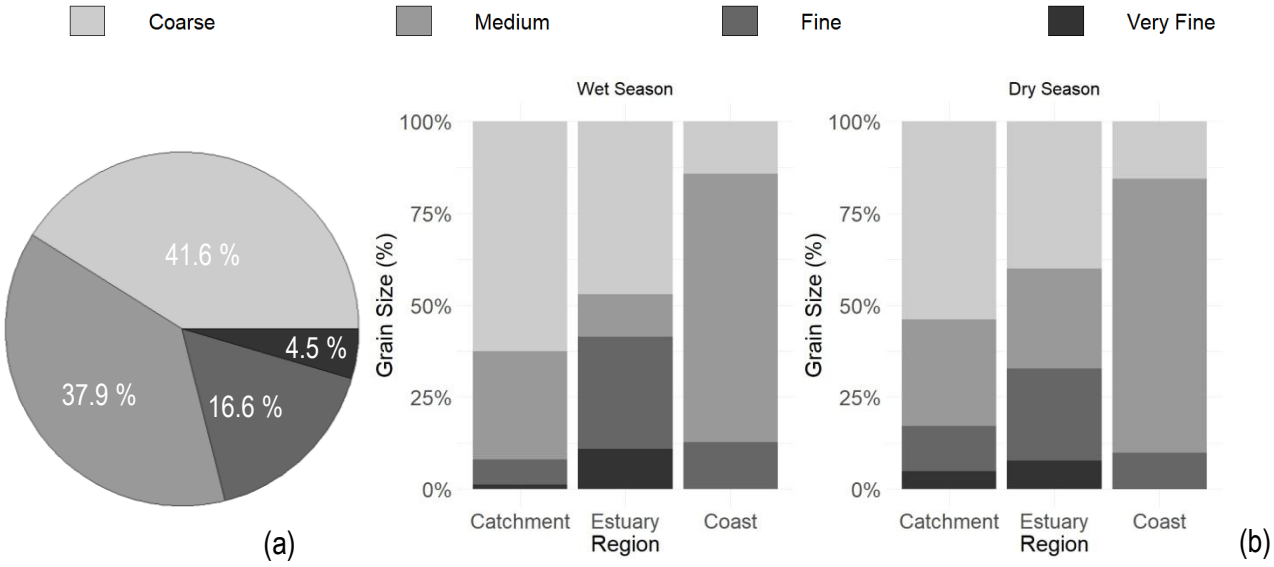

Figure 21: Grain size analysis of the sediment at (a) all seasons, regions and sites and (b) along the different regions of the Olifants system during the wet and the dry season.

4.3.6 Relationship between microplastics and environmental parameters

4.3.6.1 Surface water

For the water samples collected using the 63 µm sieve, the Spearman rank correlation coefficient indicated strong positive correlations and significant differences between microplastic concentrations and various environmental parameters (Table 5). During the wet season within the estuary, microplastic concentrations were positively correlated with salinity ($r = 0.67$, $p = 0.012$) and turbidity ($r = 0.67$, $p = 0.018$). In the dry season, significant positive correlations were observed between microplastic concentrations and temperature ($r = 0.68$, $p = 0.019$) within the catchment. Additionally, along the coast and pH ($r = 0.87$, $p = 0.002$) were also positively correlated with microplastic concentrations, all indicating significant differences.

Table 5: Spearman's rank correlation coefficient for the environmental parameters and microplastic concentrations sampled through 63 µm sieve µm within the different regions of the Olifants system

Region	Season	Temperature	Salinity	Turbidity	pH
Catchment	Wet	0.29	-0.01	-0.01	0.35
Catchment	Dry	0.68*	0.34	0.34	0.52
Estuary	Wet	0.38	0.67*	0.67*	0.11
Estuary	Dry	0.24	0.20	0.20	0.23
Coast	Wet	-0.35	-0.03	-0.12	0.20
Coast	Dry	0.60	0.27	0.27	0.87*

* Correlation is significant at $p < 0.05$

For the water samples collected using the 250 µm sieve, the Spearman rank correlation coefficient indicated strong positive correlations and significant differences between microplastic concentrations and various environmental parameters (Table 6). During the wet season, significant positive correlations were observed between microplastic concentrations and pH ($r = 0.85$, $p<0.001$) within the catchment. Along the coast, significant positive correlations were found between microplastic concentrations and salinity ($r = 0.77$, $p = 0.021$), turbidity ($r = 0.68$, $p = 0.053$) and pH ($r = 0.81$, $p = 0.010$). In the dry season, significant positive correlations were observed between microplastic concentrations temperature ($r = 0.74$, $p = 0.030$) and pH ($r = 0.82$, $p = 0.013$) along the coast.

Table 6: Spearman's rank correlation coefficient for the environmental parameters and microplastic concentrations sampled through 250 sieve µm within the different regions of the Olifants system

Region	Season	Temperature	Salinity	Turbidity	pH
Catchment	Wet	0.31	0.16	0.16	0.85*
Catchment	Dry	0.22	-0.06	-0.06	0.17
Estuary	Wet	0.27	0.47	0.47	0.43
Estuary	Dry	0.07	0.41	0.41	0.08
Coast	Wet	0.40	0.77*	0.68*	0.81*
Coast	Dry	0.74*	0.17	0.17	0.82*

*Correlation is significant at $p < 0.05$

4.3.6.2 Sediment

The Spearman's rank correlation coefficient showed no relationships between microplastics concentrations and grain size except for very-fine sand which indicated a positive relationship and significant difference ($r = 0.62$, $p = 0.014$) within the estuary during the wet season (Table 7).

Table 7: Spearman rank correlations between adjusted microplastic concentrations and percentage sediment grain size category (coarse sand: > 500 µm; medium sand: 250 – 500 µm; fine sand: 125 – 250 µm; very-fine sand: 63 – 125 µm based on region (catchment, estuary and coast) and season (wet and dry) in the Olifants system.

Region	Season	Coarse Sand	Medium Sand	Fine Sand	Very-Fine Sand
Catchment	Wet	-0.32	0.34	0.25	0.37
Catchment	Dry	0.13	-0.18	-0.31	-0.04
Estuary	Wet	-0.34	0.32	0.35	0.62*
Estuary	Dry	0.37	-0.29	0.20	0.40
Coast	Wet	0.13	-0.01	-0.30	0.12
Coast	Dry	-0.09	0.14	0.14	0.05

* Correlation is significant at $p < 0.05$

4.3.7 Disturbance index

The estuary of the Olifants system was the most disturbed region, with an average total disturbance rating of 10.3 (Figure 22). Disturbances ranged from low too high in intensity, with site O6 being the most disturbed with a TDR of 13.4 and site O8 being the least disturbed with a TDR of 6.1. The coastal region was the least disturbed, with an average total disturbance rating of 9.0. Disturbances ranged from low to moderate in intensity, with site O11 being the most disturbed with a TDR of 12.9 and site O10 being the least disturbed with a TDR of 6.3.

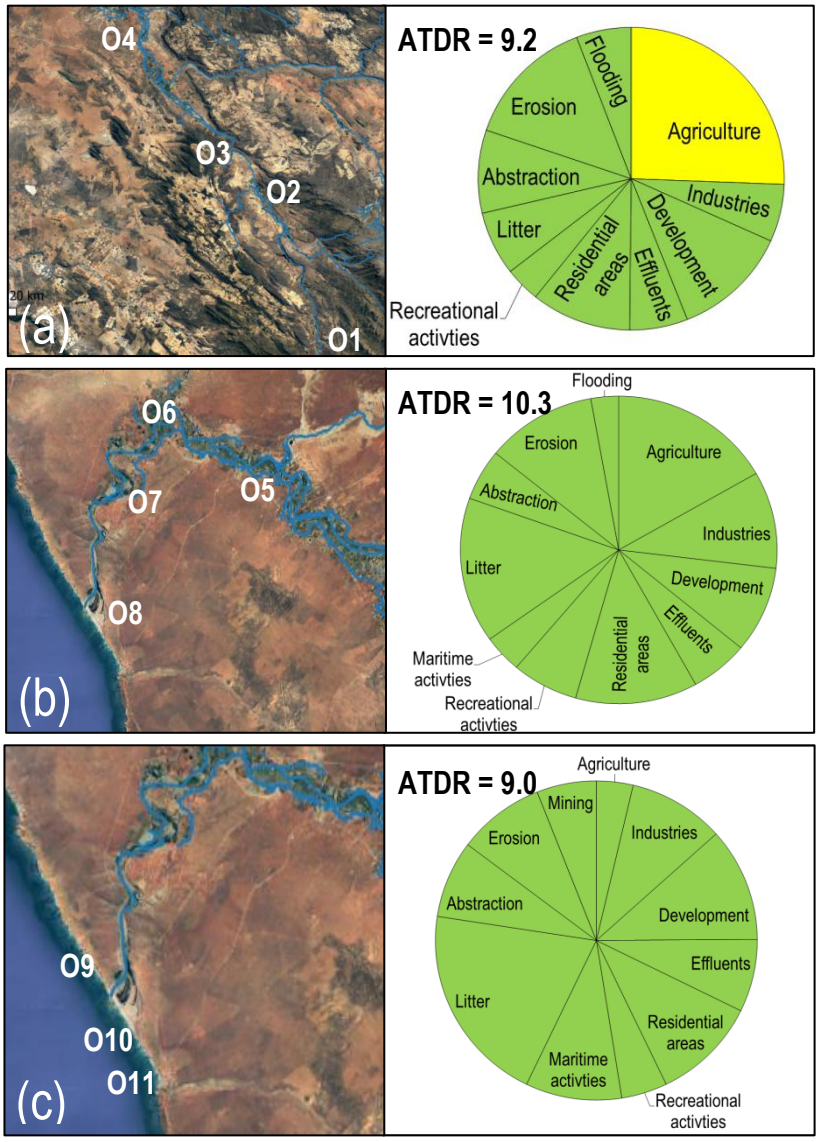

Figure 22: Disturbance index displaying the different land use types along the Olifants System within the (a) catchment, (b) estuary and (c) coastal areas. The pie chart displays the proportional contribution of each disturbance type to the average total disturbance rating (ATDR). Categories for the disturbance index are colour-coded as follows: absent = blue (0), low = green (1), moderate = yellow (2), high = orange (3) and very high = red (4).

4.3.8 Risk Assessment

Given that natural particles do not have a hazard score, these particles were excluded from the risk assessment.

For the risk assessment, the pollution load index (PLI) for both surface water and sediment within the different regions of the system were all categorised as pollution being present (> 1) in both the wet and the dry season (Table 8).

Table 8: Risk assessment for water (63 & 250 µm) and sediment sampled in the catchment, estuary and coastal regions of the system during the wet and dry season. Categories for the PLI are colour-coded as no pollution (blue) and pollution present (red) while categories for the H and PRI are colour-coded as low (blue), moderate (green), high (yellow), very-high (orange) and dangerous (red).

	Catchment			Estuary			Coast			
	PLI	H	PRI	PLI	H	PRI	PLI	H	PRI	PRI (season)
Water 63 (wet)	3.95	8.44	33.56	3.75	1303.40	48887.70	7.09	978.69	6943.30	11864.30
Water 63 (dry)	2.55	10.50	26.78	3.30	17.57	57.97	3.40	297.20	1010.50	1095.22
Water 250 (wet)	2.82	1129.93	3190.50	3.47	1658.20	5748.30	4.03	84.36	340.20	9278.94
Water 250 (dry)	3.32	7.47	24.76	4.00	14.11	56.44	2.97	344.31	1020.80	1102.01
Sediment (wet)	3.35	16.96	56.86	2.27	44.00	99.90	1.97	20.55	40.53	197.30
Sediment (dry)	2.81	8.05	22.63	4.56	6.60	30.11	4.19	47.30	198.54	251.30

The polymer risk index (H) values for water 63 ranged from low (catchment), very high (estuary) to high (coast) during the wet season and moderate (catchment & estuary) to high (coast) during the dry season. For water 250 values ranged from very high (catchment & estuary) to moderate (coast) during the wet season and low (catchment), moderate (estuary) to high (coast) during the dry season. For the sediment values were categorised as moderate (catchment, estuary & coast) during the wet season and ranged from low (catchment to estuary) to moderate (coast) during the dry season.

With the H values which indicate polymer hazards and the microplastic concentrations which indicate the pollution load index (PLI), these values provide an indication of the pollution risks (PRI) posed by the microplastics recorded within the system. The pollution risk index values for water 63 ranged from low (catchment) to dangerous (estuary & coast) during the wet season and low (catchment & estuary) to very high (coast) during the dry season. For water 250 values ranged from dangerous (catchment & estuary) to high (coast) during the wet season and from low (catchment & estuary) to very high (coast) during the dry season. For the sediment, values were categorised as low (catchment, estuary & coast) during the wet season and ranged from low (catchment & estuary) to moderate (coast) during the dry season. For the different sampling mediums, seasonally, PRI values for water were dangerous during the wet season and very high during the dry season but moderate in sediment during both the wet and the dry season.

4.4 Discussion

4.4.1 Spatiotemporal distribution of microplastics in surface water

There is a general trend in which microplastic concentrations in surface water are generally higher during the wet season compared to the dry season (Malli et al., 2022). This is mainly due to the increased hydrodynamic conditions typical of the wet season, which exacerbate microplastic inputs (Horton & Dixon, 2018; Talbot & Chang, 2022).In aquatic environments, hydrodynamic conditions such as precipitation and river flow play an important role in the level of microplastic contamination, particularly in surface water (Horton & Dixon, 2018; Govender et al., 2020). Several studies have reported higher microplastic concentrations in surface water during the wet season than in the dry season (Apetogbor et al., 2023; Samuels et al., 2024; Ariefdien et al., 2024), all of which were attributed to increased hydrodynamic conditions.

During the wet season, increased precipitation can lead to increased surface runoff, which can transport microplastics from terrestrial environments to aquatic environments, leading to increased concentrations (Horton & Dixon, 2018). Additionally, precipitation and increased river flow can remobilise microplastics that have become settled in the sediment (Horton & Dixon, 2018). During periods of heavy rainfall as well as increased river flow or strong tides, the resulting turbulence generated by these hydrodynamic conditions can enable microplastic particles to become re-suspended and return to the water column after being buried or having settled among the sediment, leading to further increases in the concentration of microplastics in the surface water (Hurley et al., 2020; Horton & Dixon, 2018; Mai et al., 2019).

However, since the results of this study showed no significant difference between the two seasons, it suggests that seasonality had no observable influence on the concentration of microplastics in the system. Similar findings have been observed by Dahms & Greenfield (2025) who also reported no significant temporal differences in the concentration of microplastics in the water of the Limpopo River Catchment in South Africa. However, average concentrations were much higher in the aforementioned study, ranging from 59 ± 46 particles/m^{-3} in the wet season to 1436 ± 4492 particles/m^{-3} in the dry season (Dahms & Greenfield, 2025), while average concentrations reported here ranged from 0.27 ± 0.02 particles/L in the wet season to 0.21 ± 0.01 particles/L in the dry season. Nonetheless, the relatively similar concentrations recorded here suggest that sources of contamination were consistent throughout the different seasons, rather than fluctuating in response to seasonal changes.

Since rivers and estuaries are lotic systems, they have relatively low retention times. As a result, they are capable of flushing out large amounts of contaminants (McLusky et al., 1993; Nel et al., 2018), particularly during the wet season, when hydrodynamic conditions become increased. Several studies have identified rivers and estuaries as major pathways for land-based sources of microplastics to reach coastal and marine environments (Moore et al., 2011; Mai et al., 2019; Latcheman et al., 2024).

It is estimated that more than 1000 rivers account for 80% of the global plastic emissions into the ocean (Meijer et al., 2021). Thus, rivers are known to serve as conduits, transporting land-based sources of microplastics to coastal and marine environments (Horton & Dixon, 2018). Similarly, estuaries are also known to serve as conduits, transporting plastics from catchments to the coast (Naidoo et al., 2015; Malli et al., 2022). For example, along the Zandvlei Catchment and Estuary in the Western Cape, South Africa, Samuels et al. (2024) reported increased microplastic concentrations closest to the estuary mouth which was attributed to increased river flow rates. Similarly, along the Buffalo River in the Eastern Cape, South Africa, Mvovo et al. (2025) reported higher microplastic concentrations at the lower reaches of the river which was attributed to increased river flow during the wet season.

Given that the hydrodynamic conditions of rivers and estuaries can facilitate the movement of microplastics, concentrations are thus expected to increase from the catchment toward the coast. Furthermore, in addition to land-based sources, microplastics along the coast may also originate from sea-based sources of contamination, further contributing to increased concentrations along the coast (Boucher & Friot, 2017). However, given that the results of this study were not significantly different across the different regions, it

suggests that the hydrodynamic conditions of the system had no influence on the concentration of microplastics. Similar findings have been observed by Apetogbor et al. (2023) who also reported no significant spatial differences in the concentration of microplastics in the water of the Plankenburg River in the Western Cape, South Africa. However, average concentrations were higher in the aforementioned study, ranging from 6.87 MPs/L to 9.25 MPs/L across all sampling sites (Apetogbor et al., 2023), while average concentrations reported here ranged from 0.20 ± 0.02 particles/L in the catchment to 0.29 ± 0.03 particles/L along the coast. Nonetheless, the relatively similar concentrations recorded here is likely a result of the consistent sources of contamination observed along the length of the system.

4.4.2 Spatiotemporal distribution of microplastics in sediment

The significantly higher microplastic concentrations observed during the dry season compared to the wet season suggests that hydrodynamic conditions can influence the accumulation of microplastics in sediment Similar findings have been observed by Mvovo et al. (2025) who also reported significantly higher microplastic concentrations in the dry season compared to the wet season in the sediment of the Buffalo River in the Eastern Cape, South Africa. However, concentrations were much lower in the aforementioned study, ranging from 14.87 ± 4.85 particles/kg^{-1} in the wet season to 20.73 ± 6.54 particles/kg^{-1} in the dry season (Mvovo et al., 2025), while average concentrations reported here ranged from 39.31 ± 6.58 particles/kg in the wet season to 57.30 ± 4.03 particles/kg in the dry season.

Contrary to microplastics in surface water, microplastic concentrations in sediment are generally higher during the dry season than in the wet season given that microplastics in sediment are expected to accumulate over time (Gray et al., 2018). Several studies have reported higher microplastic concentrations in sediment during the dry season (Weideman et al., 2020b; Nkosi et al., 2023; Dahms & Greenfield, 2025) suggesting an inverse relationship between microplastic accumulation and the hydrodynamic conditions typical of the dry season.

For example, both Nel et al. (2018) and Govender et al. (2020) observed elevated microplastic concentrations in sediment during the dry season. Although the results were not significant, according to these authors, the increased microplastic concentrations was attributed to reduced hydrodynamic conditions that occur during the dry season (Nel et al., 2018; Govender et al., 2020). Thus, as hydrodynamic conditions decrease, microplastic concentrations tend to increase.

During the dry season, when precipitation ceases and river flow rates decrease, turbulence becomes reduced (Nel et al., 2018; Horton & Dixon, 2018). This reduction in turbulence then leads to increased sedimentation, the process in which particles are removed from the water column as they settle and accumulate among the sediment (Costa et al., 2011; Horton & Dixon, 2018; Faulstich et al., 2022). Thus, during sedimentation, microplastics may either be simultaneously deposited with other particles or become buried after already having settled among the sediment (Horton & Dixon, 2018). Additionally, microplastics of a higher density may enhance sedimentation as they are more likely to sink, further contributing to the higher microplastic concentrations observed during the dry season (Horton & Dixon, 2018). Thus, the significantly higher concentrations observed in this study is attributed to the decreased hydrodynamic conditions that occur during the dry season, which enhance sedimentation and lead to greater microplastic accumulation in the sediment.

The sediment of rivers and estuaries are widely considered sinks for microplastic contamination as particles tend to accumulate in sediments, particularly particles of a higher density (Nel et al., 2018; Govender et al., 2020; Saad et al., 2024b). This accumulation typically occurs during the dry season, when hydrodynamic conditions such as river flow and turbulence become reduced, leading to enhanced microplastic deposition (Horton & Dixon, 2018; Nel et al., 2018; Faulstich et al., 2022).

Several studies have shown that sediment characteristics can influence microplastic deposition (Dahms et al., 2020; Silburn et al., 2023; Dahms & Greenfield, 2025). For example, environments dominated by fine-grained sediment, such as rivers and estuaries, are especially prone to accumulating microplastics by increasing deposition through flocculation (Tibbetts et al., 2018). Flocculation refers to a process where microplastics aggregate with other particles, increasing their density, causing them to settle more rapidly than individual microplastics (Andersen et al., 2021). Andersen et al. (2021) and Laursen et al. (2022) observed PVC and high-density polyethylene microplastics, respectively, flocculating with fine-grained sediments, which resulted in an increase in deposition rates. Thus, as sediment particle size decreases, microplastic concentrations tend to increase.

Additionally, biofouling can also contribute to higher microplastic concentrations observed in rivers and estuaries. Like flocculation, biofouling has the potential to alter the density of microplastics. These microplastic densities can be altered to such an extent that these particles eventually sink and accumulate in the sediment, leading to increased microplastic concentrations (Zhang, 2017). Kaiser et al. (2022)

reported a 16% increase in the sinking velocity of PS microplastics due to biofouling. Such processes have also been suggested in other riverine and estuarine environments elsewhere, where an increase in sediment microplastics have been observed (Alves & Figueiredo, 2019; Wu et al., 2020b)

Once deposited in the sediment of rivers and estuaries, microplastics can be retained within these environments for extended periods (Horton & Dixon, 2018), leading to their accumulation and thus allowing rivers and estuaries to serve as sinks for microplastic contamination. However, given that coastal and marine environments serve as the final sink, the role of rivers and estuaries as sinks is only temporary (Nel et al., 2018; Ryan, 2020a). Several studies have reported an increase in the concentration of microplastics in the sediment toward coastal and marine environments all of which have been attributed to hydrodynamic conditions facilitating the movement of microplastics downstream (Mai et al., 2019; Napper et al., 2023; Samuels et al., 2024).

Given that the results of this study were not significantly different across the different regions of the system, it suggests that the hydrodynamic conditions had no observable influence on the concentration of microplastics in the sediment. Similar findings have been observed by Johnson et al. (2023) who also reported no significant spatial differences in the concentration of microplastics in sediment of the Durban Bay and Mngazana estuaries. However, average concentrations were higher in the aforementioned study ranging from 99 particles/kg in Durban Bay to 82 particles/kg in Mngazana (Johnson et al., 2023), while average concentrations reported here was 48.30 ± 3.95 particles/kg dw. Nonetheless, the relatively similar concentrations observed here are attributed to the consistent sources of contamination observed along the length of the system.

4.4.3 Microplastic concentrations across 63 µm and 250 µm size fractions

There is a general trend for microplastic concentrations to be higher when sampled using sieves with smaller mesh sizes compared to larger mesh sizes (Ryan et al., 2020c). This is due to microplastic particles, fibres in particular, being smaller than the mesh size of sieves. As a result, the use of coarser mesh sizes often leads to a loss of particles as fibres can pass through the mesh, leading to an underestimation in abundance estimates (Ryan et al., 2020c; Sui et al., 2025).

Thus, given that finer mesh sizes are able to capture greater microplastic particles (Ryan et al., 2020c; Sui et al., 2025), it is expected that the 63 µm sieve would capture more microplastics than the 250 µm sieve size. However, even though the results in this study were not significant and microplastic concentrations

were similar in the 63 µm and the 250 µm sieve size, both Apetogbor et al. (2023) and Sui et al. (2025) reported higher microplastic concentrations when using finer mesh sieves compared to coarser ones.

4.4.4 Microplastic characteristics

The dominant microplastic type in both the surface water and the sediment were fibres. Similar results have been reported by Nel & Froneman (2015), Govender et al. (2020) and Johnson et al. (2023) all of who reported large proportions of fibres. The high abundance of fibres found in aquatic environments has been linked to wastewater effluents. Although wastewater effluents are treated before being released into the environment, fibres, given their small size, are able to bypass filters used during the treatment process, with removal rates exceeding 98% and 99% (Murphy et al., 2016; Talvitie et al., 2017). Although these removal rates seem significant, the small percentage that remains can amount to millions and even trillions of microplastics that get released into the environment (Murphy et al., 2016; Nizzetto et al., 2016), making WWTPs generally inefficient in removing microplastics.

Given the systems proximity to residential areas, domestic as opposed to industrial wastewater effluents is more likely the primary source of fibres found in the system. Sources of domestic wastewater effluents include fibres which have been shed during the washing of clothes and various textile transported via stormwater outlets (Samuels et al., 2024; Ariefdien et al., 2024). Domestic effluents from Informal settlements may however also release fibres into the system. South African residents that reside in rural communities often don't have access to piped water and thus utilise rivers as their primary source of water, often for the washing of clothes, releasing high a high abundance of fibres into the environment (de Villiers, 2019; Julius et al., 2023).

The dominant microplastic colour in both the surface water and sediment was black/grey. These results differ from previous findings that reported transparent microplastics as the dominant microplastic colour (Govender et al., 2020; Apetogbor et al., 2023; Samuels et al., 2024). However, given that colour can influence the bioavailability of microplastics, reporting microplastic colour becomes important, especially due to the increasing reports of microplastic ingestion (Naidoo et al., 2016; Reynolds & Ryan, 2018; Naidoo et al., 2020). Black coloured microplastics have been shown to be preferentially captured by fish when they resemble prey items, as demonstrated experimentally by (Ory et al., 2018). Both Sparks et al. (2023) and Ferguson et al. (2024) have reportedly observed black coloured microplastics in the stomach contents of

aquatic organisms. This is particularly concerning due to the high abundance of black/grey coloured microplastics observed in the current study.

The dominant microplastic size classes in both water and sediment were 500 – 1000 µm and 1000 – 2000 µm. The higher abundance of smaller microplastics may be attributed to the increased hydrodynamic conditions typical of lotic environments. Decreased residency times, combined with increased flow rates and friction, can enhance the fragmentation of microplastics, leading to a greater abundance of smaller-sized microplastics (Cornelius, 1968; Zhang et al., 2019). Given that smaller microplastics have a greater potential for ingestion by aquatic organisms, the greater abundance of these particles observed in this study further raises concerns on accidental microplastic ingestion.

4.4.5 Microplastic polymer identification

The high abundance of natural particles and/or natural fibres observed in the study is to be expected given that natural fibres are far more ubiquitous than synthetic fibres (Kwak et al., 2022). Similar findings have been observed by Weideman et al. (2023) who reported a higher abundance of natural particles than synthetic particles along the coast of Tanzania and northern Mozambique in East Africa. Apetogbor et al. (2023) also reported a higher abundance of cotton fibres than synthetic fibres in the Plankenburg River in the Western Cape, South Africa.

Distinguishing between natural and synthetic fibres does however present challenges especially when relying on microscopy for visual identification alone (Ryan et al., 2020c). These challenges often lead to fibres being excluded from abundance estimates. However, despite its natural composition, natural fibres can be ingested by aquatic organisms and can lead to clogging of the gut, similar to that of synthetic fibres (Halstead et al., 2018; Kim et al., 2021). Thus, it should be noted that for this study, all microfibres (natural & synthetic) have been included in abundance estimates.

Apart from the high abundance of natural fibres observed in this study, polyethylene terephthalate was the most prevalent synthetic polymer type recorded for both surface water and sediment, across all seasons and all regions. Although PET has a high density (1.37 – 1.45 g/cm^3) and subsequent high settling rate (Parolini et al., 2020) hydrodynamic conditions such as river flow, currents and tides can allow settled particles to become resuspended within the water column (Horton & Dixon, 2018; Hurley et al., 2020; Mai et al., 2018), explaining its high abundance in both surface water and sediment.

PET is considered as one of the most common polymer types utilised in plastic production (PlasticsEurope, 2023). PET fibres are utilised in the manufacturing of textiles and synthetic clothing (Jessieleena et al., 2023). Similarly, natural fibres, are also used for clothing and textiles such as cotton, silk, linen and wool (Ryan et al., 2020c). These microfibres, both natural and synthetic, are commonly found in aquatic environments and are often derived from domestic effluents from residential areas transported via wastewater treatment works or through stormwater outlets (Jessieleena et al., 2023).

Domestic effluents, particularly domestic laundry effluents, are known sources of high microfibre abundances (Jessieleena et al., 2023). The very first study on microplastics in domestic laundry effluent was conducted by Browne et al. (2011) who reported that for a single item of clothing 1 900 fibres are released per wash. Approximately 1.5 million tons of fibres are released into the ocean, 975 000 of which are derived from domestic laundry effluents (Boucher & Friot, 2017). These studies highlight the significant contribution of domestic laundry effluents to microplastic contamination within the environment. It is thus postulated that the high abundance of both natural and PET fibres reported here are likely derived from domestic wastewater effluents from residential areas transported through wastewater treatment works and stormwater outlets.

Additionally, domestic effluents from informal settlements may also be linked to the high abundance of both natural and PET fibres. In South Africa residents that reside in rural communities often do not have access to piped water and thus utilise rivers as their primary source of water (de Villiers, 2019). Thus, these water sources are often utilised for the washing clothes, directly releasing high concentrations of fibres into these environments (de Villiers, 2019; Julius et al., 2023).

The high abundance of microfibres observed in this study is thus a concern given that both natural and synthetic fibres can be treated with chemical additives (Stone et al., 2020; Granek et al., 2022). Microfibres are also capable of adsorbing chemical contaminants, natural fibres even more so, enabling fibres to serve as vectors, transporting chemical contaminants into the environment and to aquatic organisms (Grancaric et al., 2005; Granek et al., 2022). Additionally, the relatively quick degradation of natural fibres compared to synthetic fibres, may facilitate its toxicity. The quick degradability of natural fibres may potentially result in the quicker release of chemical contaminants (Ladewig et al., 2015; Granek et al., 2022) making natural fibres more toxic than synthetic fibres, however further research is needed to determine the effects of microfibres in the environment.

4.4.6 Relationship between microplastics and environmental parameters

4.4.6.1 Surface water

- Temperature

Temperature was positively correlated to microplastic concentrations in the catchment (63 µm) and along the coast (250 µm) during the dry season. However, temperature is not considered the direct driver of microplastic formation over short timescales. Rather, it is interpreted as a proxy for seasonal conditions like the dry season which is characterised by reduced hydrodynamic conditions such as river flow. During the dry season, when temperatures increase, hydrodynamic conditions such as river flow decreases. Decreased river flow during the dry season can result in a decrease in the diffusion and downstream transport of microplastics (Liu et al., 2022) allowing particles to be retained in river catchments for extended periods, leading to increased concentrations (Nel et al., 2018; Talbot & Chang, 2022).

Along the coast, increased prolonged exposure of microplastics to environmental conditions typical of the dry season, including increased ultra-violet (UV) solar radiation and wave action, may enhance fragmentation processes over time, contributing to higher microplastic concentrations (Horton et al., 2017). Thus, the observed positive correlation between microplastic concentrations and temperature is interpreted as reflecting seasonal hydrodynamic and environmental conditions.

- Salinity

Salinity was positively correlated to microplastic concentrations in the estuary (63 µm) and along the coast (250 µm) during the wet season. Estuarine (lower reaches) and coastal environments typically have higher water densities due to their high levels of salinity. These high levels of salinity result in an increase in water density (Talley, 2002; Jiang et al., 2020b). The positive correlation observed between microplastic concentrations and salinity may thus be attributed to the high density of saline waters as a higher density leads to higher buoyancy rates, enabling microplastics to float and accumulate on the surface of the water, leading to increased microplastics concentrations in the water column (Jiang et al., 2020b).

- Turbidity

Turbidity was positively correlated to microplastic concentrations in the estuary (63 µm) and along the coast (250 µm) during the wet season. The turbidity in estuarine and coastal environments is typically

higher during the wet season as opposed to the dry season as it driven by increased precipitation, consistent freshwater inflows transporting suspended sediments, wind, currents and waves (Gillanders & Kingsford, 2002; Seers & Shears, 2015; Zhou et al., 2021). These turbulent forces not only increase turbidity but allow microplastic to become re-suspended within the water column (Gillanders & Kingsford, 2002; Seers & Shears, 2015; Zhou et al., 2021). Thus, the positive correlation between microplastic concentrations and turbidity may be attributed to the increased hydrodynamic conditions that occur during the wet season, which lead to an increase in turbidity and the re-suspension of microplastics, leading to greater concentrations in the water column.

- pH

pH was also positively correlated to microplastic concentrations in the catchment (250 µm) during the dry season and along the coast (63 & 250 µm) during both the wet and the dry season. This may be due to pH's ability to influence the surface charge of particles in aquatic environments. When water conditions are acidic, at low pH levels (< 3), microplastics retain an electrostatic force of attraction (Lu et al., 2018; Kumar et al., 2021). This attraction leads to flocculation of microplastics, where particles aggregate together, leading to an increase in their density which causes them to sink. In contrast, when water conditions are more neutral or more basic, at higher pH levels (> 6.5 and < 9), microplastics retain an electrostatic force of repulsion (Kumar et al., 2021). This force of repulsion prevents microplastics from aggregating, decreasing their ability to sink and leading to increased concentrations in the water column. Thus, the positive correlation observed between microplastic concentrations and pH is attributed to microplastics retaining an electrostatic force of repulsion at higher pH levels.

4.4.6.2 Sediment

- Grain size

There was a positive correlation and significant difference between microplastic concentrations and very-fine sand within the estuary during the wet season. This suggests that very-fine sand can influence the movement and accumulation of microplastics and further explains the higher microplastic concentrations observed within the estuary. Similar findings have been reported by Dahms et al. (2020) and Dahms & Greenfield (2025) who observed a relationship between fine sediment and the concentration of microplastics.

Environments dominated by fine and very-fine sediment tend to enhance microplastic deposition, as these sediments adhere to microplastics, leading to flocculation (Harris, 2020). This is particularly likely if these fine sediments have a high organic content, which could then also lead to bio-fouling (Alves & Figueiredo, 2019; Harris, 2020). These processes are especially prevalent in high-turbidity estuarine environments, where microplastic deposition is enhanced due to increased settling rates and burial (Andersen et al., 2021).

4.4.7 Disturbance index

In aquatic environments, microplastics have often been linked to anthropogenic disturbances, with higher concentrations often reported in areas with higher levels of disturbances (Naidoo et al., 2015; Townsend et al., 2019; Li et al., 2023). Thus, it has become increasingly important to identify microplastic hotspots and potential sources of contamination.

The Olifants system is subjected to varying levels of anthropogenic disturbances (Western Cape Government, 2021a). Disturbances such as agricultural, industrial and recreational activities, residential areas, mining and development were all well observed throughout this study, all of which are known to significantly contribute to microplastic contamination (Horton & Dixon, 2018; Shikwambana et al., 2024). Located in the Matzikama municipal area, the Olifants system is considered rural (Western Cape Government, 2021b). As a result, the system was not as disturbed as other systems located in more urbanised settings (Govender et al., 2020; Johnson et al., 2023). Nonetheless, the estuarine region was the most disturbed across the different regions (ATDR of 10.3) with the system predominantly surrounded by agricultural land-use.

Agriculture serves as the foundation of the region's economy (Western Cape Government, 2021a). However, despite its importance, agricultural land-use can degrade water quality, particularly through irrigation and agricultural runoff as it can transport contaminants, such as microplastics, into aquatic environments (Horton & Dixon, 2018; Western Cape Government, 2021a). High microplastic concentrations have been linked to agricultural land-use as sewage sludge, the by-product of wastewater treatment, is commonly used as fertiliser (Horton & Dixon, 2018).

Although wastewater treatment can remove significant amounts of microplastics, most of these particles are retained in the resulting sewage sludge (Horton & Dixon, 2018). For example, Lv et al. (2019) and Ziajahromi et al. (2021) both reported high microfibre concentrations in the sewage sludge of wastewater.

Moreover, these studies have suggested that laundry effluents were the likely source of these fibres as they were predominantly composed of PET (Lv et al., 2019; Ziajahromi et al., 2021). These findings highlight a link between the microplastics from residential areas and the microplastics from agricultural land-use.

Thus, given that sewage sludge may contain high concentrations of microplastics, the use of this sludge as fertiliser may significantly contribute to the accumulation of microplastics in the environment. Nizzetto et al. (2016) and Schell et al. (2022) both reported high microplastic concentrations in agricultural soils after sewage sludge application. While these microplastics may be retained within the soil for extended periods (Nizzetto et al., 2016; Schell et al., 2022), hydrodynamic conditions such as increased surface runoff due to precipitation can transport these particles from terrestrial to aquatic environments (Horton & Dixon, 2018). Thus, given that the Olifants system is predominantly surrounded by agricultural land-use, agricultural disturbances may serve as another significant source contributing to the accumulation of microplastics in the system.

4.4.8 Risk assessment

For the 63 µm water samples, the H values was highest in the estuary (very high) compared to the catchment (low) and coast (high) during the wet season. The higher H values along the estuary and coast was attributed to the polymer epoxy with its high hazard score which was present along both the estuary and the coast (Lithner et al., 2011). The PRI values were highest along the estuary (dangerous) and coast (dangerous) during the wet season. These higher values may have been attributed to the hydrodynamic conditions of the system as during the wet season, increased flow rates can flush particles from the catchment toward the estuary and coast (McLusky et al., 1993; Nel et al., 2018), leading to increased microplastic concentrations along these regions (estuary & coast) during the wet season. During the dry season, the H values were highest along the coast (high) compared to the catchment (moderate) and estuary (moderate) during the dry season. The higher H value observed along the coast was again attributed to the polymer epoxy (Lithner et al., 2011) which was present along the coastal region of the system. The PRI values were also highest along the coast (very high) compared to the catchment (low) and estuary (low) during the dry season which may have been attributed to the hydrodynamic conditions of the system. During the dry season the microplastics retained within the catchment and estuary will eventually settle among the sediment due to low flow rates and a decrease in turbulence (Nel et al., 2018; Alves & Figueiredo, 2019), resulting in less particles in the water column. However, along the coast, the system is

subjected to daily and monthly tidal movements, regardless of season, and can thus allow settled particles to become resuspended in the water column (Malli et al., 2022), increasing microplastic concentrations along the coast during the dry season. These results indicate that the microplastics that accumulate in the estuary (wet season) and along the coast (dry season) pose a greater risk to the system. Seasonally, the PRI value was higher during the wet season (dangerous) as opposed to the dry season (very high) thus indicating that the microplastics that accumulate in the surface water during the wet season poses a greater risk to the system than the microplastics that accumulate during the dry season.

For the 250 µm water samples, the H values were highest along the catchment (very high) and estuary (very high) compared to the coast (moderate) during the wet season. The higher H values along the catchment and estuary was attributed to the polymers epoxy and styrene acrylonitrile (SAN) present along the catchment and estuary which both have high hazard scores (Lithner et al., 2011). The PRI values were highest along the catchment (dangerous) and estuary (dangerous) during the wet season which may be attributed to the hydrodynamic conditions of system as greater microplastic inputs occur during the wet season (Horton & Dixon, 2018) as well as due to the catchment and estuary's proximity to sources of contamination (Grbić et al., 2020; Talbot & Chang, 2022). This indicates that the microplastics that accumulate along the catchment and estuary during the wet season pose a greater risk to the system than those that accumulate along the coast. Contrastingly, during the dry season, the H values were highest along the coast (high) compared to the catchment (low) and estuary (moderate) during the dry season. These higher H values were also attributed to the polymer epoxy which was present along the coastal region of the system. The PRI values were also highest along the coast (very high) compared to the catchment (low) and estuary (low) during the dry season which may be attributed to the hydrodynamic conditions of the system. Given that the hydrodynamic conditions in catchments, and to some extent in estuaries, become reduced during the dry season, it allows for increased settling rates of microplastics (Nel et al., 2018; Alves & Figueiredo, 2019) thus decreasing microplastic concentrations in the water column. However, along the coast, the system experiences daily and monthly tidal movements which can resuspend particles that have settled (Malli et al., 2022), increasing microplastic concentrations along the coast during the dry season. These results indicate that the microplastics that accumulate along the coast during the dry season pose a greater risk to the system than those that accumulate along the catchment and estuary. Seasonally, and like the 63 µm water samples, the PRI values was higher during the wet season (dangerous) compared to the dry season (very high) again indicating that the microplastics that

accumulate in the surface water during the wet season poses a greater risk to the system than the microplastics that accumulate during the dry season.

For the sediment samples, both H and PRI ranged from low to moderate across all regions during both the wet and the dry season. Seasonally, PRI values were moderate for both the wet and the dry season. A variety of polymer types were observed in the sediment across the different region during both the wet and the dry season, however, these polymers were generally of a lower hazard score than the polymers observed in the surface water. For example, PET, despite the high abundance of PET fibres found in this study, and particularly in the sediment, PET only has a hazard score of 4 (Lithner et al., 2011) and thus the low to moderate risks in the sediment is attributed to the lower hazard scores of the polymers. However, despite the low to moderate risk for the polymers found in the sediment, the results still indicate that there is risk to the system although it may not be as significant when compared to the risk of polymers in the surface water.

The results from this study indicate that the higher H values are attributed to the polymers epoxy, styrene-acrylonitrile (SAN) and polyester (PY) as these polymers have high hazard scores. The high hazard scores for both epoxy and SAN are a result of these polymers being made up of at least one monomer which is considered to be carcinogenic (Lithner et al., 2011). Whereas the high hazard score for PY is linked to respiratory issues and skin sensitisation which may occur after exposure (Lithner et al., 2011). The higher PRI values were attributed to the microplastic concentrations and the hydrodynamic conditions affecting the movement and accumulation of microplastics. Additionally, the risk assessment also indicated that the microplastics in the water pose a greater risk than the microplastics in the sediment, particularly during the wet season. Similar findings have been observed by Samuels et al. (2024) who also reported dangerous rankings for the microplastic in the water of the Zandvlei Catchment and Estuary in the Western Cape, South Africa. The Zandvlei Catchment and Estuary falls within an urban matrix and thus microplastic concentrations were higher (2.62 ± 0.41 MP/L) than the concentrations in the present study (0.24 ± 0.01 particles/L). However, given the similar dangerous rankings observed in the aforementioned study, it highlights that the risks posed by microplastics are mainly influenced by the composition of polymers and their assigned hazard scores as opposed to their concentrations.

The dangerous rankings recorded for the water in the catchment, estuary and coast poses a serious threat to the Olifants system. Given the high abundance of marine resources along the West Coast as well as the

reliance of the local fishing communities on those marine resources, it provides a valid reason for the development and implementation of necessary risk reduction measures in order to enhance the protection of the biodiversity within the system as well as the ecosystem as a whole (Lithner et al., 2011).

4.5 Conclusion

The aim of the study was to determine the environmental concentrations, characteristics and risk assessment of microplastics in the Olifants River catchment, estuary and coastal areas in the Western Cape, South Africa. This was the first study to report on microplastic contamination in the Olifants system within the context of catchment-to-coast. Average microplastic abundances were 0.24 ± 0.01 particles/L in water and 48.3 ± 4.0 particles/kg dry weight in sediment samples across the sampling sites. The results for this study were similar for surface water and sediment across the different regions and seasons and were thus not reflective of any spatial or seasonal variations. The predominant microplastic characteristics recorded in this study were black/grey fibres, 500 – 100 µm and were mainly of natural origin, while polyethylene terephthalate was the dominant synthetic polymer type. The high abundance of fibres was attributed to the laundering of clothes from residential areas entering the system through wastewater treatment works and stormwater outlets. The high abundance of fibres poses a threat to the health of the Olifants system and potentially poses an ecological risk to its overall functioning. Given that the Olifants system plays an important role in maintaining its marine resources and is of both ecological and socio-economic significance, the monitoring of the system is crucial. The high concentrations of microfibres reported here thus provides a baseline and further emphasises the need for future monitoring and research efforts either to identify microplastic hotspots or to identify the major pathways in which these microplastics enter the system. This study does however also serve to inform policy makers that govern the protection of the Olifants system, so that they may be able to develop and implement appropriate mitigation measures to enhance the protection of this system.

Chapter 5: Environmental concentrations, characteristics and risk assessment of microplastics in the Breede catchment, estuary and coastal areas, Western Cape, South Africa

Abstract

Microplastic (< 5mm) contamination is now increasingly being reported in South African aquatic envrionments but few studies have been done from catchment to coast. Therefore, the aim of this study was to determine the concentrations, characteristics and risk assessment of microplastics in the Breede River catchment, estuary and coastal areas. Surface water and sediment were sampled and analysed for microplastics along the catchment, estuary and coast in the wet and the dry season in relation to disturbances acting in on the system. Microplastics were extracted and identified using microscopy and fourier transform infared spectroscopy (FTIR) analyses. Seasonally, average microplastic concentrations in water were similar and ranged from 0.27 ± 0.03 particles/L to 0.26 ± 0.03 particles/L during the wet and the dry season. Average microplastic concentrations in sediment were significantly different ($p < 0.05$) and ranged from 35.20 ± 2.76 particles/kg to 52.11 ± 4.40 particles/kg dry weight in the wet and the dry season, respectively. Spatially, average microplastic concentrations in water were similar and ranged from 0.31 ± 0.04 particles/L in the catchment, 0.23 ± 0.02 particles/L in the estuary and 0.25 ± 0.03 particles/L along the coast and in sediment. Average microplastic concentrations in sediment were significantly different ($p < 0.05$) and ranged from 40.23 ± 6.49 particles/kg dw in the catchment, 41.63 ± 4.77 particles/kg dw in the estuary and 48.01 ± 2.92 particles/kg dw along the coast. Microplastics were mainly black/grey fibres, 500 – 1000 µm in size and polyethylene terephthalate (72%) was the most common polymer type recorded. Pollution load indices indicated that pollution was present (> 1) throughout the different regions of the system during both the wet and the dry season for both water and sediment. Polymer risk indices ranged from low (4.00) to high (942.20) in the water and from low (4.00) to moderate (57.70) in sediment. Spatially, pollution risk indices in water was categorised as dangerous in the catchment during the wet season (6790.50) and along the coast during the wet (2746.40) and the dry season (3136.10) while in sediment indices were high (421.80) in the estuary during the wet season. Seasonally, pollution risk indices in water were categorised as dangerous during the wet (63 µm: 1223.30 & 250 µm: 9605.10) and the dry season (3273.20), while ranging from high (703.20) to low (104.40) in the sediment during the wet and the dry season , respectively. The results from this study serves a baseline for future reaserch efforts and to inform policy makers that govern the protection of the Breede system so they may be able to develop and implement regular monitoring and the necessary mitigation measures to reduce contamination

within the system. The Breede system is an ecological important system both for its unique biodiversity and its high level of endemism. The results from the risk assessment does however indicate that the polymers in water during the wet season pose a threat to the overall health and functioning of the Breede system from catchment-to-coast. Thus, regular monitoring of the system is crucial.

5.1 Introduction

Given that the amount of plastic released into the environment currently exceeds recovery rates, the prevalence of microplastics (1 µm to 5 mm) have become a global environmental concern (Auta et al., 2017; Frias & Nash, 2019; Vivekanand et al., 2021). This prevalence is largely driven by the high demand for plastic products (PlasticsEurope, 2022) and inadequate waste management, particularly in developing countries such as South Africa (Jambeck et al., 2015).

South Africa is known to significantly contribute to plastic emissions into the ocean (Verster & Bouwman, 2020), with research on microplastics in the country dating back to the 1980's (Ryan, 1988; Ryan & Moloney, 1990). Although research on microplastics initially focused on coastal and marine environments, more recent research has expanded to include freshwater and estuarine systems (Govender et al., 2020; Johnson et al., 2023; Samuels et al., 2024; Khan et al., 2025). However, research investigating microplastics across connected aquatic environments, such as from catchment-to-coast, remains limited.

Considering that freshwater, estuarine and coastal and marine environments are closely connected (Horton & Dixon, 2018), this gap in research is concerning, especially in South Africa as the country's rich biodiversity may be adversely affected by microplastic contamination (Griffiths et al., 2010). Thus, understanding the distribution of microplastics from catchment to coast is essential for the development and implementation of informed mitigation measures in order to protect South Africa's biodiversity (Meijer et al., 2021).

The Breede system is a region of significant endemism, supporting a high level of biodiversity. The Breede Estuary, in particular, supports 59 fish species, 65% of which are endemic (Harrison, 2002; Western Cape Government, 2025). Additionally, 30% of these species depend on the estuary to complete their lifecycle, making the Breede system critical as both a habitat and nursery site (Western Cape Government, 2025). Despite its ecological significance, the Breede system faces numerous environmental pressures including, urban development, agriculture, industrial activities, forestry, mining, recreational activities and tourism, all

of which can contribute to microplastic contamination within the system (Horton & Dixon, 2018; Western Cape Government, 2025).

Although prior research on microplastics has been conducted in the Breede Estuary, the focus was on investigating concentrations in two species of estuarine mullet (Elliott, 2023), no prior research investigated the concentration of microplastics in the Breede system from catchment to coast. Thus, the aim of this study is to determine the environmental concentrations, characteristics and risk assessment of microplastics in the Breede River catchment, estuary and coastal areas. This study will serve as a baseline for future investigations and will 1) identify microplastic concentrations and characteristics within the catchment, estuary and coastal areas of the Breede system; 2) identify microplastics based on polymer type using spectroscopy; 3) assess the risks posed by microplastics through conducting a risk assessment; 4) evaluate whether environmental parameters influence the concentration of microplastics and 5) assess whether the degree of disturbance associated with surrounding land-use patterns acting on the Breede system influences the concentrations and characteristics of microplastics found therein.

5.2 Research methods

5.2.1 Study site

Sampling was conducted at the Breede system along the South Coast in the Western Cape, South Africa (Figure 23) (Refer to chapter 3 for a more detailed description of the study area and for details on the field sampling methodology and laboratory analysis). Sampling took place during both the wet (August 2023) and the dry season (December 2023). The system was divided into three regions (catchment, estuary and coast) and 13 sites were sampled along the system, with four sites located along the catchment (Site B1 – B4), four sites located along the estuary (Site B5 – B8) and five sites located along the coast (Site B9 – B13) (Table 9).

Table 9: Location of the sites sampled along the Breede system in the Western Cape, South Africa

Region	Site	Latitude	Longitude	Urban/Rural
Catchment	B1	34°08'30.7"S	20°00'07.0"E	Urban
Catchment	B2	34°04'46.1"S	20°17'09.6"E	Urban
Catchment	B3	34°02'44.8"S	20°32'05.1"E	Rural
Catchment	B4	34°10'36.4"S	20°29'29.2"E	Rural
Estuary	B5	34°18'08.1"S	20°35'20.4"E	Rural
Estuary	B6	34°21'10.6"S	20°35'56.2"E	Rural
Estuary	B7	34°23'18.7"S	20°44'00.1"E	Rural
Estuary	B8	34°23'47.3"S	20°50'24.6"E	Rural
Coast	B9	34°23'50.7"S	20°51'15.9"E	Rural
Coast	B10	34°23'23.4"S	20°52'03.5"E	Rural
Coast	B11	34°24'36.0"S	20°50'56.8"E	Rural
Coast	B12	34°25'10.2"S	20°51'18.5"E	Rural
Coast	B13	34°25'19.7"S	20°51'21.8"E	Rural

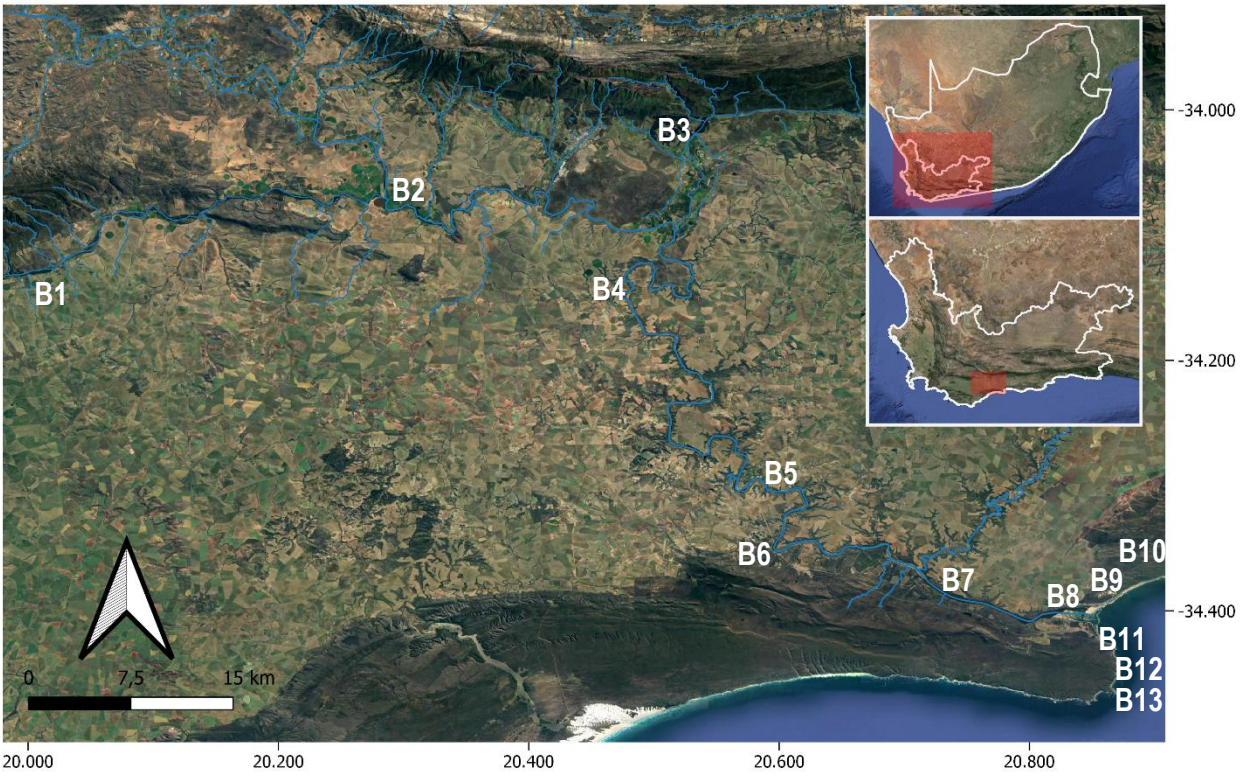

Figure 23: Map of the Breede system along the South Coast in the Western Cape, South Africa displaying the different sampling sites (Map made with QGIS 3.14)

5.3 Results

5.3.1 Microplastic concentrations and characteristics in the surface water

The average concentration of microplastics within the surface water (63 & 250 µm) samples was 0.26 ± 0.02 particles/L (Figure 24). Microplastic concentrations were similar in the wet season (0.27 ± 0.03 particles/L) compared to the dry season (0.26 ± 0.03 particles/L) ($Z = 0.91$, $p = 0.36$). Across the different regions of the system, microplastic concentrations were similar ($H = 0.21$, $df = 2$, $p = 0.90$) and ranged from 0.31 ± 0.04 particles/L in the catchment, 0.23 ± 0.02 particles/L in the estuary and 0.25 ± 0.03 particles/L at the coast. Across the different sampling sites, microplastic concentrations were similar ($H = 16.06$, $df = 12$, $p = 0.19$) and ranged from 0.15 ± 0.02 particles/L at site B5 to 0.60 ± 0.14 particles/L at site B1.

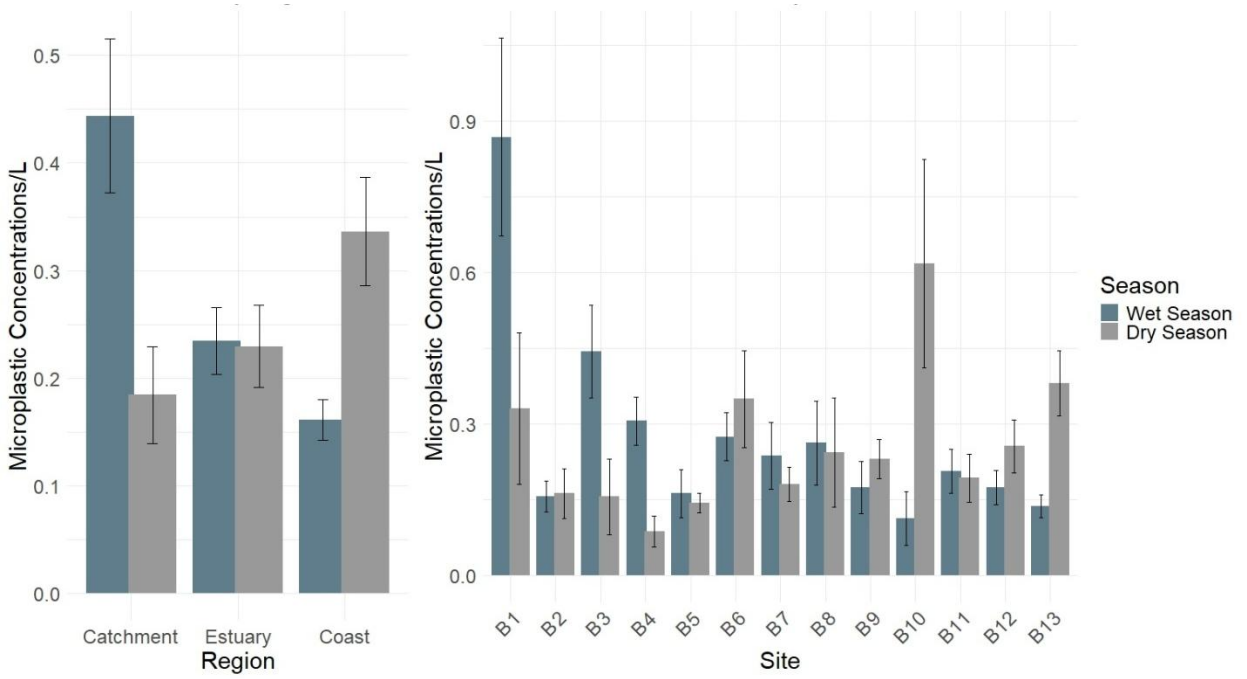

Figure 24: Microplastic concentrations in the surface water (63 & 250 µm) at the different regions (catchment, estuary & coast) and sites (B1 – B13) along the Breede system during the wet and the dry season (Error bars = SEM)

Microplastic fibres were the most abundant type, constituting 96.5% of the total microplastics recorded, followed by fragments (2.4%), films (1.1%) and foams (0.1%) (Figure 25). This trend was consistent across both sampling seasons and the different sampling regions of the system. The most abundant microplastic colour was black/grey (53.5%), followed by transparent (23.0%) and blue/green (13.4%) (Figure 26). Regarding size, the most abundant microplastic size class was 500–1000 µm (47.2%), followed by 1000–2000 µm (34.6%) (Figure 27).

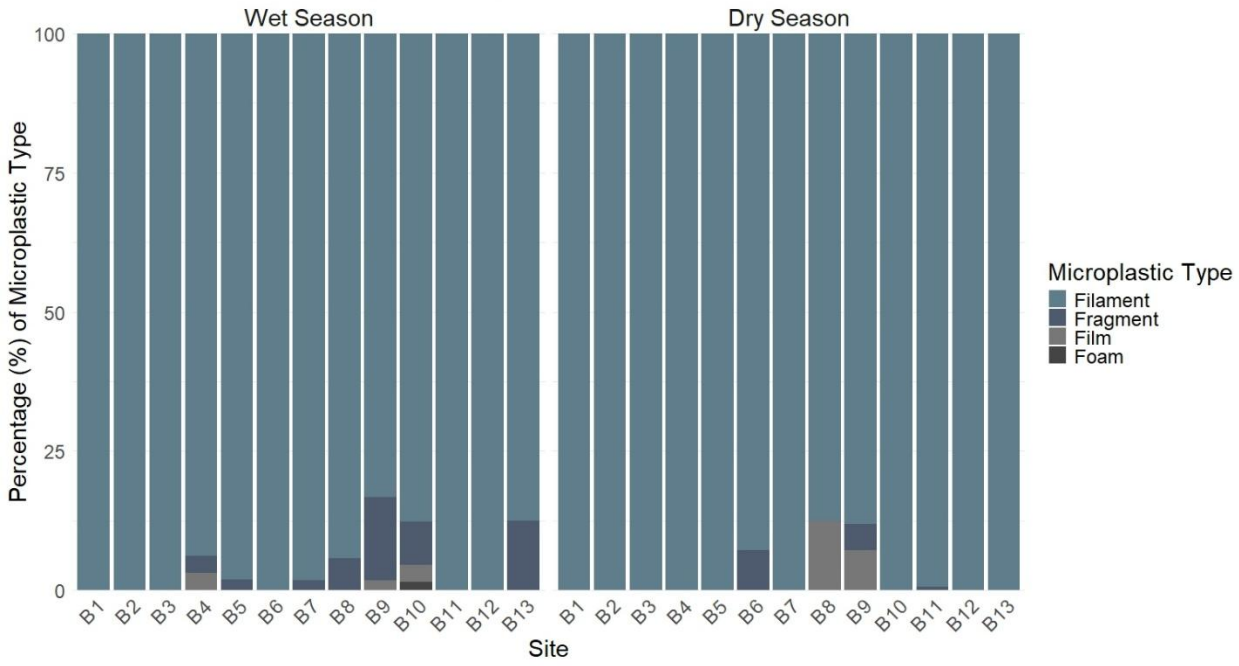

Figure 25: Percentage of microplastic types sampled in the surface water (63 & 250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

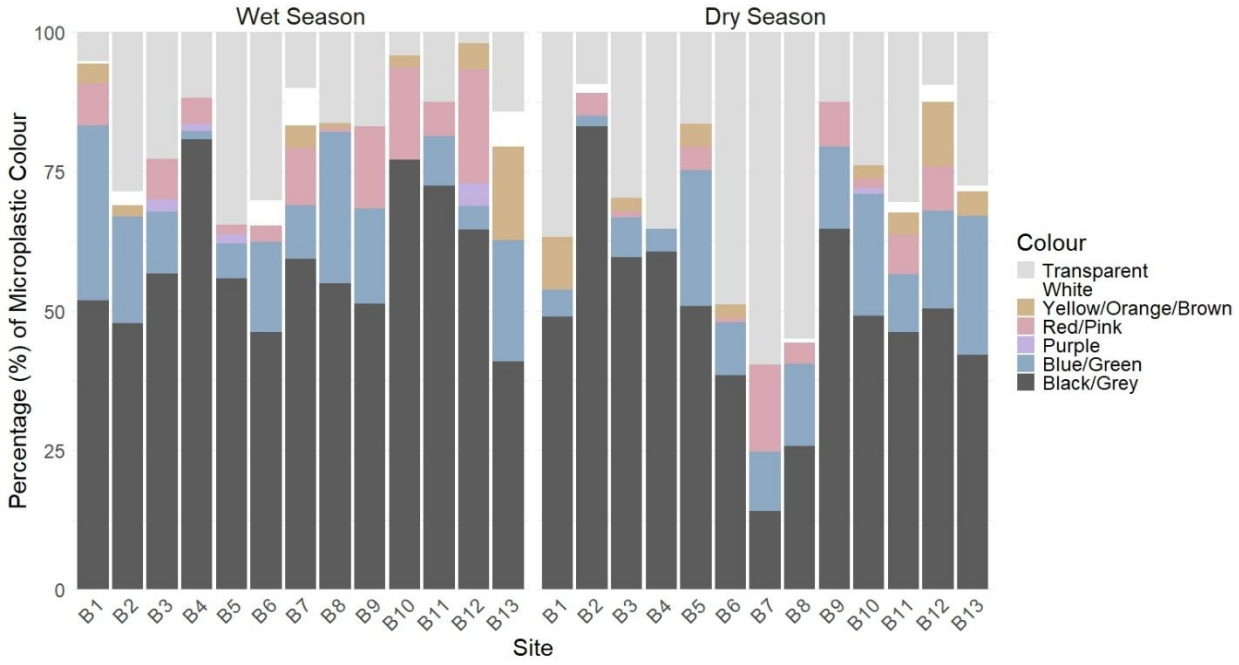

Figure 26: Percentage of microplastic colours sampled in the surface water (63 & 250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

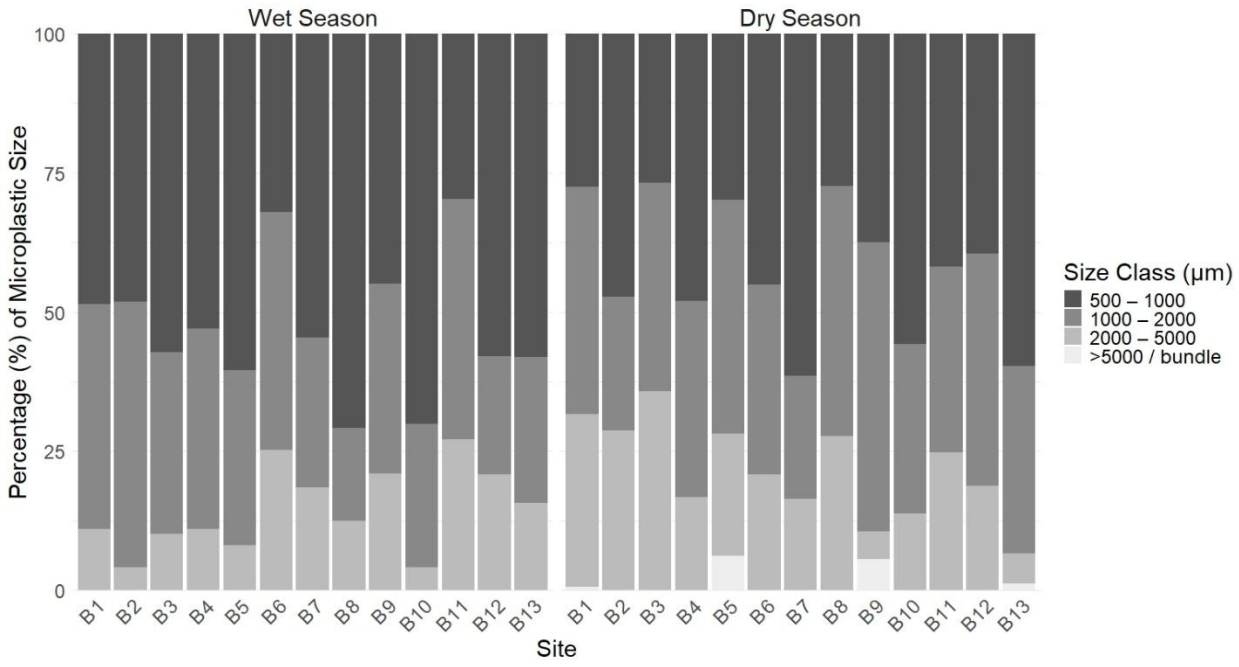

Figure 27: Percentage of microplastic size classes sampled in the surface water (63 & 250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

The average concentration of microplastics for the surface water samples collected through the 63 µm sieve was 0.25 ± 0.03 particles/L (Figure 28). Microplastic concentrations were similar in the wet season (0.28 ± 0.04 particles/L) compared to the dry season (0.21 ± 0.04 particles/L) ($Z = 1.45$, $p = 0.15$). Across the different regions of the system, microplastic concentrations were similar ($H = 0.56$, $df = 2$, $p = 0.76$) and ranged from 0.31 ± 0.07 particles/L in the catchment, 0.19 ± 0.03 particles/L in the estuary and 0.24 ± 0.04 particles/L at the coast. Across the different sampling sites, microplastic concentrations were similar ($H = 7.91$, $df = 12$, $p = 0.79$) and ranged from 0.12 ± 0.04 particles/L at site B2 to 0.51 ± 0.22 particles/L at site B1.

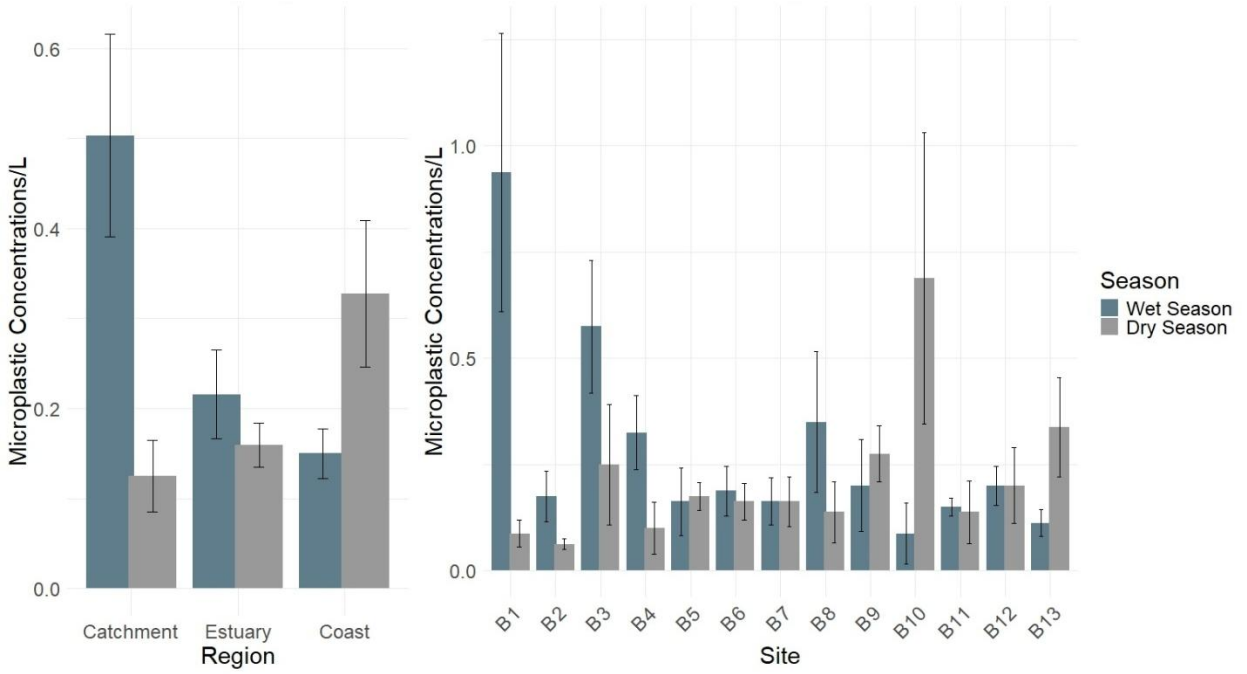

Figure 28: Microplastic concentrations in the surface water (63 µm) at the different regions (catchment, estuary & coast) and sites (B1 – B13) along the Breede system (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 98.8%, followed by fragments (0.9%) and films (0.3%) (Figure 29). The most dominant microplastic colour was black/grey comprising 49.6%, followed by transparent (28.6%) and blue/green (11.6%) coloured microplastics (Figure 30). The most dominant microplastic size class was 500 – 1000 µm comprising 52.0%, followed by 1000 – 2000 µm (29.5%) and 2000 – 5000 µm (18.4%) in size (Figure 31). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

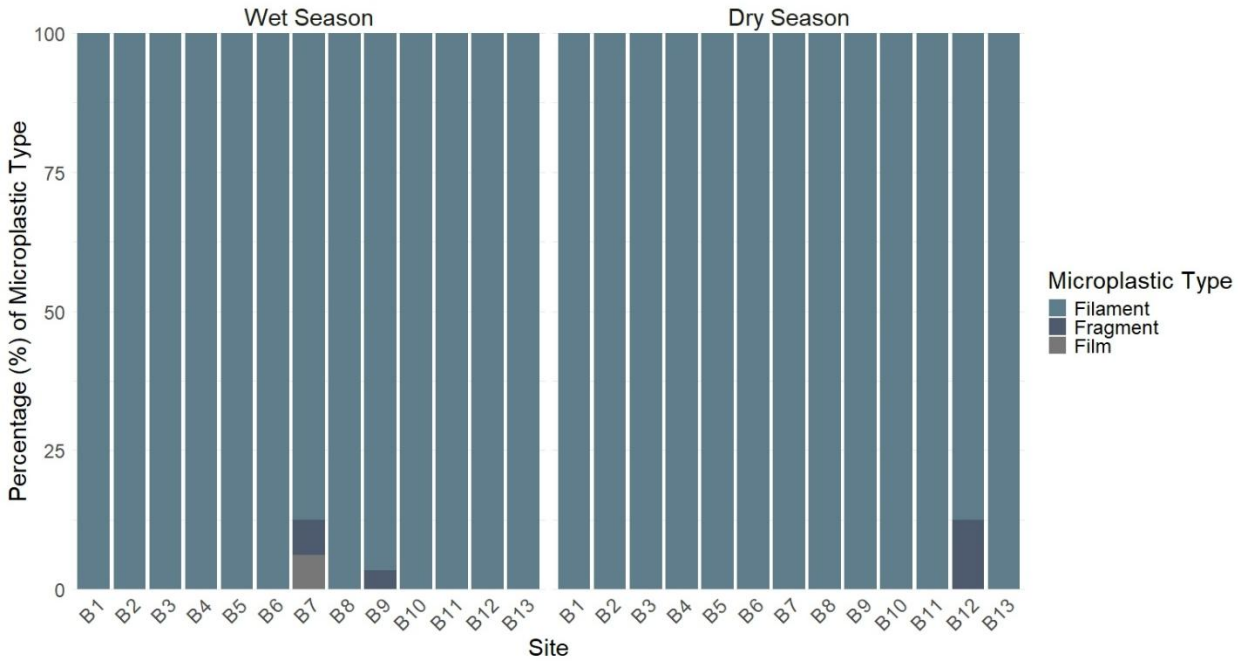

Figure 29: Percentage of microplastic types sampled in the surface water (63 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

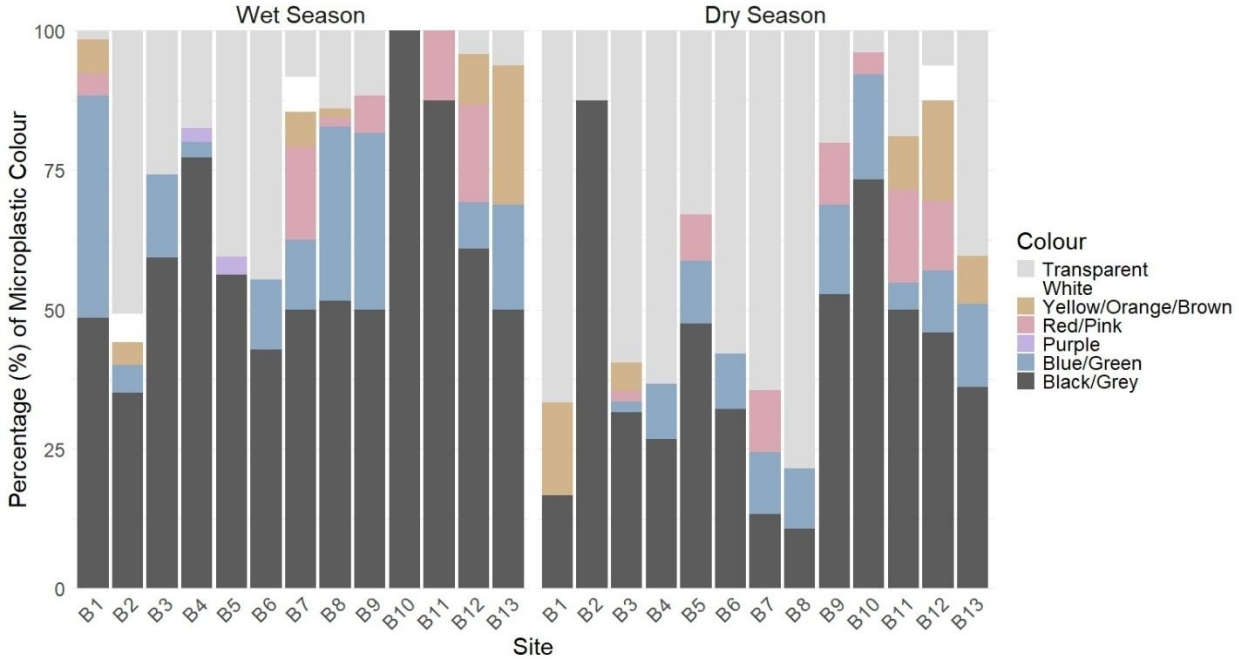

Figure 30: Percentage of microplastic colours sampled in the surface water (63 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

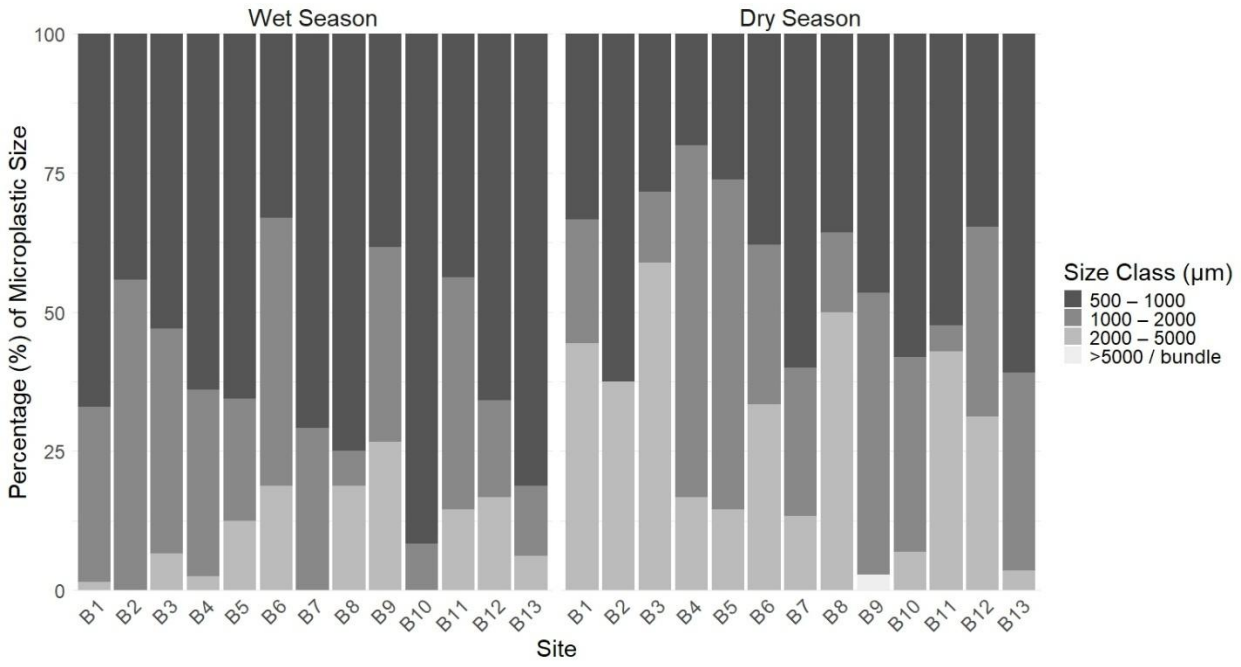

Figure 31: Percentage of microplastic size classes sampled in the surface water (63 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

The average concentration of microplastics for the surface water samples collected through the 250 µm sieve was 0.28 ± 0.03 particles/L (Figure 32). Microplastic concentrations were similar in the wet season (0.26 ± 0.03 particles/L) compared to the dry season (0.30 ± 0.04 particles/L) ($Z = -0.26$, $p = 0.80$). Across the different regions of the system, microplastic concentrations were similar ($H = 0.06$, $df = 2$, $p = 0.97$) and ranged from 0.31 ± 0.06 particles/L in the catchment, 0.28 ± 0.04 particles/L in the estuary and 0.26 ± 0.04 particles/L at the coast. Across the different sampling sites, microplastic concentrations were significantly different ($H = 25.09$, $df = 12$, $p = 0.01$) and ranged from 0.14 ± 0.02 particles/L at site B2 to 0.80 ± 0.26 particles/L at site B1.

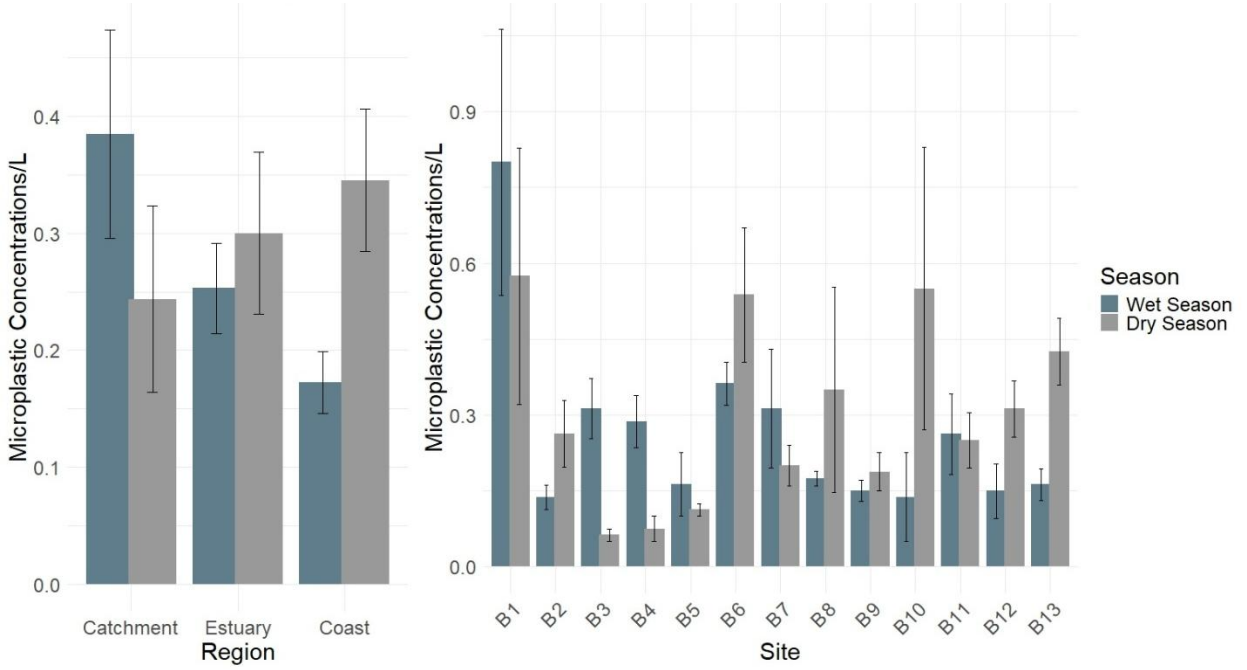

Figure 32: Microplastic concentrations in the surface water (250 µm) at the different regions (catchment, estuary & coast) and sites (B1 – B13) of the Breede system (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 94.4%, followed by fragments (3.7%) and films (1.8%) (Figure 33). The most dominant microplastic colour was black/grey comprising 57.1%, followed by transparent (17.9%) and blue/green (15.0%) coloured microplastics (Figure 34). The most dominant microplastic size class was 500 – 1000 µm comprising 42.9%, followed by 1000 – 2000 µm (39.3%) and 2000 – 5000 µm (16.9%) in size (Figure 35). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

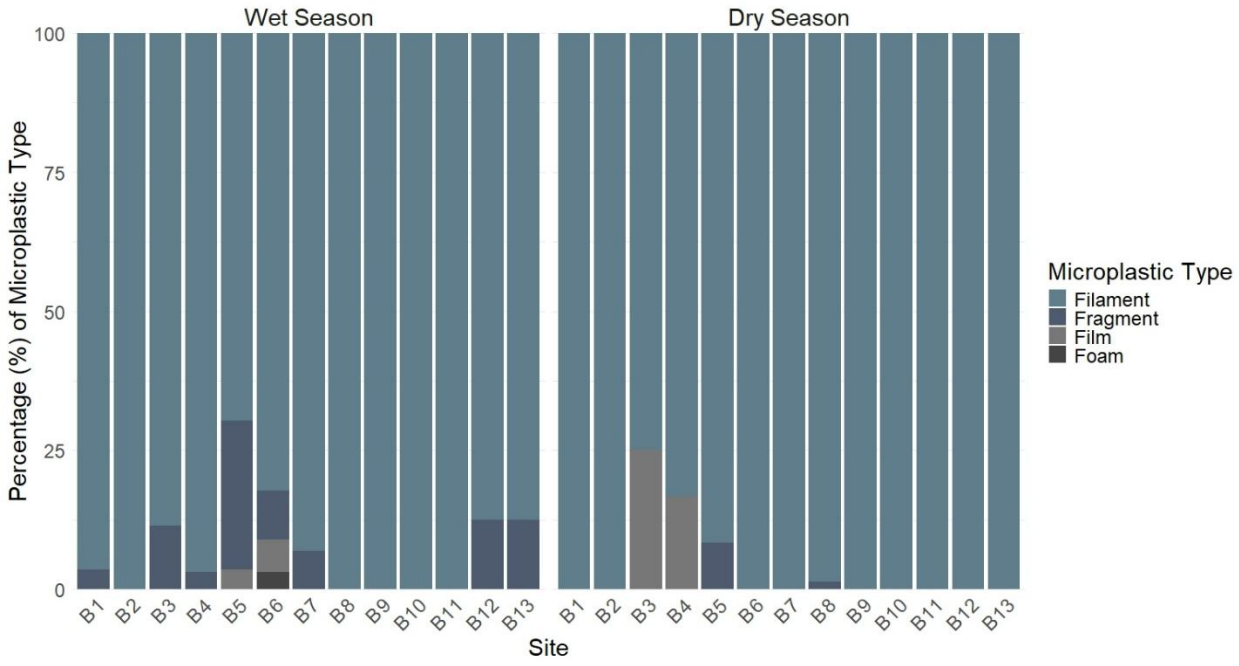

Figure 33: Percentage of microplastic types sampled in the surface water (250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

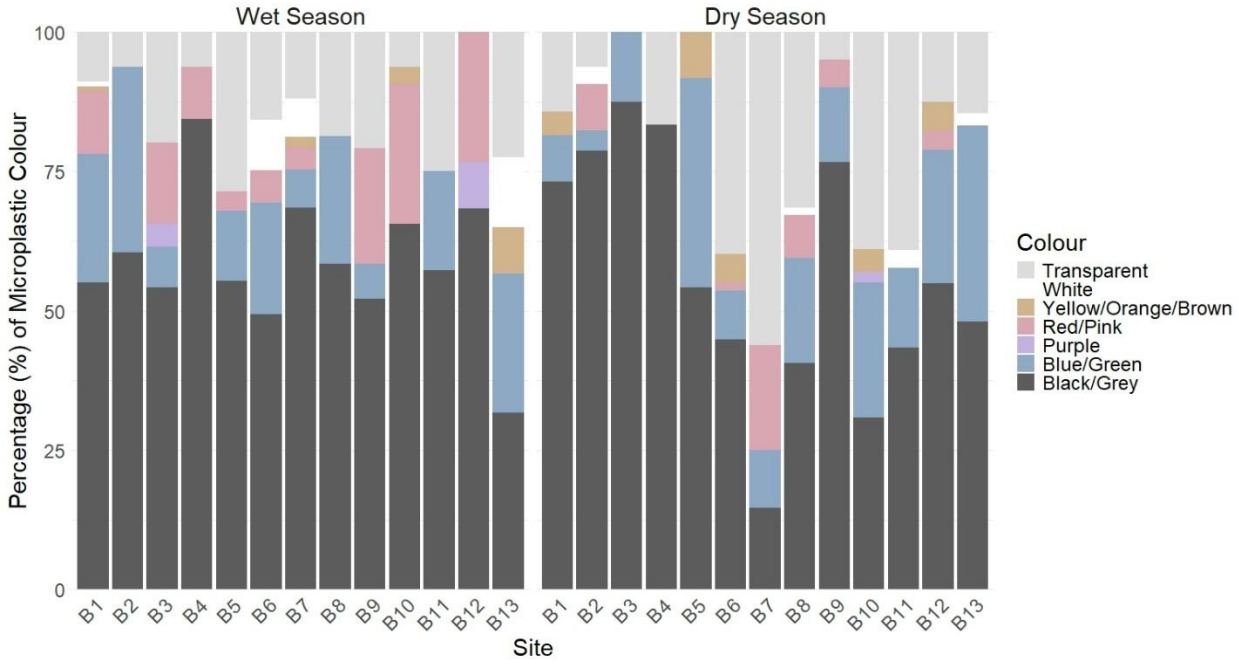

Figure 34: Percentage of microplastic colours sampled in the surface water (250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

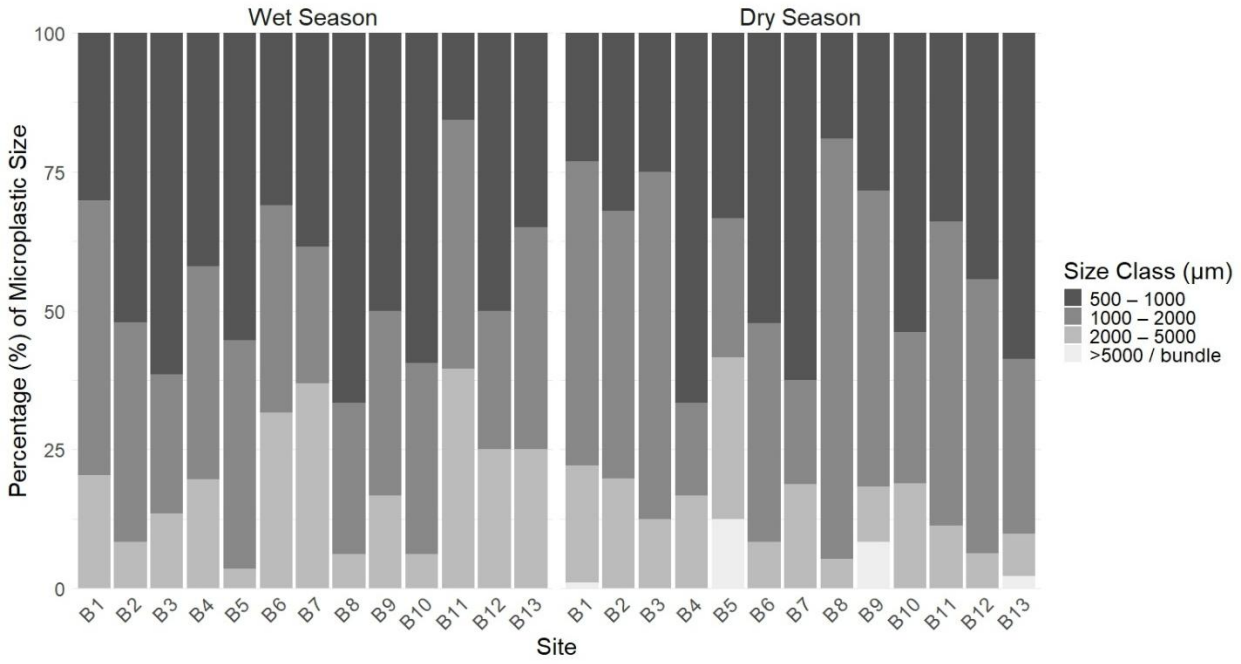

Figure 35: Percentage of microplastic size classes sampled in the surface water (250 µm) at the different sites (B1 – B13) along the Breede system during the wet and the dry season

5.3.2 Microplastic concentrations across 63 µm and 250 µm size fractions

For the surface water samples collected through the different sieve sizes, microplastic concentrations were significantly different ($Z = -2.11$, $p = 0.04$) and ranged from 0.25 ± 0.03 particles/L in the 63 µm sieve to 0.28 ± 0.04 particles/L in the 250 µm sieve (Figure 36).

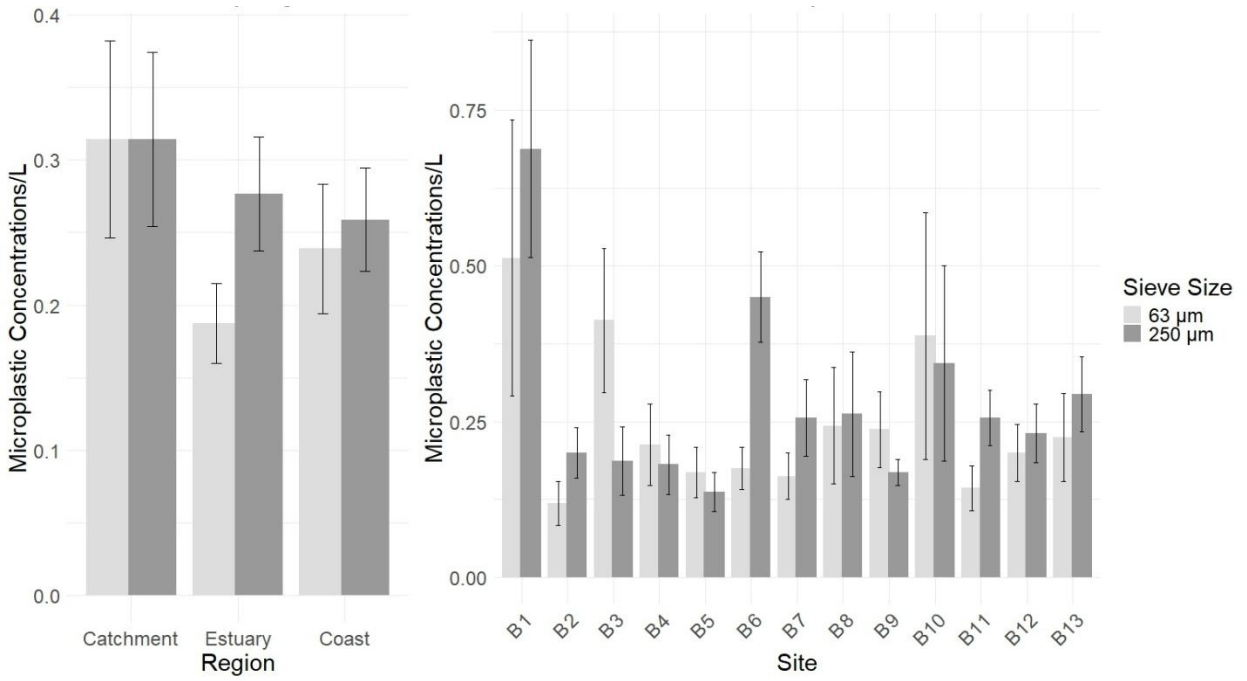

Figure 36: Microplastic concentrations in the surface water using the 63 µm and 250 µm sieve sizes at the different regions (catchment, estuary & coast) and sites (B1 – B13) along the Breede system (Error bars = SEM)

5.3.3 Microplastic concentrations and characteristics in the sediment

The average concentration of microplastics within the sediment samples was 43.65 ± 2.71 particles/kg dw (Figure 37). Microplastic concentrations were significantly different in the wet season (35.20 ± 2.76 particles/kg dw) compared to the dry season (52.11 ± 4.40 particles/kg dw) ($Z = -3.02$, $p = 0.003$). Across the different regions of the system, microplastic concentrations were significantly different and ranged from 40.23 ± 6.49 particles/kg dw in the catchment, 41.63 ± 4.77 particles/kg dw in the estuary and 48.01 ± 2.92 particles/kg dw at the coast ($H = 8.11$, $df = 2$, $p = 0.02$). Across the different sampling sites, microplastic concentrations were similar ($H = 17.07$, $df = 12$, $p = 0.15$) and ranged from 23.08 ± 3.26 particles/kg dw at site B4 to 57.35 ± 5.40 particles/kg dw at site B10.

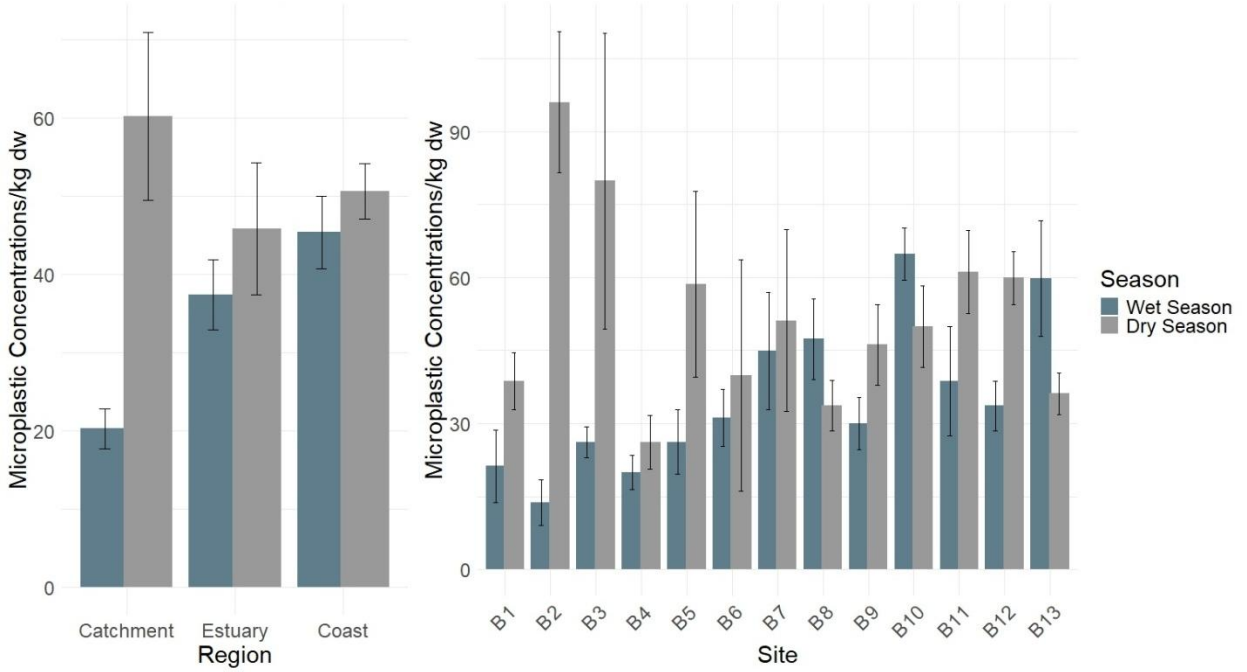

Figure 37: Microplastic concentrations in the sediment at the different regions (catchment, estuary & coast) and sites (B1 – B13) along the Breede system (Error bars = SEM)

Microplastic fibres were the most dominant type, comprising 97.3%, followed by films (1.4%) and fragments (1.2%) (Figure 38). The most dominant microplastic colour was transparent comprising 38.7%, followed by black/grey (35.6%) and blue/green (15.9%) coloured microplastics (Figure 39). The most dominant microplastic size class was 500 – 1000 µm comprising 43.4%, followed by 1000 – 2000 µm (38.5%) and 2000 – 5000 µm (17.5%) in size (Figure 40). These trends were consistent during both the wet and the dry season as well as throughout the catchment, estuary and coast.

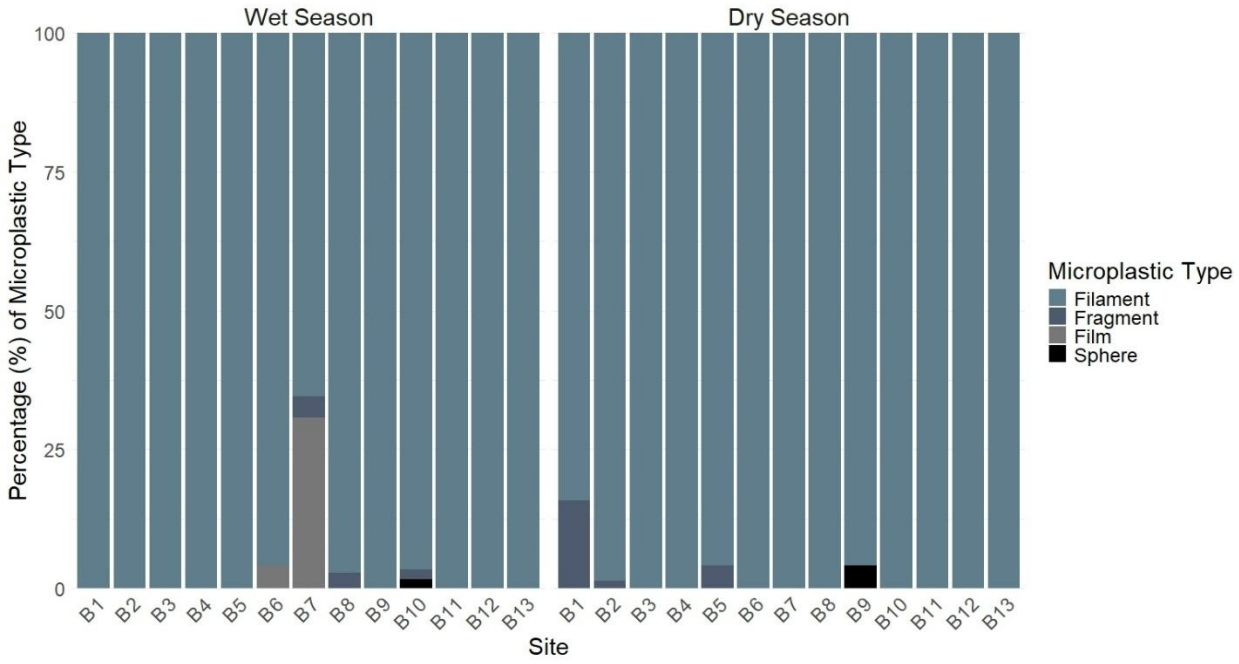

Figure 38: Percentage of microplastic types sampled in the sediment at the different sites (B1 – B13) along the Breede system during the wet and the dry season

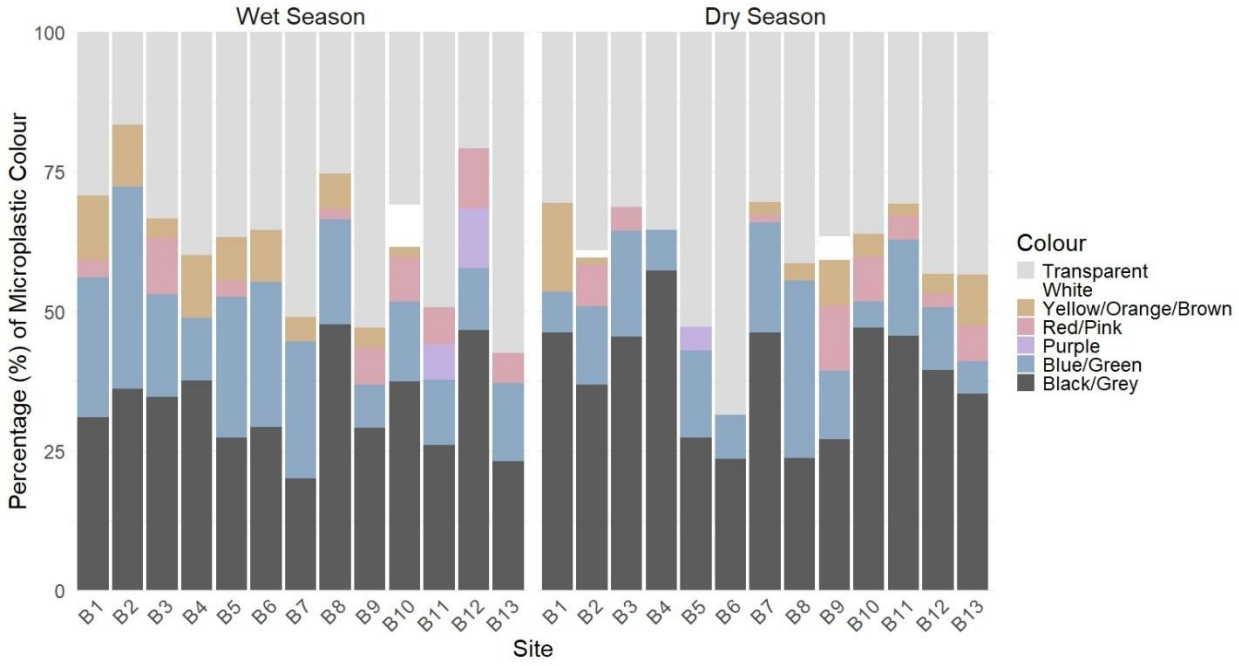

Figure 39: Percentage of microplastic colours sampled in the sediment at the different sites (B1 – B13) along the Breede system during the wet and the dry season

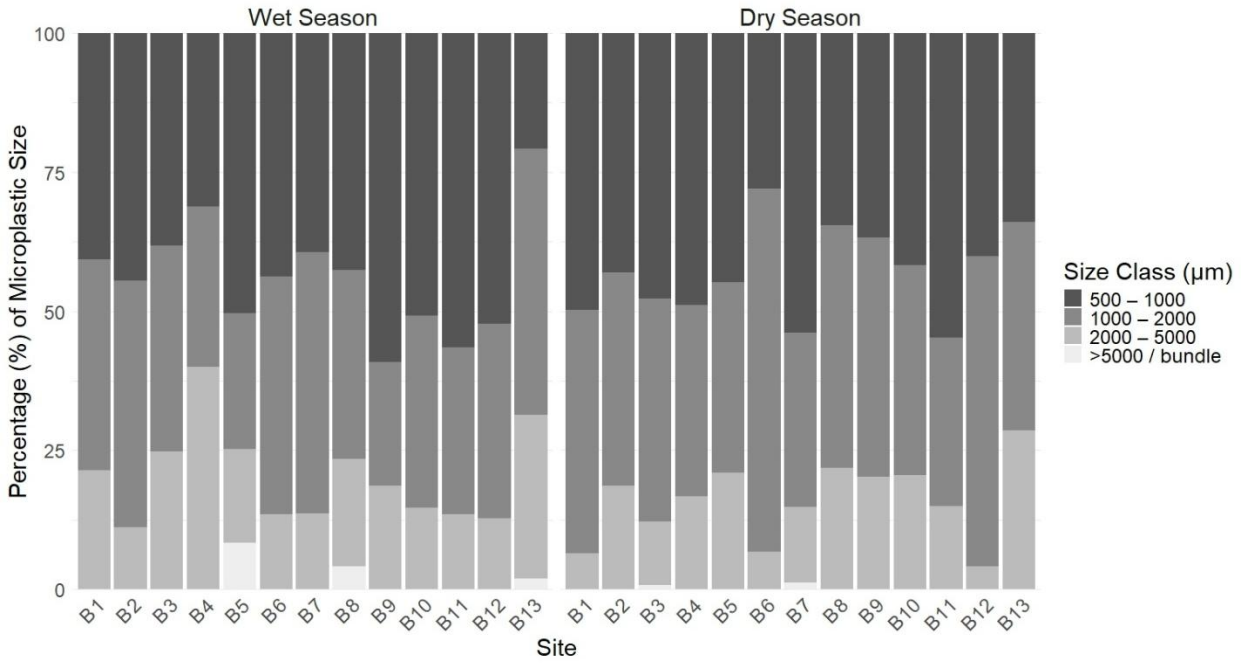

Figure 40: Percentage of microplastic size classes sampled in the sediment at the different sites (B1 – B13) along the Breede system during the wet and the dry season

5.3.4 Microplastic polymer identification

A 100% of all microplastic particles recorded were identified according to their polymer composition using FTIR analyses. Of these, 60% of particles were natural (cotton) and 2% were semi-synthetic, which were excluded from further polymer abundance estimates (Figure 41). Thus, for synthetic (38%) microplastics, polymers recorded in the water samples recorded in the water samples were mainly PET during both the wet (78.0%) and the dry (56.9%) season as well as in the catchment (72.4%), estuary (65.2%) and along the coastal region (62.9%) of the system. Similarly, polymers recorded in the sediment samples were also mainly PET during both the wet (70%) and the dry (88%) season as well as in the catchment (77%), estuary (76%) and along the coastal region (85.5%) of the system.

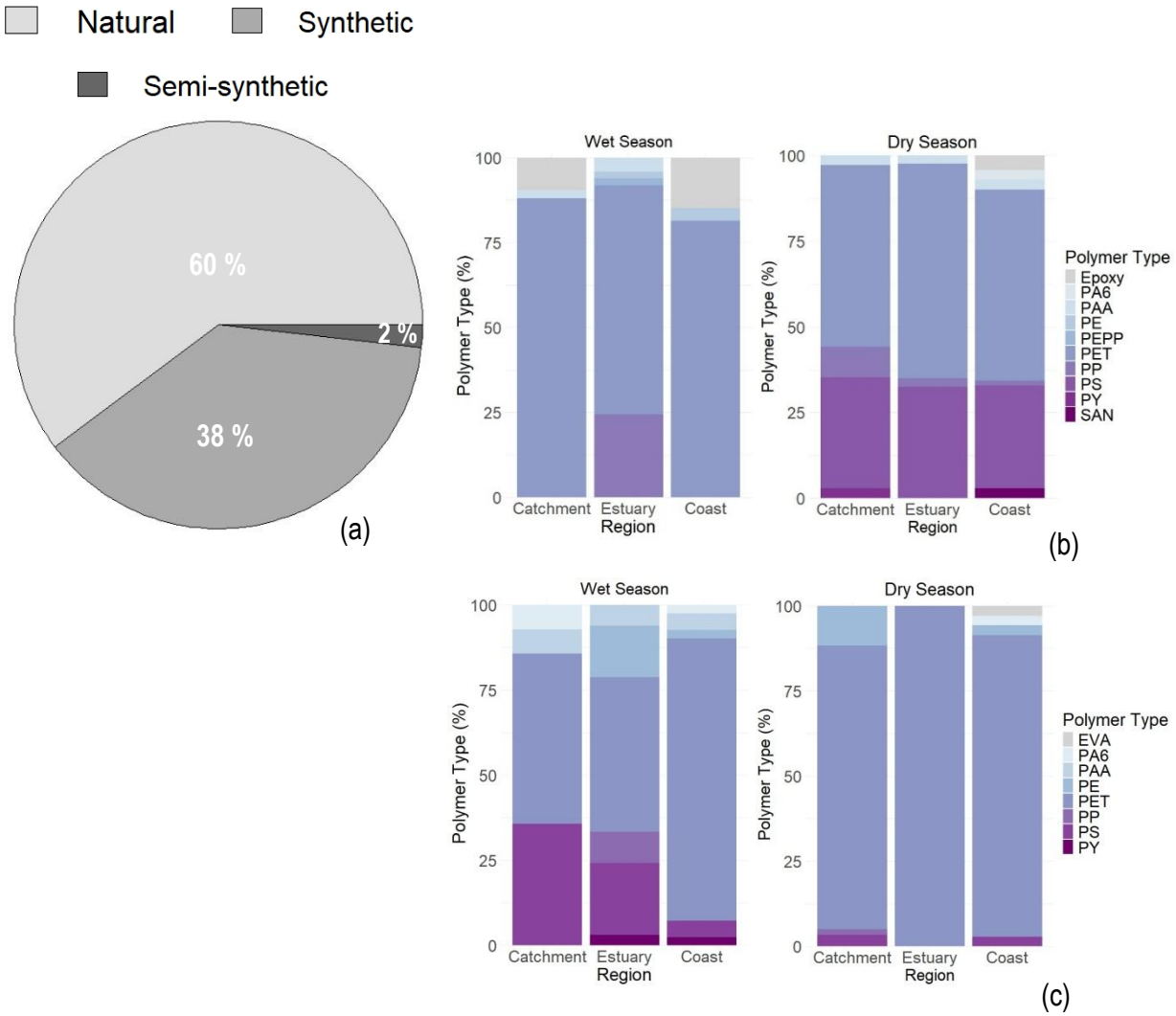

Figure 41: Percentage of microplastic composition in (a) all samples, seasons, regions and sites, microplastic polymer composition in (b) surface water samples and in (c) sediment samples collected during the wet and the dry season along the catchment (sites 1 - 4), estuary (sites 5 – 8) and coast (sites 9 – 11) (Epoxy: Epoxy Resin; EVA: Ethylene vinyl acetate; PA6: Polyamide 6 / nylon 6; PAA: Polyacrylic acid; PE: Polyethylene; PEPP; Polyethylene-polypropylene; PET; Polyethylene Terephthalate; PP: Polypropylene; PS: Polystyrene; PY: Polyester: SAN: Styrene acrylonitrile).

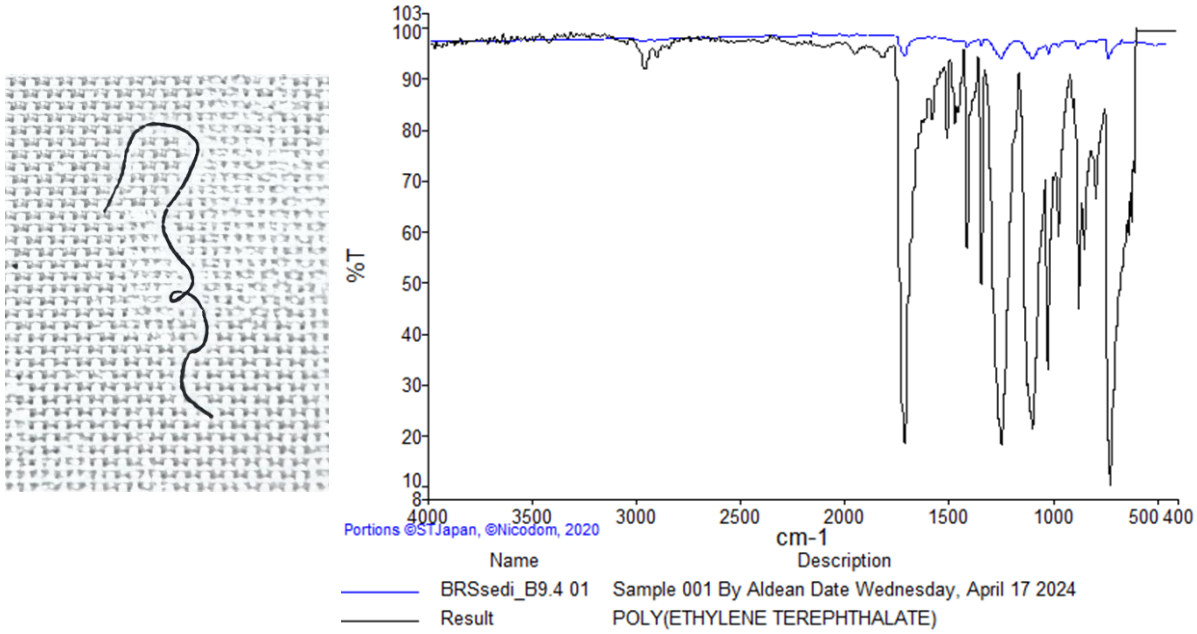

Figure 42: FTIR scan of black/grey PET fibre (2 – 5 mm) sampled in the sediment along the coastal region of the Breede system during the dry season

5.3.5 Grain size analysis

All sediment was classified as sand, with coarse (> 500 µm) and medium (250 - 500 µm) sized grain sediment being the most dominant followed by fine (125 - 250 µm) and very-fine (63 -125 µm) sediment (Figure 43).

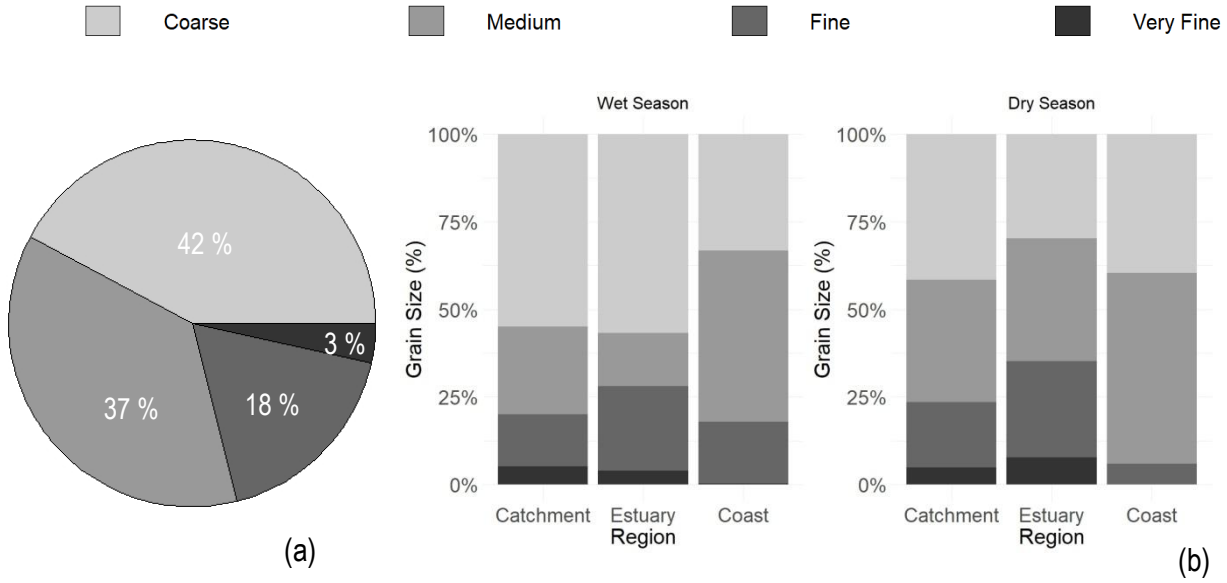

Figure 43: Grain size analysis of the sediment at (a) all seasons, regions and sites and (b) along the different regions of the Breede system during the wet and the dry season

5.3.6 Relationship between microplastics and environmental parameters

5.3.6.1 Surface water

For the water samples collected using the 63 µm sieve, the Spearman rank correlation coefficient only indicated a strong positive correlation and significant difference between microplastic concentrations and temperature within the catchment ($r = 0.81$, $p = 0.003$) during the wet season (Table 10).

Table 10: Spearman's rank correlation coefficient for the environmental parameters and microplastic concentrations sampled through 63 sieve µm within the different regions of the Breede system

Region	Season	Temperature	Salinity	Turbidity	pH
Catchment	Wet	0.81*	0.24	0.24	0.43
Catchment	Dry	0.50	-0.05	-0.05	0.16
Estuary	Wet	0.20	0.39	0.39	-0.10
Estuary	Dry	0.33	0.20	0.20	0.30
Coast	Wet	0.28	0.32	0.24	0.40
Coast	Dry	0.10	0.34	0.31	-0.05

* Correlation is significant at $p < 0.05$

For the water samples collected using the 250 µm sieve, the Spearman rank correlation coefficient indicated strong positive correlations and significant differences between microplastic concentrations and various environmental parameters (Table 11). During the wet season, significant positive correlations were observed between microplastic concentrations and temperature in the catchment ($r = 0.68$, $p = 0.018$) as well as pH within the catchment ($r = 0.62$, $p = 0.036$), estuary ($r = 0.60$, $p = 0.044$) and the coast ($r = 0.50$, $p = 0.070$). During the dry season, significant positive correlations were observed between microplastic concentrations and salinity ($r = 0.59$, $p = 0.021$) as well as turbidity along the coast ($r = 0.56$, $p = 0.037$).

Table 11: Spearman's rank correlation coefficient for the environmental parameters and microplastic concentrations sampled through 250 sieve µm within the different regions of the Breede system

Region	Season	Temperature	Salinity	Turbidity	pH
Catchment	Wet	0.68*	0.44	0.44	0.62*
Catchment	Dry	-0.31	0.28	0.28	-0.02
Estuary	Wet	0.28	0.09	0.09	0.60*
Estuary	Dry	-0.08	0.06	0.06	0.34
Coast	Wet	0.31	0.23	0.19	0.50*
Coast	Dry	0.42	0.59*	0.56*	0.32

* Correlation is significant at $p < 0.05$

5.3.6.2 Sediment

The Spearman's rank correlation coefficient showed no relationships between microplastics concentrations and grain size except for very-fine sand which indicated a negative relationship and significant difference ($r = -0.62$, $p = 0.012$) within the estuary during the wet season (Table 12).

Table 12: Spearman rank correlations between adjusted microplastic concentrations and percentage sediment grain size category (coarse sand: > 500 µm; medium sand: 250 – 500 µm; fine sand: 125 – 250 µm; very-fine sand: 63 – 125 µm based on region (catchment, estuary and coast) and season (wet and dry) in the Breede system.

Region	Season	Coarse	Medium	Fine	Very Fine
Catchment	Wet	-0.11	0.11	-0.04	-0.09
Catchment	Dry	0.19	-0.32	-0.19	-0.34
Estuary	Wet	0.33	0.002	-0.43	-0.62*
Estuary	Dry	-0.05	-0.07	-0.03	0.12
Coast	Wet	0.15	-0.26	-0.13	0.07
Coast	Dry	-0.05	0.12	0.16	0.17

*Correlation is significant at $p < 0.05$

5.3.7 Disturbance index

The catchment of the Breede system was the most disturbed region, with an average total disturbance rating of 10.5 (Figure 44). Disturbances ranged from low to moderate in intensity, with site B3 being the most disturbed with a TDR of 13.5 and site B4 being the least disturbed with a TDR of 7.1. The coastal region was the least disturbed, with an average total disturbance rating of 8.5. Disturbances also ranged from low to moderate in intensity, with site B9 being the most disturbed with a TDR of 11.1 and site B13 being the least disturbed with a TDR of 6.8.

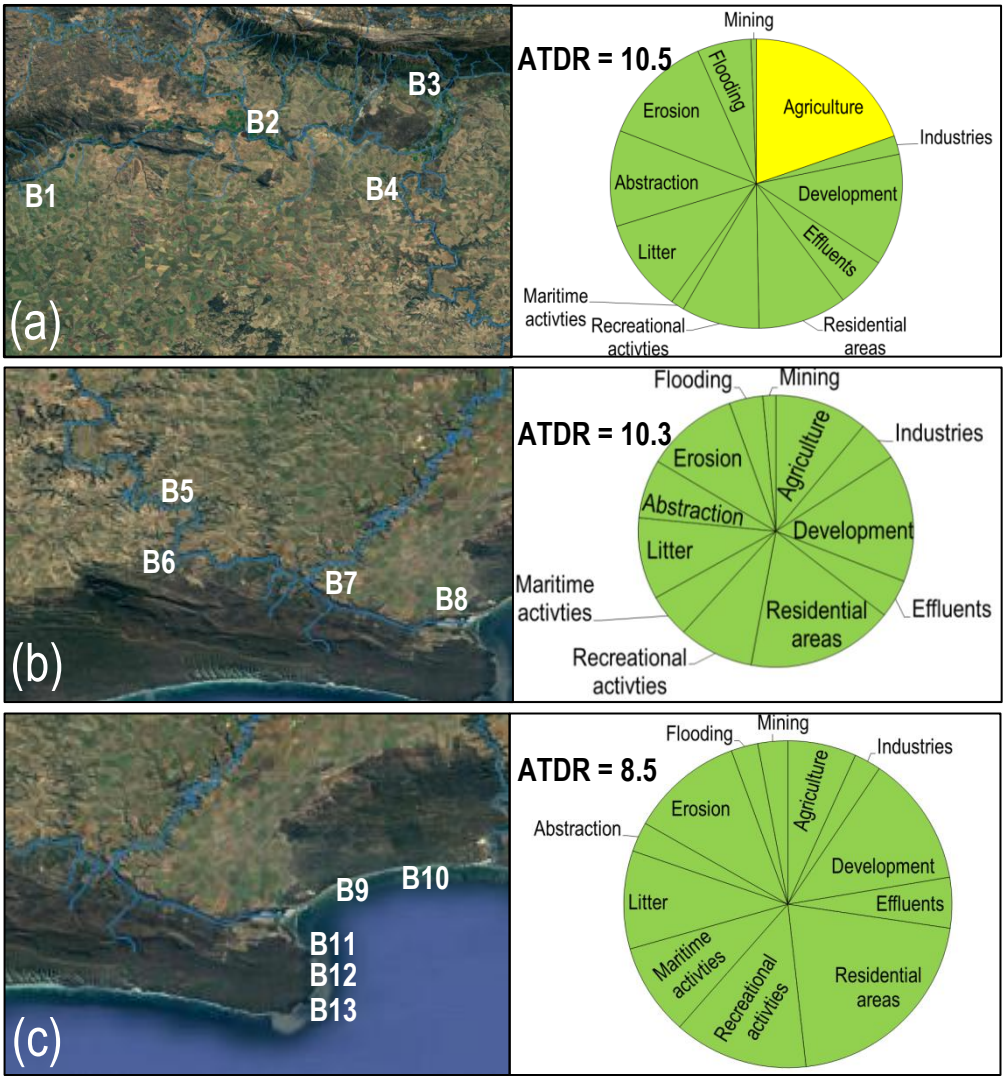

Figure 44: Disturbance index displaying the different land use types along the Breede System within the (a) catchment, (b) estuary and (c) coastal areas. The pie chart displays the proportional contribution of each disturbance type to the average total disturbance rating (ATDR). Categories for the disturbance index are colour-coded as follows: absent = blue (0), low = green (1), moderate = yellow (2), high = orange (3) and very high = red (4).

5.3.8 Risk assessment

Given that natural particles do not have a hazard score, these particles were excluded from the risk assessment.

For the polymer risk assessment, the pollution load index (PLI) for both water (63 & 250 µm) and sediment within the different regions of the system were all categorised as pollution being present (> 1) during both the wet and the dry season (Table 13).

Table 13: Risk assessment for water (63 & 250 µm) and sediment sampled in the catchment, estuary and coastal regions of the system during the wet and dry season. Categories for the PLI are colour-coded as no pollution (blue) and pollution present (red) while categories for the H and PRI are colour-coded as low (blue), moderate (green), high (yellow), very-high (orange) and dangerous (red).

	Catchment			Estuary			Coast			
	PLI	H	PRI	PLI	H	PRI	PLI	H	PRI	PRI (season)
Water 63 (wet)	10.60	13.04	131.18	4,24	4.00	16,96	2,80	383,98	1075,14	1223.30
Water 63 (dry)	2,50	36,46	91,15	3,19	14,40	45,90	6,55	478,80	3136,14	3273.19
Water 250 (wet)	7,21	942,20	6790,50	4,19	16,29	68,20	3,45	796,10	2746,42	9605.10
Water 250 (dry)	4,75	61,80	293,60	5,32	20,20	107,51	6,90	14,97	103,27	504.33
Sediment (wet)	1,48	32,71	48,33	7,31	57,73	421,77	5,21	44,73	233,10	703.17
Sediment (dry)	10,90	5,63	61,40	4,90	4.00	19,60	3,70	6,40	23,51	104.42

The polymer risk index (H) values for water 63 ranged from moderate (catchment), low (estuary) to high (coast) during the wet season and moderate (catchment & estuary) to high (coast) during the dry season. For water 250 values ranged from high (catchment), moderate (estuary) to high (coast) during the wet season and were categorised as moderate (catchment, estuary & coast) during the dry season. For the

sediment values were categorised as moderate (catchment, estuary & coast) during the wet season and were categorised as low (catchment, estuary & coast) during the dry season.

With the H values which indicate polymer toxicity and the microplastic concentrations which indicate the pollution load index (PLI), these values provide an indication of the pollution risks (PRI) posed by the microplastics recorded within the system. The pollution risk index values for water 63 ranged from low (catchment & estuary) to very high (coast) during the wet season and low (catchment & estuary) to dangerous (coast) during the dry season. For water 250 values ranged from dangerous (catchment), low (estuary) to dangerous (coast) during the wet season and from moderate (catchment) to low (estuary & coast) during the dry season. For the sediment, values ranged from low (catchment), high (estuary) to moderate (coast) during the wet season to generally low (catchment, estuary & coast) during the dry season. Seasonally, PRI values were generally higher during the wet season compared to the dry season for all sampling mediums. For the different sampling mediums, seasonally, PRI values for water were dangerous during the wet season and ranged from high too dangerous during the dry season but ranged from very high to low in the sediment during the wet and the dry season, respectively.

5.3 Discussion

5.4.1 Spatiotemporal distribution of microplastics in surface water

Seasonally, microplastic concentrations in surface water are expected to increase during the wet season as opposed to the dry as increased hydrodynamic conditions can influence the movement and accumulation of microplastics (Horton & Dixon, 2018). When hydrodynamic conditions, such as precipitation, increase, microplastic inputs increase due to increased surface runoff from terrestrial environments (Horton & Dixon, 2018).

Several studies have reported higher microplastic concentrations in surface water during the wet season compared to the dry season, all of which was attributed to increased microplastic inputs (Samuels et al., 2024; Ariefdien et al., 2024; Khan et al., 2025). Additionally, precipitation, increased river flow and tidal input can further contribute to increased concentrations during the wet season as increased river flow due to precipitation and the resulting turbulence from these conditions can dislodge microplastics from the sediment allowing them to become redistributed within the water column (Hurley et al., 2020; Peller et al., 2022).

This postulation is supported by Dahms et al. (2020) who reported that the hydrodynamic conditions of streams have the potential to assist in the dislodging and transport of microplastics into the water column. Similarly, along the Swartkops and Buffalo River Catchments, Owowenu et al. (2025) reported higher concentrations of suspended microplastics in flush zones compared to sink zones which were attributed to hydrodynamic conditions such as increased flow rates and increased turbulence facilitating the entrainment of these particles.

Given that hydrodynamic conditions can influence the movement and accumulation of microplastics in surface water, concentrations are expected to increase during the wet season. However, since the results in this study were not significantly different, it suggests that seasonality had no observable influence on the concentration of microplastics in the system. Similar findings have been observed by Mvovo et al. (2025) who also reported no significant temporal differences in the concentration of microplastics in the water of the Buffalo River in the Eastern Cape, South Africa. However, in the aforementioned study, average microplastic concentrations were slightly higher ranging from 0.60 ± 0.18 particles/L^{-1} in the wet season to 0.53 ± 0.13 particles/L^{-1} in the dry season (Mvovo et al., 2025), while average concentrations reported here ranged from 0.27 ± 0.03 particles/L in the wet season to 0.26 ± 0.03 particles/L in the dry season. Nonetheless, the similar concentrations reported here suggest that sources of contamination were consistent throughout the different seasons rather than fluctuating in relation to seasonal changes.

Much of the microplastics that end up in coastal and marine environments originate from land-based sources of contamination transported by rivers (Meijer et al., 2021). Approximately 98% of the microplastics in the ocean stem from land-based sources (Boucher & Friot, 2017). Moreover, in addition to the annual plastic emissions into the ocean, 98.5% of plastic waste remains and accumulates within terrestrial environments before progressively contaminating aquatic environments (Meijer et al., 2021).

Given that rivers support human populations along their length, rivers serve as a significant source of land-based microplastics to coastal and marine environments (Weideman et al., 2020b; Meijer et al., 2021). Similarly, estuaries also serve as major conduits transporting microplastics from rivers to coastal and marine environments (Naidoo et al., 2015). Given that rivers and estuaries are lotic systems, they are capable of flushing out large amounts of contaminants (McLusky et al., 1993; Nel et al., 2018).

Several studies have reported an increase the concentration of microplastics toward coastal and marine environments. For example, along Durban Bay, Latcheman et al. (2024) reported higher microplastic

concentrations at sites located adjacent to river inflows which were attributed to increased rainfall. Similarly, along the Diep River, Khan et al. (2025) reported higher microplastic concentrations at sites downstream of the river which was also attributed to increased rainfall as well as strong winds. Given that the hydrodynamic conditions of rivers and estuaries can facilitate the movement of microplastics, concentrations are expected to increase from the catchment toward the coast. Moreover, additional to land-based sources, coastal and marine environments also receive microplastics from sea-based sources of contamination (Boucher & Friot, 2017). Sea-based sources can thus further contribute to the increase in microplastic concentrations along the coast (Boucher & Friot, 2017).

However, given that the results of this study were not significantly different across the different regions, it suggests that the hydrodynamic conditions of the system had no influence on the concentration of microplastics. Similar findings have been observed by Shikwambana et al. (2024) who also reported no significant spatial differences in the concentration of microplastics in the water of the Sabie and Olifants Rivers in the Kruger National Park, South Africa. However, average concentrations were higher in the aforementioned study, ranging from 18 particles/L^{-1} in the Sabie River to 27 particles/L^{-1} in the Olifants River (Shikwambana et al., 2024), while average concentrations reported here was 0.26 ± 0.02 particles/L. Nonetheless, the relatively similar concentrations recorded here is likely a result of the consistent sources of contamination observed along the length of the system.

5.4.2 Spatiotemporal distribution of microplastics in sediment

The significantly higher microplastic concentrations observed during the dry season compared to the wet season suggests that the hydrodynamic conditions can influence microplastic accumulation in the sediment. Similar findings were reported by Nkosi et al. (2023) who also observed significantly higher microplastic concentrations in the dry season in the sediment of the Crocodile River in Mpumalanga, South Africa. However, average concentrations were much higher in the aforementioned study, ranging from 86 particles/kg-1 in the wet season to 568 particles/kg-1 in the dry season (Nkosi et al., 2023), while average concentrations reported here ranged from 35.20 ± 2.76 particles/kg dw in the wet season to 52.11 ± 4.40 particles/kg dw in the dry season.

Several studies have supported this trend, reporting higher microplastic concentrations during the dry season (Costa et al., 2011; Nel et al., 2018; Govender et al., 2020) all of which were attributed to decreased hydrodynamic conditions. During the dry season when hydrodynamic conditions, such as

precipitation and river flow, decrease, the resulting turbulence decreases, enhancing sedimentation and leading to increased microplastic deposition and accumulation within the sediment (Dahms et al., 2020; Faulstich et al., 2022)

These studies indicate that decreased hydrodynamic conditions can inversely influence microplastic concentrations in sediment. Thus, as the hydrodynamic conditions decrease, microplastic concentrations in sediment increase. Additionally, microplastics of a higher density may further contribute to an increase in concentrations as they are more likely to sink and accumulate in the sediment (Horton & Dixon, 2018). Thus, the significantly higher microplastic concentrations observed in the sediment during the dry season is attributed to the decreased hydrodynamic conditions that facilitate the deposition and accumulation of microplastics.

The significantly higher concentrations observed along the coast suggests that the hydrodynamic conditions can influence the movement and accumulation of microplastics in sediment. Similar findings have been observed by Julius et al. (2023) who also reported significant spatial differences in the microplastics in sediment at sites along the Western Cape coastline which was attributed to inflows from adjacent rivers. However, average concentrations were much higher in the aforementioned study (185.07 ± 15.25 particles/kg dw) (Julius et al., 2023) than in the present study (43.65 ± 2.71 particles/kg dw).As rivers and estuaries are lotic systems with low retention times, they can act as major conduits, flushing contaminants, to the coast (McLusky et al., 1993; Bakir et al., 2014; Nel et al., 2018). As a result, coastal and marine environments are considered the final sink for microplastics (Nel et al., 2018; Ryan, 2020a). Therefore, concentrations are expected to increase from the catchment toward the coast.

Given that the hydrodynamic conditions can influence the movement and accumulation of microplastics, the higher concentrations observed along the coast may be attributed to the annual precipitation experienced by the system along the South Coast as well as the resulting continuous river flow and turbulence, all of which can contribute to the resuspension and flushing of microplastics to the coast (Nel et al., 2018; Graham et al., 2024). Additionally, seasonal variations in wind movement can also influence the movement of microplastics, with strong winds driving them from the catchment, through the estuary and to the coast (Browne et al., 2011; Samuels et al., 2024).

Although these movements initially increase concentrations within the water column, once at the coast, microplastics are subjected to the hydrodynamic conditions of coastal and marine environments. Once at

the coast, hydrodynamic conditions, such as tidal movements, can transport microplastics with rising tides, carrying them from the water column and depositing them along the shore and in the sediment as the tide recedes (GESAMP, 2019; Ryan et al., 2020b). Thus, the significantly higher microplastic concentrations observed along the coast is attributed to the combined effects of the hydrodynamic conditions of the catchment, estuary and the coast facilitating the movement and accumulation of microplastics.

5.4.3 Microplastic concentrations across 63 µm and 250 µm size fractions

The significantly higher microplastic concentrations observed in the 250 µm sieve compared to the 63 µm sieve was unexpected given that finer mesh sizes are able to capture more microplastics than coarser ones (Ryan et al., 2020c; Sui et al., 2025). Previous studies have reported higher microplastic concentrations in finer mesh sizes compared to coarser mesh sizes (Apetogbor et al., 2023; Khan et al., 2025). This is due to particles being able to pass through coarser mesh sizes, leading to a loss of particles and an underestimation in abundance estimates (Ryan et al., 2020c; Sui et al., 2025).

However, given the field sampling methodology used in this study, where the two sieve sizes were stacked on top of each other, the top (250 µm) sieve would allow particles to pass through and be retained by the bottom (63 µm) sieve. Thus, the higher microplastics concentrations observed in the 250 µm sieve does not suggest a loss of particles but rather indicates that a greater number of microplastics ≥ 250 µm in size were present.

5.4.4 Microplastic characteristics

The dominant microplastic type in both the surface water and the sediment were fibres. Similar results have been reported by Apetogbor et al. (2023), Julius et al. (2023) and Ariefdien et al. (2024) all of whom reported high fibre abundances. In aquatic environments, high fibre abundances have been linked to effluents from wastewater treatment works as the small size of microplastics, fibres in particular, are able to bypass filtration processes during wastewater treatment (Horton & Dixon, 2018; Jessieleena et al., 2023). Wastewater treatment works are thus inefficient in removing microplastics from wastewater, with microplastic retention rates of as low as 5%, 2% and even 1% (Carr et al., 2016; Murphy et al., 2016; Talvitie et al., 2017). Despite these seemingly low retention rates, the presence of even small quantities means that a significant amount of microplastics gets released into aquatic environments given that large volumes of effluent are regularly discharged (Murphy et al., 2016).

It is thus postulated that the high abundance of fibres is mainly derived from domestic effluents, particularly domestic laundry effluent, transported through wastewater treatment works or through stormwater outlets. Additionally, informal settlements can also release synthetic fibres into the system through the washing of clothes as many residents residing in rural communities do not have access to piped water and thus utilise rivers as their primary source of water, directly releasing fibres into the environment (Browne et al., 2011; de Villiers, 2019).

The dominant microplastic colour in both water and sediment was black/grey. Similar results were reported in the Diep River within the same province as the current study (Khan et al., 2025). The colour of microplastics is significant as it can affect its bioavailability in aquatic environments. According to Rezania et al. (2018) black and blue coloured microplastics are the most dominant microplastic colours in aquatic environments as well as the most ingested by aquatic organisms. This is concerning given the greater abundance of black coloured microplastics observed in this study as well due to the fact that black coloured microplastics are able to adsorb more chemicals than other colours (Ma et al., 2020; Antunes et al., 2013) which could lead to greater ecotoxicological effects.

The dominant microplastic size class in both water and sediment was 500 – 1000 µm. The size of microplastics can reflect the degree of weathering (Wu et al., 2018). Thus, the higher abundance of smaller sized microplastics either suggests that fragmentation is enhanced within lotic environments due to greater hydrodynamic conditions or that the retention of smaller sized microplastics is favoured (Govender et al., 2020). Several studies, both internationally (Tibbetts et al., 2018; Liu et al., 2024; Unnikrishnan et al., 2024) and in South Africa (Naidoo et al., 2015; Govender et al., 2020; Samuels et al., 2024), report a higher abundance of smaller microplastics as opposed to larger microplastics. These reports further raise concerns as smaller microplastics are more frequently ingested by aquatic organisms.

5.4.5 Microplastic polymer identification

The high abundance of natural particles and/or natural fibres observed in this study is not unlikely, given that natural fibres are more ubiquitous than synthetic fibres (Kwak et al., 2022). Several recent reports indicate that microfibres of natural origin are more prevalent than synthetic microfibres (Stanton et al., 2019; Suaria et al., 2020; Weideman et al., 2023). However, when it comes to microfibre identification, challenges do arise in terms of distinguishing natural fibres from synthetic fibres, especially when visual identification is solely based on microscopy (Ryan et al., 2020c). As a result, research on microplastics

excludes these fibres from abundance estimates. However, whether natural or synthetic, fibres are generally ingested by aquatic organisms and can lead to clogging of the gut regardless of its composition (Halstead et al., 2018; Kim et al., 2021). Thus, for this study, it should be noted that all fibres (natural & synthetic) were included in abundance estimates.

Apart from the high abundance of natural fibres observed in this study, polyethylene terephthalate was the most prevalent synthetic polymer recorded for both surface water and sediment, across all seasons and all regions. PET has a relatively high density ranging between 1.37 – 1.45 g/cm^3 and thus it has a high settling rate (Parolini et al., 2020). However, increased hydrodynamic conditions and increased turbulence can result in the resuspension of settled particles (Dahms et al., 2020), owing to the high abundance found in both the surface water and the sediment.

PET is one the most commonly produced polymers, particularly in the form of microfibres (PlasticsEurope, 2023; Jessieleena et al., 2023). Microfibres can enter aquatic environments through various sources, with domestic wastewater effluents often reported as ones of its major sources (Jessieleena et al., 2023). Microfibres found in domestic wastewater effluents from residential areas can be derived by common household activities such as dish washing, bathing, toilet usage and laundry washing (Boucher & Friot, 2017; Jessieleena et al., 2023). The washing of laundry in particular is known to release a considerable amount of microfibres into domestic wastewater effluents (Browne et al., 2011; Boucher & Friot, 2017).

Microfibres in laundry water constitute 35% of the overall primary microplastics present in the ocean (Boucher & Friot, 2017). Galvão et al. (2020) reported that for a 6kg load of washing, 18 000 000 synthetic fibres were released. Additionally, other studies have reported a synthetic microfibre release rate ranging between 140 000 – 730 000 (Napper & Thompson, 2016) and 1 000 000 – 6 500 000 (Belzagui et al., 2019). Despite the differences in these release concentrations, these studies highlight the significant contribution of laundry water to the release of microfibres in the environment.

Both natural and PET fibres are derived from textiles. Natural fibres are used for manufacturing clothing and textiles such as cotton, wool, linen and silk (Ryan et al., 2020c). Similarly, PET fibres are used for the manufacturing of textiles and synthetic clothing (Jessieleena et al., 2023). Thus, given the high abundance of both natural and PET fibres, it is postulated that the main sources of contamination are domestic laundry effluents from residential areas transported through wastewater treatment works and stormwater outlets.

Additionally, the high abundance of both natural and PET fibres found within the system may also be linked to domestic wastewater effluents derived from informal settlements (de Villiers, 2019). In South Africa, residents residing in rural communities rely on rivers as their primary source of water as they often do not have access to piped water (de Villiers, 2019). Therefore, activities such as utilising rivers for the washing of clothes can result in the direct release of fibres into the environment (de Villiers, 2019), further owing to the high abundance of both natural and PET fibres found in the system.

Given that both natural and synthetic fibres are often treated with chemical additives (Stone et al., 2020; Granek et al., 2022), the high abundance of fibres observed in this study is concerning. Not only are microfibres treated with chemical additives but they are also capable of adsorbing chemical contaminants. This capability can facilitate the transport of chemical contaminants into the environment and to aquatic organisms with microfibres serving as vectors (Grancaric et al., 2005; Granek et al., 2022). Additionally, and for natural fibres in particular, their toxicity may further be facilitated by their quicker degradability, as the quicker they able to degrade, the quicker they are able to release chemical contaminants and given the relatively long degradation time of synthetic fibres (Ladewig et al., 2015; Granek et al., 2022), natural fibres may thus be more toxic than synthetic fibres, however the effects of natural fibres in the environment require further research.

5.4.6 Relationship between microplastics and environmental parameters

5.4.6.1 Surface Water

- Temperature

Temperature was positively correlated to microplastic concentrations in the catchment (63 & 250 µm) during the wet season. The temperature of surface runoff is typically warmer than the water of the environment that it flows into (Liu et al., 2022). Thus, surface runoff can alter the temperature of the environment that it flows into (Liu et al., 2022) and the given that greater microplastic source inputs occur during the wet season coupled with the catchments proximity to sources of contamination (Grbić et al., 2020; Talbot & Chang, 2022), the positive correlation observed between microplastic concentrations and temperature in the catchment during the wet season may thus be attributed to increase microplastic inputs entering the system through increased surface runoff.

- Salinity

Salinity was positively correlated to microplastic concentrations along the coast (250 µm) during the dry season. Coastal environments typically have higher water densities due to their high levels of salinity. These salinity levels become particularly high during the dry season due to decreased precipitation and freshwater inflow as well due to increased evaporation rates (Talley, 2002). This increase in salinity leads to an increase in water density (Talley, 2002). Thus, the positively correlation observed between microplastic concentrations and salinity during the dry season is attributed to the high density of saline waters enabling microplastics, particularly those of a low density, to float on the surface, leading to increased concentrations in the surface water along the coast (Jiang et al., 2020b).

- Turbidity

Turbidity was positively correlated to microplastic concentrations along the coast (250 µm) during the dry season. Turbidity is typically higher during the wet season as opposed to the dry season due to the increased hydrodynamic conditions (Gillanders & Kingsford, 2002). However, wind-induced bottom currents that occur along the coast, causing increased turbulence, can result in an increase in turbidity and the re-suspension and retention of microplastics (Zhou et al., 2021; Malli et al., 2022). Thus, the positive correlation between microplastic concentrations and turbidity in these environments are attributed to bottom currents and its resulting turbulence, causing both an increase in turbidity and the re-suspension of microplastics, leading to the increased accumulation of microplastics in the surface water within the estuary and along the coast.

- pH

pH was positively correlated to microplastic concentrations in the catchment (250 µm), estuary (250 µm) and along the coast (250 µm) during the wet season. Given that pH can influence the surface charge of microplastics, the positive correlation may be due to the higher pH levels preventing microplastics from aggregating and settling among the sediment. Low pH levels (< 3) can result in microplastics retaining an electrostatic force of attraction, leading to the flocculation and aggregation of particles (Lu et al., 2018; Kumar et al., 2021). This in turn results microplastics accumulating among the sediment due to their increased density causing them to sink. In contrast, High pH levels (> 6.5 and < 9) can result in microplastics retaining an electrostatic fore of repulsion which prevents aggregation, decreasing their ability to sink and leading to increased concentrations in the water column (Kumar et al., 2021). Thus, the positive

correlation observed between microplastic concentrations and pH is attributed to higher pH levels preventing the aggregation of particles by influencing the electrostatic force of microplastics.

5.4.6.2 Sediment

- Grain size

Several studies have shown a positive correlation between microplastic concentrations and fine-grained sediment, attributed to processes like flocculation and bio-fouling, which can enhance microplastic deposition (Alves & Figueiredo, 2019; Harris, 2020; Andersen et al., 2021). However, this study found a negative correlation between microplastic concentrations and very-fine sediment in the estuary during the wet season, suggesting that microplastic concentrations decrease as sediment grain size decreases. This could be due to the cohesive nature of finer sediments making microplastic deposition challenging unless aided by flocculation and the suspension of sediment (Andersen et al., 2021; Govender et al., 2020). Similar results were reported by Alomar et al. (2016) and Govender et al. (2020) who found lower microplastic concentrations in finer sediments.

5.4.7 Disturbance index

Identifying microplastic hotspots and potential sources of contamination has become increasingly important given that microplastics in aquatic environments have been linked to anthropogenic disturbances. Several studies have linked microplastic concentrations to anthropogenic disturbances, with concentrations increasing, relative to an increase in the level of disturbances (Yonkos et al., 2014; Kunz et al., 2023; Ferguson et al., 2024).

The Breede system is subjected to varying levels of anthropogenic disturbances (Western Cape Government, 2025). Disturbances such as agricultural, industrial and recreational activities, residential areas as well as development adjacent to the system were all well observed throughout this study and are all potential sources of microplastic contamination (Horton & Dixon, 2018; Shikwambana et al., 2024). Located in the Breede Valley municipal area, the system is largely rural although it spans an urban-rural gradient (Western Cape Government, 2021c). As a result, the system was not as disturbed as more urbanised systems (Govender et al., 2020; Johnson et al., 2023). Nonetheless, the catchment was the most disturbed across the different regions (ATDR of 10.5) with the system predominantly surrounded by agricultural land-use.

Agriculture is considered the primary economic driver within the region (Western Cape Government, 2025). However, despite its importance, agricultural activities can often result in a decline in water quality as it has the potential to introduce contaminants, such as microplastics, into aquatic environments (Department of Water & Sanitation, 2011; Cullis et al., 2018). High concentrations of microplastics have been linked to agriculture as modern-day agricultural practices utilise sewage sludge, the by-product of wastewater treatment, as fertiliser (Zubris & Richards, 2005; Nizzetto et al., 2016).

Although wastewater treatment works are considered generally inefficient in removing microplastics, removal rates can exceed 90%, with many of these particles retained in sewage sludge (Carr et al., 2016; Murphy et al., 2016). For example, Jiang et al. (2020a) reported a concentration of 126.0 ± 14.0 microplastic particles/L in wastewater influent, 76% of which was retained in the resulting sewage sludge. Similarly, Menéndez-Manjón et al. (2022) reported 79% of microplastic particles retained in sludge. Sewage sludge may thus significantly contribute to the accumulation of microplastics in the environment.

Moreover, both studies attributed these microplastics to domestic laundry effluents from residential areas given that PET microfibres were the dominant microplastic characteristics (Jiang et al., 2020a; Menéndez-Manjón et al., 2022). This suggests a link between the microplastics from residential areas and the microplastics from agricultural practices. While microplastics can be retained in agricultural soils for extended periods (Schell et al., 2022), hydrodynamic conditions can facilitate their movement from terrestrial to aquatic environments (Horton & Dixon, 2018).Thus, given that the Breede system is predominantly surrounded by agricultural land-use, agricultural disturbances may serve as another significant source contributing to the accumulation of microplastics in the system.

5.4.8 Risk assessment

For the 63 µm water samples, the H values was highest in the coast (high) compared to the catchment (moderate) and estuary (low) during the wet season. The higher H value along the coast was attributed to the high polymer hazard score of the polymer epoxy which was present along the coast during the wet season (Lithner et al., 2011). In correspondence with the H values, the PRI values were also highest along the coast (very high) during the wet season compared to the catchment (low) and estuary (low). The higher PRI values observed along the coast may be attributed to the hydrodynamic conditions of the system such as the lower residency times of catchments and estuaries (Nel et al., 2018). During the wet season, when precipitation increase, river flow increases, which can enhance the flushing rates of particles from the

catchment, through the estuary and toward the coast (McLusky et al., 1993; Bakir et al., 2014; Nel et al., 2018). Thus, leading to increased microplastic concentrations along the coast. During the dry season, the H values were highest along the coast (high) compared to the catchment (moderate) and estuary (moderate). The higher H value was again attributed to the polymer epoxy observed along the coast during the dry season (Lithner et al., 2011). The PRI values were also highest along the coast (dangerous) compared to the catchment (low) and estuary (low). Similarly, the higher PRI values observed along the coast may be attributed to the systems hydrodynamic conditions. During the dry season, microplastic concentrations in the water of catchment and estuaries often decrease due to reduced river flows enabling particles to settle among the sediment. However, along the coast, microplastic particles are subjected to daily and monthly tidal movements which allow settled microplastic to become resuspended within the column (Horton & Dixon, 2018; Malli et al., 2022), increasing concentrations along the coast. These results indicate that the microplastics that accumulate along the coast pose a greater risk to the system than the microplastics in the catchment and estuarine region during both the wet and the dry season. Seasonally, the PRI values for both the wet and the dry season was categorised as dangerous thus indicating that the microplastics that accumulate in the surface water poses a great risk to the system during both the wet and the dry season.

For the 250 µm water samples, the H values were highest along the catchment (high) and coast (high) compared to the estuary (moderate) during the wet season. The higher H values along the catchment and coast was attributed to polymers epoxy and styrene acrylonitrile (SAN) present along the catchment and coast which both have high hazard scores (Lithner et al., 2011). In correspondence to the H values, the PRI values were also highest along the catchment (dangerous) and coast (dangerous) during the wet season. These higher PRI values may have been attributed to both increased microplastic inputs within the catchment and its proximity to sources of contamination (Horton & Dixon, 2018; Grbić et al., 2020; Talbot & Chang, 2022), explaining the higher values observed along the catchment but also due to the increased flushing rates that occur during the wet season (Nel et al., 2018), transporting microplastics from the catchment toward the coast, explaining the higher values observed along the coast. During the dry season, the H values were moderate across the different regions of the system. The PRI values also ranged from moderate within the catchment region to low along both the estuary and the coast. Despite, the lower microplastic concentrations observed along the catchment during the dry season, the slightly higher H and PRI values observed along the catchment was attributed to the polymer polyester observed in the catchment which has a high hazard score (Lithner et al., 2011). These results indicate that the

microplastics that accumulate in the catchment (wet & dry season) and coast (wet season) pose a greater risk to the system than the microplastics in the estuary. Seasonally, the PRI values were dangerous during the wet season and high during the dry season which may be due greater microplastic concentrations observed during the wet season thus indicating that the microplastic observed in the system during the wet season pose a greater risk to the system than in the dry season.

For the sediment samples, the H values were moderate throughout the different regions during the wet season. The PRI values were highest along the estuary (high) during the wet season compared to the catchment (low) and coast (moderate). The slightly higher H and PRI values along the estuary was attributed to both the high polymer hazard score of the polymer polyester combined with the microplastic concentrations observed along the estuarine region of the system (Lithner et al., 2011). During the dry season both the H and PRI values were low throughout the different regions. These lower H and PRI values were attributed to polymers of low hazards scores present in the sediment during the dry season. For example, PET, despite the high abundance of the polymer PET observed in this study and within the sediment, it has a low hazard ranking score (Lithner et al., 2011). Thus, the low to moderate values observed in the sediment is attributed to the presence of polymers with low hazard scores (Lithner et al., 2011). These results indicate that the microplastics present in the sediment along the estuary pose a greater risk to the system than those present along the catchment and coast, particularly during the wet season. Seasonally, the PRI values for sediment were categorised as very high during the wet season and low during the dry season again indicating that the microplastics that accumulate in the system during the wet season pose a greater risk than those that accumulate during the dry season.

The results from this study indicate that the higher H and PRI values are attributed to the polymers epoxy, styrene-acrylonitrile (SAN) and polyester (PY) as these polymers have high hazard scores. Both epoxy and SAN have high hazard scores as it is made up of at least one monomer which is considered to be carcinogenic (Lithner et al., 2011). As for polyester, exposure may result in respiratory issues and skin sensitisation, resulting in its high hazard score (Lithner et al., 2011). Additionally, the risk assessment also indicated that the microplastics in water pose the greatest risk to the system. Similar findings have been observed by Sparks et al. (2023) who also reported dangerous rankings for the microplastics in water in the Cape Town Harbour in the Western Cape, South Africa. The Cape Town Harbour is an area where high levels of industrial and recreational activities take place, with microplastic concentrations (12.08 ± 1.3 MPs/L) orders of magnitude higher than the concentrations reported here (0.26 ± 0.02 particles/L).

However, given the similar dangerous rankings observed in the aforementioned study, it highlights that the risks posed by microplastics are not dependent on its concentration but rather on the composition of polymers and their assigned hazard scores.

The very high to dangerous rankings recorded for the microplastics in water along the catchment, estuary and coast thus poses a serious threat to the Breede system. Given that the Breede system is known for its unique biodiversity and relatively high level of endemism, the development and implementation of necessary risk reduction measures will be essential in terms of enhancing the protection of both the biodiversity within the system as well as the ecosystem as a whole (Lithner et al., 2011).

5.5 Conclusion

The aim of the study was to determine the environmental concentrations, characteristics and risk assessment of microplastics in the Breede River catchment, estuary and coastal area in the Western Cape of South Africa. This was the first study to report on microplastic contamination in the Breede system within the context of catchment-to-coast. Average microplastic abundances were 0.26 ± 0.02 particles/L in water and 43.65 ± 2.71 particles/kg dry weight in sediment samples across the sampling sites. The results for the surface water were similar across the different regions and seasons and were thus not reflective of any spatial or seasonal variations. However, the results for sediment were significantly higher along the coast during the dry season and were reflective of the hydrodynamic conditions of the system. Thus, the coastal region of the system can be considered a sink for microplastics. The predominant microplastic characteristics recorded in this study were black/grey fibres, 500 – 100 µm and were mainly of natural origin, while polyethylene terephthalate was the dominant synthetic polymer type. The high abundance of fibres was attributed to the laundering of clothes from residential areas entering the system through wastewater treatment works and stormwater outlets.

The high abundance of fibres poses a threat to the health of the Breede system and potentially poses an ecological risk to its overall functioning. Given that the Breede system is of high conservation importance with its unique biodiversity and high level of endemism, the monitoring of the system is crucial. The high concentrations of microfibres reported here thus provides a baseline and further emphasises the need for future monitoring and research efforts either to identify microplastic hotspots or to identify the major pathways in which these microplastics enter the system. This study does however also serve to inform

policy makers that govern the protection of the Breede system, so that they may be able to develop and implement appropriate mitigation measures to enhance the protection of this system.

Chapter 6: General conclusion, limitations and recommendations of the research

6.1 General conclusion

Microplastics are prevalent in freshwater, estuarine and coastal and marine environments, all of which are interconnected. Thus, determining the seasonal and spatial distribution of microplastics from catchment to coast is important for understanding their distribution and accumulation across these environments as it will allow for more targeted waste management approaches. Accordingly, the aim of the study was to determine the concentrations, characteristics and risk assessment of microplastics in the Olifants and Breede River catchments, estuaries and coastal areas. This is the first study in South Africa to investigate microplastics from catchment-to-coast simultaneously, focusing on two representative systems: the Olifants system on the West Coast and the Breede system on the South Coast.

The inclusion of both systems enabled a comparative assessment across differing environmental, ecological and socio-economic contexts. The Olifants system features commercial and small-scale fisheries which supports local livelihoods, a protected estuary and abundant marine resources along the West Coast. Elephant Rock Island Reserve (Robeiland) off the coast further highlights the systems ecological significance although the system faces multiple environmental pressures, including agriculture, residential development and tourism (Western Cape Government, 2021a). River health assessments indicate that these pressures are reflected in the condition of the rivers as stretches of both the Olifants and the Breede rivers show signs of modification ranging from largely natural (Category B) to largely modified, particularly due to land use practices, with the Olifants estuary classified as moderately modified (Category C) (Van Niekerk et al., 2019). In contrast, the Breede system is characterised by a protected estuary, indigenous fish species and a high level of endemism while similarly experiencing environmental pressures from agriculture, tourism, residential development and recreation (Western Cape Government, 2025). The Breede estuary, however, remains in good ecological condition (Category B/C) and the river runs through Bontebok National Park, highlighting its ecological and conservation significance (Van Niekerk et al., 2019; South African National Parks, 2013). Studying both systems simultaneously allowed the identification of system-specific patterns while revealing consistent trends, strengthening the overall understanding of microplastic distribution from catchment to coast. Presenting the results in separate chapters allowed for more detailed intra-system analyses, while the comparative synthesis in this general conclusion integrates both systems to highlight common trends and system-specific patterns.

Despite these contextual differences, the results observed among both systems were broadly similar. Microplastic concentrations ranged from 0.24 ± 0.01 particles/L to 0.26 ± 0.02 particles/L ($Z = 0.57$, $p = 0.56$) in the surface water, while concentrations ranged from 48.30 ± 3.95 particles/kg dw to 43.65 ± 2.71 particles/kg dw ($Z = 1.006$, $p = 0.315$) in the sediment of the Olifants and Breede systems, respectively. While each system was analysed independently in separate chapters to determine system specific patterns, these results were formally compared using statistical tests, confirming that differences between these systems were not statistically significant and allowing meaningful inter-system synthesis. Similarly, the proportions of the microplastic characteristics were also largely similar. Microplastics were mainly fibres for both the Olifants (93.4 %) and the Breede (92.8 %) system. Microplastics were also mainly black/grey in colour, 500 – 1000 µm in size and mainly of natural origin or composed of PET. These similarities are attributed to comparable levels of anthropogenic disturbances and consistent sources of contamination across both systems.

The dominance of fibres, particularly natural and PET fibres, across both systems has been directly linked to prevailing land-use practices within the Olifants and Breede systems. Residential areas, WWTWs and stormwater outlets and effluents from surrounding informal settlements are well documented sources of textile-derived fibres, while agricultural activities may contribute fibres through synthetic materials, irrigation runoff and sewage sludge application. Thus, the combination of both point and diffuse sources plays a role in the high abundance and consistent presence of fibres throughout catchment to coast. Additionally, the limited occurrence of other microplastic morphologies such as fragments, films, spheres and foams likely reflect the predominantly rural to semi-rural nature of both systems as these systems are not as disturbed as other systems in more urbanised settings typically associated with these microplastic types.

The high abundance of natural fibres observed in this study is highly significant. Like that of synthetic fibres, natural fibres can be treated with chemical additives and are often more likely to adsorb chemical contaminants, enabling them to serve as vectors, transporting chemicals into the environment and to aquatic organisms. Furthermore, the relatively quick degradation time of natural fibres may facilitate its toxicity as their quick degradability may potentially result in the quicker release of chemicals. Thus, natural fibres may pose a greater risk to aquatic environments than synthetic fibres. While the effects of natural fibres in the environment are still unknown, their high abundance in aquatic environments and ability to serve as vectors for chemical contaminants provide a strong argument for future research to be

undertaken. Moreover, given that the microplastic polymers that accumulate in surface water pose the greatest risk to both systems, it further strengthens the need for future research work.

The Olifants and the Breede systems are both ecologically and socio-economically important systems, thus the ongoing monitoring of these systems is crucial. Given that the results observed among these two systems were so similar, the development, implementation and management recommendations on microplastics can thus be applied to both systems and may even be applied globally to similar areas of concern. At the same time, system-specific ecological and socio-economic contexts are considered, ensuring that management strategies account for both shared and unique environmental characteristics.

6.2 Limitations of the research

This study contributes to the growing body of research on microplastic contamination in South African aquatic environments. However, several limitations arose throughout conducting this research. One of the first challenges faced during the study was the limited access to sampling sites. During the proposal stage of the research, 18 sites (6 per region) were initially supposed to be sampled along both systems and five replicate samples were to be collected at each site. However, because both systems ran through private property and few property owners responded to access requests, the number of sampling sites was reduced to 12 sites per system and four replicate samples were collected at each site.

Attempts were made to measure river flow using cost-effective methods during fieldwork. However, because all sampling was conducted from the shore, being able to successfully measure the flow rate proved difficult and was thus excluded from the study. Many of the methods used to accurately measure river flow require advanced and expensive equipment, such as a flow meter as well as a vessel, both of which were inaccessible. It should thus be acknowledged that researchers may not have access to certain equipment due to both budget constraints and limited access. This limitation thus highlights the need for collaboration by combining resources and expertise to enhance research efforts and to achieve more effective research outcomes.

Environmental parameters were measured using a YSI water multi-meter. Parameters such as salinity, temperature, conductivity, turbidity and pH were all measured successfully. However, measurements of dissolved oxygen were deemed inaccurate, and were therefore excluded from the study.

The methodology used throughout the study enabled the successful extraction and identification of microplastics in the surface water and sediment samples from each system. However, it is acknowledged that some underestimation may have occurred while using a NaCl solution to extract microplastics from the sediment, given the 80% extraction efficiency observed during density separation. Although there are other solutions that could have been used, such as zinc chloride (ZnCl) which has a higher density than NaCl, which could have potentially yielded higher extraction rates, using NaCl during density separation was due to the method being both cost effective and easy to replicate.

Lastly, the lack of a standardised methodology while conducting the research presented a challenge. Due to the varying methodologies used in microplastic research there is limited availability of comparative results which hinders progress in terms of understanding microplastic concentrations and the level of contamination in aquatic environments. This also hinders the development and implementation of effective management strategies and highlights the need for the development of a standardised methodology as it would allow researchers to conduct microplastic research more efficiently.

6.3 Recommendations

Given that the results observed in this study were similar among both the Olifants and the Breede systems, a series of actions focused on the prevention and management of microplastics is recommended. These recommendations are directed at various levels of government and can be applied to both systems (Figure 45). Firstly, given that domestic laundry effluents from residential areas are considered the likely source for microplastic contamination in these systems, technological advancements should focus on the development of more advanced filtration systems capable of capturing microplastics. These technologies should then be integrated at both a household level, particularly in washing machines, and at wastewater treatment facilities to reduce the release rates of microplastics entering aquatic environments through wastewater discharge.

At the local government level, specifically the Matzikama and Breede Valley municipalities, authorities should implement regular clean-ups within the surrounding areas. Targeting known plastic hotspots along these systems and reducing macroplastic pollution can help limit its degradation into microplastics, resulting in less microplastic inputs into these systems. The local government should also initiate regular monitoring and conducting of litter surveys to try and pin-point the exact origin of these macro- and/or microplastic debris and should evaluate the effectiveness of these interventions.

Moreover, waste management practices within the surrounding areas can be improved on. Local government should thus look into installing either litter booms or the litter traps utilised in stormwater outlets, to intercept plastic before it enters aquatic environments. In addition to these interventions, the local government should also look into conducting regular environmental education programmes in line with Constitution of the Republic of South Africa (No. 108 of 1996) Chapter 7, Section 152(1)(d) which states that "The objects of local government - are to promote a safe and healthy environment" (South African Government, 1996). Conducting regular environmental education programmes can thus be implemented to educate the surrounding community and to raise awareness on microplastic contamination.

At the provincial government level, CapeNature who manages both the Olifants and the Breede systems, should develop and implement a microplastic monitoring protocol. Both systems already have estuarine management plans in place, which outlines strategic conservation measure for each estuary (Western Cape Government, 2021a; Western Cape Government, 2025). These plans can thus be expanded on to incorporate microplastic monitoring which can facilitate future research work and the development of microplastic management strategies, to enhance the protection of these systems.

At the national government level, the South African government, specifically the Department of Forestry, Fisheries and the Environment (DFFE) should look into minimising the production of single-use plastics while also promoting the use of non-plastic substitutes. The Department of Water and Sanitation (DWS) together with the Department of Agriculture, Land Reform and Rural Development (DALRRD) should prohibit the use of sewage sludge as fertilisers for agricultural practices, unless microplastics were properly screened for. Additionally, the DWS should consider the development and implementation of greywater systems in informal settlements as it may significantly contribute toward reducing the concentrations of microplastics entering aquatic environments.

At the international level, international authorities and treaties, such as the Global Plastics Treaty, should advocate for the global ban of hazardous polymers, such as epoxy, styrene-acrylonitrile and polyester, which are known to cause significant adverse effects to aquatic organisms.

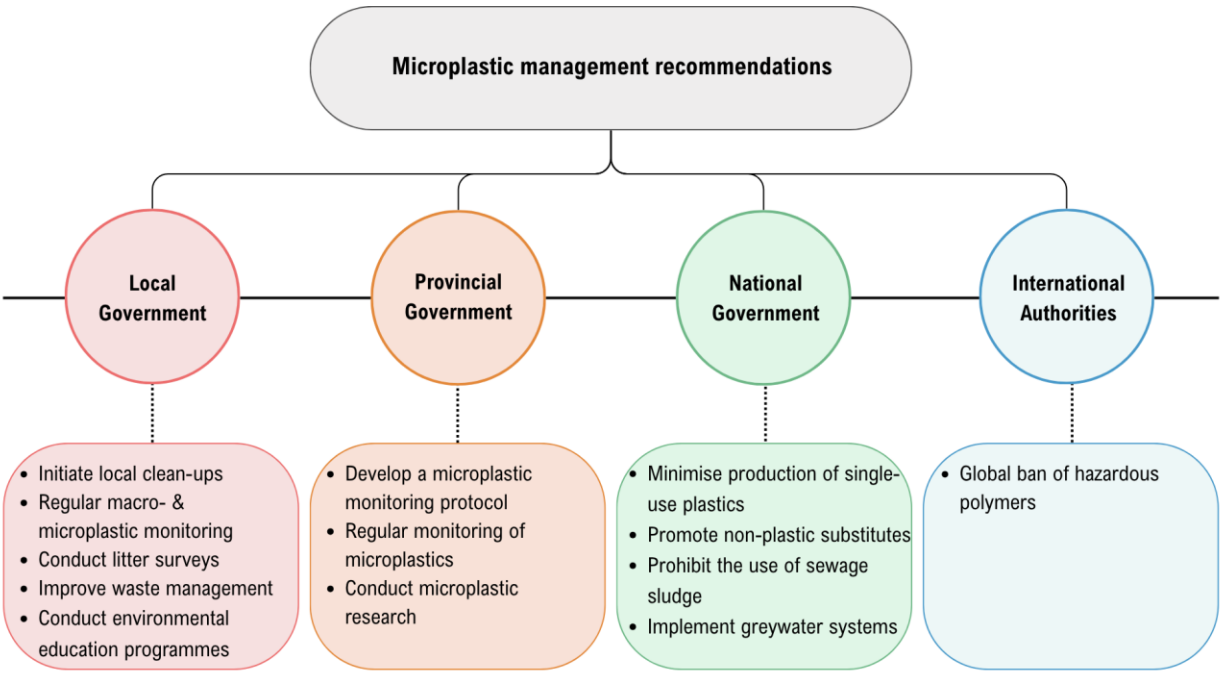

Figure 45: Microplastic management recommendations for various levels of government

Finally, research efforts should focus on the effects of environmental exposure and ingestion of microfibres. More knowledge is needed on the impacts of microfibres to determine how severe exposure and ingestion risks are to aquatic organisms. Only once the impacts of these microfibres are understood, can the relevant authorities begin to address the issue.

While some of the microplastic management recommendations discussed here may seem small in scope, microplastic contamination is a long-term issue. Thus, even small-scale interventions and research efforts, when consistently applied, can help to curb the release of plastic and microplastics into aquatic environments as opposed to doing nothing to try and help address the problem.

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Appendices

Appendix 1: Environmental data measured in the surface water of the Olifants system in the wet season.

Season	Region	Site	Temperature	Salinity	Turbidity	pH	MP Unit (63 µm)	MP Unit (250 µm)
Wet	Catchment	O1	13,02	0,062	88,42	6,191	180	300
Wet	Catchment	O1	13,01	0,061	88,41	6,04	110	120
Wet	Catchment	O1	13	0,06	88,4	5,93	80	20
Wet	Catchment	O2	12.92	0,082	111,152	6,19	100	120
Wet	Catchment	O2	12.91	0,081	111,151	5,8	65	50
Wet	Catchment	O2	12.9	0,08	111,15	5,73	20	20
Wet	Catchment	O3	16.71	3,591	4251	6,132	160	100
Wet	Catchment	O3	16.7	3,59	4244,51	6,131	105	65
Wet	Catchment	O3	16.6	3,58	4244,5	6,13	60	40
Wet	Catchment	O4	14.8	0,142	193,7	6,41	80	300
Wet	Catchment	O4	14.6	0,141	193,05	6,21	50	170
Wet	Catchment	O4	14.5	0,14	192,4	6,09	20	60
Wet	Estuary	O5	14.52	0,212	281,45	6,12	40	80
Wet	Estuary	O5	14.51	0,211	279,51	6	25	55
Wet	Estuary	O5	14.5	0,21	279,5	5,91	20	20
Wet	Estuary	O6	14.8	0,26	343,85	6,21	300	140
Wet	Estuary	O6	14.71	0,25	329,55	6,05	170	90
Wet	Estuary	O6	14.7	0,24	321,75	5,97	60	20
Wet	Estuary	O7	14.62	0,591	734,52	5,93	200	120
Wet	Estuary	O7	14.61	0,59	734,51	5,67	125	60
Wet	Estuary	O7	14.6	0,47	734,5	5,64	60	20
Wet	Estuary	O8	12.91	33,41	33085,5	5,74	220	100
Wet	Estuary	O8	12.9	31,54	30706,5	5,721	135	80
Wet	Estuary	O8	12.8	30,26	30257,5	5,72	60	60
Wet	Coast	O9	12.5	33,23	33299,5	5,791	100	180
Wet	Coast	O9	12.31	33,2	33065,5	5,79	40	110
Wet	Coast	O9	12.3	32,55	32857,5	5,71	0	40
Wet	Coast	O10	12,01	31,96	26513,5	5,761	280	100
Wet	Coast	O10	12	30,85	26390	5,76	205	90
Wet	Coast	O10	11.9	30,69	24563,5	5,75	140	80
Wet	Coast	O11	12,03	33,141	32942	5,771	380	260
Wet	Coast	O11	12,02	33,14	32935	5,77	310	155
Wet	Coast	O11	12	33,02	32838	5,76	220	120

Appendix 2: Environmental data measured in the surface water of the Olifants system in the dry season.

Season	Region	Site	Temperature	Salinity	Turbidity	pH	MP Unit (63 µm)	MP Unit (250 µm)
Dry	Catchment	O1	32.8	0,09	121,55	5,22	200	260
Dry	Catchment	O1	30,2	0,081	117,651	5,17	105	130
Dry	Catchment	O1	25,8	0,08	117,65	5,07	40	40
Dry	Catchment	O2	21,5	0,062	83,21	5,26	60	160
Dry	Catchment	O2	21,4	0,061	83,2	5,02	35	100
Dry	Catchment	O2	21,1	0,06	82,56	4,97	20	60
Dry	Catchment	O3	27,11	0,252	338,02	5,68	80	100
Dry	Catchment	O3	27,1	0,251	338,01	5,66	55	45
Dry	Catchment	O3	26,4	0,25	338	5,43	40	0
Dry	Catchment	O4	25,42	0,812	1053,02	5,09	160	160
Dry	Catchment	O4	25,41	0,811	1053,01	5,081	60	70
Dry	Catchment	O4	25,4	0,81	1053	5,08	0	0
Dry	Estuary	O5	25,5	1,94	2405	5,45	100	100
Dry	Estuary	O5	25,4	1,88	2333,5	5,43	70	80
Dry	Estuary	O5	24,8	1,81	2242,5	5,4	40	60
Dry	Estuary	O6	25,11	2,151	2646,51	5,391	200	180
Dry	Estuary	O6	25,1	2,15	2645,5	5,39	90	110
Dry	Estuary	O6	25	2,14	2632,5	5,37	0	20
Dry	Estuary	O7	24,2	9,36	10400	5,371	120	160
Dry	Estuary	O7	24	9,26	10302,5	5,34	115	85
Dry	Estuary	O7	23,8	9,03	10055,5	5,3	100	40
Dry	Estuary	O8	18	30,25	30225	4,83	100	180
Dry	Estuary	O8	17,9	29,18	29263	4,75	55	125
Dry	Estuary	O8	17,8	28,58	28723,5	4,58	0	40
Dry	Coast	O9	15,82	33,85	33455,5	5,17	140	100
Dry	Coast	O9	15,81	33,71	33332	5,12	115	80
Dry	Coast	O9	15,8	33,65	33283,5	4,99	80	40
Dry	Coast	O10	16,3	33,9	33527	5,02	80	60
Dry	Coast	O10	14,4	33,57	33241	4,91	35	40
Dry	Coast	O10	14,3	33,47	33104,5	4,85	0	20
Dry	Coast	O11	16,3	33,51	33143,5	5,11	140	180
Dry	Coast	O11	16,21	32,67	32396	5,04	110	105
Dry	Coast	O11	16,2	28,66	28801,5	4,71	80	40

Appendix 3: Environmental data measured in the surface water of the Breede system in the wet season.

Season	Region	Site	Temperature	Salinity	Turbidity	pH	MP Unit (63 µm)	MP Unit (250 µm)
Wet	Catchment	B1	12.31	5.102	5895.52	5.81	640	620
Wet	Catchment	B1	12.3	5.101	5895.51	5.80	375	320
Wet	Catchment	B1	12.2	5.10	5895.5	5.78	140	220
Wet	Catchment	B2	11.1	0.292	382.85	4.62	120	80
Wet	Catchment	B2	11.0	0.291	382.2	4.56	70	55
Wet	Catchment	B2	10.9	0.29	381.55	4.39	20	40
Wet	Catchment	B3	12.5	0.142	191.1	4.77	380	160
Wet	Catchment	B3	12.4	0.141	190.451	4.70	230	125
Wet	Catchment	B3	12.3	0.14	190.45	4.65	100	60
Wet	Catchment	B4	11.3	0.282	378.31	6.46	200	160
Wet	Catchment	B4	11.1	0.281	378.3	6.37	130	115
Wet	Catchment	B4	11.2	0.28	377.0	6.29	60	80
Wet	Estuary	B5	11.11	0.342	448.52	6.20	160	140
Wet	Estuary	B5	11.1	0.341	448.51	6.14	65	65
Wet	Estuary	B5	11.0	0.34	448.5	6.09	20	40
Wet	Estuary	B6	12.2	0.45	585.0	6.60	140	180
Wet	Estuary	B6	12.1	0.421	552.51	6.45	75	145
Wet	Estuary	B6	12.0	0.42	552.5	6.37	40	100
Wet	Estuary	B7	16.3	0.501	656.5	6.57	120	260
Wet	Estuary	B7	16.21	0.50	650.01	6.51	65	125
Wet	Estuary	B7	16.2	0.49	650.0	6.47	20	40
Wet	Estuary	B8	12.22	11.16	12200.5	4.96	320	80
Wet	Estuary	B8	12.21	10.96	11979.5	5.07	140	70
Wet	Estuary	B8	12.2	10.85	11875.5	5.15	40	60
Wet	Coast	B9	12.81	19.58	21235.5	5.61	200	80
Wet	Coast	B9	12.8	18.51	19305.5	5.46	80	60
Wet	Coast	B9	12.5	17.24	18200.0	5.27	0	40
Wet	Coast	B10	14.0	33.24	32896.5	5.56	120	160
Wet	Coast	B10	13.7	31.8	31778.5	5.40	35	55
Wet	Coast	B10	13.1	30.45	30472.0	5.08	0	20
Wet	Coast	B11	14.1	8.38	9841.5	6.071	80	160
Wet	Coast	B11	13.61	8.21	9464.0	6.07	60	105
Wet	Coast	B11	13.6	6.42	7442.5	6.041	40	40
Wet	Coast	B12	15.8	32.40	32181.5	6.04	120	120
Wet	Coast	B12	15.71	32.301	32155.5	5.98	80	60
Wet	Coast	B12	15.7	32.30	32077.5	5.90	40	20
Wet	Coast	B13	15.81	32.91	32591.5	5.96	80	100
Wet	Coast	B13	15.71	32.83	32545.5	5.93	45	65
Wet	Coast	B13	15.6	31.53	32220.5	5.67	20	40

Appendix 4: Environmental data measured in the surface water of the Breede system in the dry season.

Season	Region	Site	Temperature	Salinity	Turbidity	pH	MP Unit (63 µm)	MP Unit (250 µm)
Dry	Catchment	B1	23.71	6.80	7735.00	6.291	60	480
Dry	Catchment	B1	23.7	6.79	7728.50	6.29	35	230
Dry	Catchment	B1	22.8	6.77	7702.50	6.17	0	20
Dry	Catchment	B2	23.6	0.65	845.00	6.19	40	160
Dry	Catchment	B2	23.5	0.64	832.00	6.02	25	105
Dry	Catchment	B2	23.3	0.62	825.50	5.90	20	60
Dry	Catchment	B3	24.31	0.40	533.00	6.04	260	40
Dry	Catchment	B3	24.3	0.35	468.00	5.80	100	100
Dry	Catchment	B3	24.0	0.30	395.50	5.71	20	20
Dry	Catchment	B4	25.9	0.74	962.00	6.53	100	40
Dry	Catchment	B4	25.7	0.731	955.501	6.51	40	30
Dry	Catchment	B4	25.3	0.73	955.50	6.50	0	0
Dry	Estuary	B5	25.51	0.89	1144.00	6.13	100	60
Dry	Estuary	B5	25.5	0.821	1059.50	6.03	70	45
Dry	Estuary	B5	25.4	0.82	1053.00	5.32	40	40
Dry	Estuary	B6	25.3	0.80	1027.00	6.45	100	340
Dry	Estuary	B6	25.2	0.781	1014.00	6.27	65	215
Dry	Estuary	B6	25.1	0.78	1007.50	6.20	20	100
Dry	Estuary	B7	24.0	13.16	14235.00	5.46	100	120
Dry	Estuary	B7	23.91	12.95	14027.00	5.44	65	80
Dry	Estuary	B7	23.9	12.92	13988.00	5.36	0	40
Dry	Estuary	B8	22.62	29.15	29497.00	4.98	140	380
Dry	Estuary	B8	22.61	27.39	29263.00	4.92	55	140
Dry	Estuary	B8	22.6	24.41	27664.00	4.63	20	40
Dry	Coast	B9	21.12	33.56	33176.00	5.06	180	100
Dry	Coast	B9	21.11	33.01	32688.50	5.03	110	75
Dry	Coast	B9	21.1	32.47	32214.00	4.93	60	40
Dry	Coast	B10	21.72	33.64	33254.00	5.20	540	540
Dry	Coast	B10	21.71	33.631	33241.001	5.08	275	220
Dry	Coast	B10	21.7	33.63	33241.00	5.07	0	20
Dry	Coast	B11	22.9	29.42	29503.50	5.79	140	100
Dry	Coast	B11	22.71	29.33	29432.00	5.771	55	100
Dry	Coast	B11	22.7	29.32	29419.00	5.77	0	60
Dry	Coast	B12	28.3	34.34	33878.00	5.87	180	180
Dry	Coast	B12	22.2	34.30	33839.00	5.86	80	125
Dry	Coast	B12	22.1	34.00	33770.00	5.76	20	80
Dry	Coast	B13	23.0	34.24	33800.00	5.691	260	220
Dry	Coast	B13	22.51	34.20	33748.00	5.69	135	170
Dry	Coast	B13	22.5	34.19	33741.50	5.65	40	100