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Microplastic dynamics in Ramsar-declared wetlands: A case study of Makuleke and Nylsvley, South Africa

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ABSTRACT

Microplastic pollution has emerged as a pervasive environmental challenge, threatening freshwater ecosystems and biodiversity worldwide. Despite extensive studies on marine systems, research on freshwater wetlands, particularly in Africa, has been limited, with these ecosystems playing vital roles in biodiversity conservation, nutrient cycling, and water purification. This study investigated the abundance, distribution, and characteristics of microplastics in two Ramsar-declared wetlands in South Africa, Makuleke (Kruger National Park) and Nylsvley Nature Reserve (Limpopo Province), across contrasting hydrological seasons (wet and dry). Water, surface sediment, and sediment core samples were collected and analyzed using density Separation and Fourier Transform Infrared (FTIR) spectroscopy to identify the types and morphologies of microplastic polymers. The results revealed substantial microplastic contamination in both wetlands, with sediments acting as major sinks. Fibres, fragments, and beads were the dominant morphotypes, while black, transparent, and white were the most common colours detected. The Nylsvley Wetland exhibited higher microplastic abundance and ecological risk levels compared to Makuleke, reflecting stronger anthropogenic influences from adjacent agricultural and peri-urban activities. Seasonal variation was evident, with significantly high concentrations of microplastics during the wet season, primarily due to increased hydrological transport and runoff. Sediment core analysis further indicated that microplastic deposition patterns were influenced by sediment composition and hydrodynamic conditions, suggesting long-term accumulation and potential remobilisation during flood events. This study presents the first comparative assessment of microplastic dynamics in Ramsar-designated wetlands in South Africa, providing valuable baseline data for future monitoring efforts. The findings highlight that even protected ecosystems are vulnerable to diffuse emerging pollutants such as microplastics. Effective mitigation requires integrated catchment management, improved waste disposal practices, and continued monitoring of both surface and sedimentary microplastic loads. Overall, the study highlights the ecological significance of wetlands in regulating microplastic transport and emphasizes the importance of integrating plastic pollution management into wetland conservation policies.

Keywords: Microplastics, Wetlands, Sediments, Ramsar sites, Hydrological variability, Ecological risk, South Africa

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DECLARATION OF INTEREST

I, Nelisiwe Ngomane, student number 201803712, hereby declare that the study on "**Microplastic dynamics in Ramsar declared wetlands: A case study of Makuleke and Nylsvley, South Africa**" has not been submitted by anyone else or any other institution and is my own research work and all sources that I used have been acknowledged by the means of references at the end of this dissertation.

Signature: Nelly Date: 30/11/2025

CHAPTER 1: GENERAL INTRODUCTION

1.1 General background

Plastics are synthetic polymers primarily derived from petroleum-based monomers, such as those derived from natural gas and crude oil (Shi et al., 2023). Since the 1940s, their production has increased rapidly, resulting in extensive use in nearly every sector (Geyer et al., 2017; Chen et al., 2021; Mashamba et al., 2023). While plastics have significantly contributed to modern society, they are also recognized as a significant environmental issue due to the vast amounts of waste they generate (Nkwachukwu et al., 2013; Evode et al., 2021; Jansen et al., 2023). Inadequate waste management, inappropriate disposal practices, and accidental losses allow plastics to enter aquatic systems, where they pose significant ecological and health risks (Nkosi et al., 2023; Gqomfa et al., 2025).

Plastics accumulate across terrestrial and aquatic ecosystems. They undergo degradation naturally through processes such as biodegradation, thermo-oxidation, photodegradation, and hydrolysis, which are influenced by temperature and ultraviolet exposure (Alshehrei, 2017; Rani and Shanker, 2021; Mashamba et al., 2024), and form smaller particles referred to as microplastics (Cole et al., 2011; Hidalgo-Ruz et al., 2012; Horton et al., 2017). Recent investigations confirm their widespread occurrence in freshwater systems, including African rivers, with abundance, type, and distribution varying across habitats and seasons (Mbedzi et al., 2020; Dalu et al., 2023; Owowenu et al., 2025).

Microplastics, smaller than 5 mm, remain in the environment for extended periods and affect a wide range of aquatic organisms, from microscopic zooplankton to large mammals (Miranda and de Carvalho-Souza, 2016; Avio et al., 2017; Hale et al., 2020; Yardy et al., 2022). Laboratory studies have shown that they can cause physical harm, including blockage of digestive tracts, reduced feeding efficiency, and impaired reproduction and growth (Avio et al., 2017; Dalu et al., 2023). Chemically, they adsorb and transport trace organic and inorganic contaminants, increasing exposure of aquatic species to toxic substances (Kinigopoulou et al., 2022). Ingestion of microplastics can therefore amplify ecological toxicity throughout the food web (Dalu et al., 2023) and raise human health concerns through consumption (Miranda and de Carvalho-Souza, 2016).

Detection and quantification of microplastics in aquatic environments have increased significantly (Murphy et al., 2016; Horton et al., 2021). Determining their exact sources remains challenging due to varied origins, including domestic wastewater, industrial effluents, surface runoff, and atmospheric deposition (Anderson et al., 2016; Lebreton et al., 2017). Microplastic pollution is often concentrated in areas of intense human activity, such as industrial zones, urban centres, harbours, and wastewater discharge points (Nel and Froneman, 2015; Wang et al., 2017; Dalu et al., 2019; Nel et al., 2019; Li et al., 2023).

While the occurrence of microplastics in coastal and marine systems is well documented, less is known about their sources and abundance in estuarine and freshwater environments (Anderson et al., 2016; Zhang et al., 2022). Rivers, streams, and estuaries transport microplastics from inland sources to the ocean (Eerkes-Medrano et al., 2015; Mani et al., 2020). Freshwater functions as both sinks and conduits for microplastic pollution, with seasonal hydrological variations influencing the amount and type of particles transported (Zhang et al., 2022; Li et al., 2023). Rivers transport an estimated 1.15–2.41 million tonnes of plastic into the oceans annually (Lebreton et al., 2017). Wetlands often function as key interceptors, trapping plastics before they reach coastal zones. Dams and wetland systems can retain up to 65 % of plastics carried by rivers, leading to significant accumulation within these ecosystems (Lebreton et al., 2017). This dual role makes wetlands both critical and vulnerable zones for microplastic contamination. (Xia et al., 2022).

The impacts of microplastics in wetlands are diverse (Yang et al., 2022). Wetland organisms, including invertebrates, fish, and birds, may ingest microplastics, which can result in physical harm, reduced growth, and reproductive challenges (Eresanya et al., 2025). Microplastics also carry harmful contaminants such as phthalates and heavy metals, which can bioaccumulate through the food web (Hamann et al., 2024). Their accumulation alters sediment properties, affecting plant growth, microbial activity, and nutrient cycling, which in turn impacts ecosystem health (Kalev and Toor, 2018). Microplastic pollution in wetlands occurs in both water and sediment. In the water column, microplastics are transported with surface flows and can be ingested by aquatic organisms, affecting feeding, digestion, and reproduction (Dalvand and Hamidian, 2023). Wetland waters frequently contain fibres, fragments, and beads originating from urban runoff, wastewater discharge, and atmospheric deposition (Free et al., 2014; Dris et al., 2016; Lebreton et al., 2017; Zhang et al., 2022; Zhu et al., 2024).

Sediments act as sinks for microplastics, as particles settle under conditions of reduced water flow. Studies have shown that sediments often contain higher concentrations of microplastics than water (Hurley et al., 2018; Dalu et al., 2023). Distribution depends on sediment composition, hydrodynamics, vegetation cover, and seasonal water flow, with vegetated sediments being particularly effective at trapping particles (Zhang et al., 2022; Li et al., 2022). Sediment contamination has ecological implications that extend beyond accumulation, including altered sediment structure, interference with plant root systems, and changes in microbial communities, which affect nutrient cycling and the health of wetlands (Free et al., 2014; Rillig et al., 2017). Sediments can also function as long-term reservoirs, gradually releasing microplastics back into the water column during flow changes or disturbances, creating a persistent contamination source (Horton et al., 2021; Xia et al., 2022). Both waterborne and sediment-bound microplastics carry adsorbed pollutants, including heavy metals, pesticides, and persistent organic compounds, which can be transferred through the food web (Smith et al., 2022; Akhbarizadeh et al., 2022).

1.2 Problem statement

Plastics are widely used worldwide due to their ease of production, low cost, chemical stability, and water resistance (Batzer and Boix, 2016). These properties have made plastics essential in modern life, but they have also led to significant environmental challenges (Evode et al., 2021) Land-based activities, including sewage overflow, urban and stormwater runoff, inadequate waste management, and industrial operations, are significant sources of plastic waste in aquatic environments (Napper et al., 2015). Once in the environment, plastics break down into smaller particles called microplastics, which persist for extended periods and are now commonly found in aquatic systems worldwide (Issac and Kandasubramanian, 2021; Dalu et al., 2023; Li et al., 2023). Microplastic pollution poses a serious threat to aquatic life at various levels of the food chain, from zooplankton to fish and mammals, which may ingest microplastics unintentionally because these particles resemble natural food sources in terms of size and shape (Ziajahromi et al., 2016). Such ingestion can cause physical damage, including blockage of the digestive tract, reduced feeding efficiency, slower growth, and lowered reproductive capacity (Sruthy and Ramasamy, 2017; Li et al., 2018; Abidli et al., 2019). Microplastics can absorb and carry pollutants, such as heavy metals and persistent organic compounds, thereby increasing the exposure of aquatic organisms to toxic substances and posing risks to human health.

Wetlands are among the most important ecosystems for maintaining water quality. They act as natural filters, removing pollutants and supporting biodiversity (Long et al., 2022; Hamidian and Dalvand, 2023). However, the accumulation of microplastics is affecting these functions. Wetlands can trap microplastics in sediments and vegetation, but they may also release them during periods of high flow or disturbance. Accumulated microplastics can clog pores and channels in wetland substrates, thereby reducing water movement and disrupting the exchange of gases and nutrients that sustain ecosystem health (Biginagwa et al., 2016; Jansen et al., 2023; Yu et al., 2025). This can limit wetlands' ability to filter pollutants effectively. In addition, the presence of microplastics in sediments can alter sediment structure, disrupt microbial communities, impact nutrient cycling, and inhibit plant growth, with negative consequences for ecosystem functioning and the services that communities depend on (Seeley et al., 2020; de Souza Machado et al., 2020). Given their ecological significance and the growing threat of microplastic pollution, it is crucial to investigate how microplastics enter wetlands, their distribution, and the impacts they have on these ecosystems. This knowledge is essential for developing strategies that protect wetlands and the vital ecological services they provide.

1.3 Justification of the study

Wetlands of international importance, such as those designated under the Ramsar Convention, are recognized as biodiversity hotspots, and play a crucial role in maintaining ecological balance through water purification, flood regulation, nutrient cycling, and carbon sequestration (Sharma and Naik, 2024). Despite their importance, wetlands are increasingly exposed to anthropogenic pressures, including pollution from plastics (Helcoski et al., 2020; Qian et al., 2021). While marine and coastal systems have been extensively studied in relation to microplastic contamination (Browne et al., 2007; Dalu et al., 2022; Dalvand and Hamidian, 2023), research on freshwater wetlands, particularly in the Global South, has been limited. This presents a significant knowledge gap given the role of wetlands as sinks for pollutants and their vulnerability to degradation. South Africa hosts Ramsar-declared wetlands, such as Makuleke in Kruger National Park and Nylsvley

Nature Reserve, both of which are ecologically significant and provide critical ecosystem services (Nel et al., 2019; Dzurume et al., 2021; Makhuvha, 2021). However, they face growing threats from waste mismanagement, agricultural practices, and hydrological changes (Rathod et al., 2024). Investigating microplastic dynamics in these wetlands is therefore essential, not only for understanding the extent of contamination but also for assessing its implications for biodiversity conservation and ecosystem function.

The study provides baseline data on microplastic abundance in wetland water, surface sediments, and sediment cores, thereby offering insights into both present and historical deposition trends. By examining how sediment characteristics influence microplastic retention, the research will help predict pollutant behavior in wetland environments. These findings will support the development of mitigation strategies and contribute to more effective conservation and management policies at local, national, and international levels. Moreover, the study addresses broader ecological and societal concerns. Microplastics have the potential to impact wetland-dependent organisms and bioaccumulate through food webs, thereby increasing risks to wildlife and human health. Understanding these pathways in Ramsar wetlands will enhance the global evidence base on freshwater pollution while providing context-specific knowledge critical for South African wetland management. In this way, the research contributes to both scientific advancement and the protection of ecosystems that underpin community livelihoods and biodiversity conservation.

1.4 Aim and objectives

Aims

The study aims to assess and compare the dynamics of microplastic abundance in water and sediment, including sediment cores, of two Ramsar-declared wetlands in South Africa, Makuleke, located in Kruger National Park, and Nylsvley, located in Nylsvley Nature Reserve, in the Limpopo province, during wet and dry seasons to determine how hydrological conditions influence their distribution.

Objectives

- To review water and sediment microplastic dynamics in African inland freshwater systems

- To compare the amount of microplastics deposited in water and sediment between the two wetland systems across two seasons (wet and dry).
- To investigate whether the sediment cores extracted from both the wetlands (i.e., Makuleke and Nylsvley) will vary in the deposition of microplastics throughout the soil layers.

1.5 Hypotheses

- Sediments with finer grain sizes and varying organic matter content will retain higher concentrations of microplastics compared to sediments with coarser grain sizes.
- Microplastic concentrations will be higher in surface layers compared in deep layers due to increased deposition and anthropogenic activities and will also be influenced by previous flood events.
- Fluctuations in microplastic concentrations along the wetland's horizontal axis would be influenced by factors such as proximity to pollution sources and hydrodynamic processes.

1.6 Thesis structure

Chapter 1: General background

This introductory chapter establishes the research context by providing an overview of global and regional plastic pollution, its transformation into microplastics, and the environmental implications of this transformation. It discusses the ecological importance of wetlands as sinks and potential sources of microplastic contamination. The chapter also outlines the problem statement, justification, aims, objectives, and hypotheses guiding the research.

Chapter 2: Water and sediment microplastic dynamics in African inland freshwater systems – a review

This chapter provides a comprehensive review of existing literature on microplastic contamination in African inland water bodies, including rivers, lakes, reservoirs, and wetlands. It examines the distribution, sources, types, and environmental behavior of microplastics across the continent. The review highlights the limited research attention given to freshwater wetlands in Africa and identifies knowledge gaps and research priorities essential for developing standardized monitoring frameworks and management strategies.

Chapter 3: Silent intruders–microplastic distribution in water and sediment of Ramsar-declared wetlands

This chapter focuses on quantifying and comparing the abundance, morphology, and seasonal variability of microplastics in the water and surface sediments of the Makuleke and Nylsvley wetlands. It includes detailed descriptions of sampling methods, laboratory analyses (including density separation and Fourier Transform Infrared spectroscopy, or FTIR spectroscopy), and data interpretation. The results and discussion sections explore spatial and seasonal variations, polymer composition, and potential ecological risks associated with microplastic contamination in the studied wetlands.

Chapter 4: Microplastic dynamics in sediment layers of two Ramsar-designated wetlands in South Africa

This chapter investigates the vertical distribution and historical deposition trends of microplastics in sediment cores collected from the two wetlands (Makuleke and Nylsvley). It assesses how sediment characteristics such as grain size, organic matter, and hydrodynamics influence microplastic accumulation and retention. The findings offer insight into long-term contamination patterns and the potential for sediments to act as both sinks and secondary sources of pollution.

Chapter 5: General synthesis

This concluding chapter integrates findings from the preceding chapters to provide a holistic understanding of microplastic dynamics in freshwater wetlands. The study discusses its implications, highlights its limitations, and provides recommendations for policy, management, and future research. The overall conclusion emphasizes the significance of wetlands in the global microplastic cycle and underscores the need for enhanced conservation strategies to protect these ecologically sensitive systems. The references will be listed at the end of the thesis.

CHAPTER 2: WATER AND SEDIMENT MICROPLASTIC DYNAMICS IN AFRICAN INLAND FRESHWATER SYSTEMS: A REVIEW

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ABSTRACT

Owing to its exceptional properties and versatility, plastic is among the most widely manufactured and used materials globally. Its extensive use, coupled with inadequate plastic waste management, has harmed ecosystems and poses significant risks to human health. When plastic degrades in the environment, it breaks down into microplastics. These tiny particles are a growing global issue due to their widespread presence in aquatic environments. This review summarizes existing information on microplastic contamination in water and sediment samples from African freshwater systems based on 41 published studies from eight countries. The data reveal extensive microplastic contamination in rivers, lakes, and reservoirs across Africa, with polyethylene, polypropylene, and polystyrene being the most common polymers. Microplastics were more commonly detected in sediments than in water. Most microplastics were found during the rainy season, underscoring the need to intensify plastic waste recycling efforts prior to the onset of the rainy season. Fibres and fragments were the most frequently identified types of microplastics, with their distribution strongly influenced by seasonal variations, human activities, and proximity to urban centres. As microplastic contamination increases, more research is needed to better understand how its potential impacts on inland waters can be mitigated.

Keywords: Microplastic; Freshwater systems; Poor waste management; Rivers; Lakes; Reservoirs; Wetlands; Plastic pollution; Sediments; Water.

2.1 Introduction

Plastics are synthetic organic polymers produced through the polymerization of materials derived from crude oil and gas extractions (Mutmainna et al., 2024). Since their initial production in the early 1940s, the volume of plastics manufactured has grown significantly, leading to their widespread use in various applications (Dalu et al., 2022; Boctor et al., 2024; Dalu et al., 2023. While plastics offer numerous societal advantages, they have become an increasing ecological concern due to their substantial contribution to municipal waste and their share in global waste generation. Their persistence degrades habitat, harms species by ingestion and entanglement, and emits hazardous chemicals, altering ecosystems and endangering biodiversity (Alimi et al., 2021; Yang et al., 2021; Gautam et al., 2024).

When plastic waste enters the environment, it is exposed to mechanical abrasion, water, wind, and sunlight, causing it to degrade and break into smaller particles known as microplastics (Guerranti et al., 2019; Dalu et al., 2023; Yang et al., 2024; Themba et al., 2024). Microplastics are defined as plastic particles that are less than 5 mm in size and have emerged as a concerning contaminant in both aquatic and terrestrial ecosystems (Andrady, 2011; Wong et al., 2020b; Dalu et al., 2021). Microplastics are categorized based on their origin: (i) primary microplastics are intentionally produced in micro–sizes (<5 mm), for example, pre–production powders and pellets such as polypropylene and polyethylene microbeads found in personal care products (i.e., toothpaste and facial scrubs) (Guerranti et al., 2019; Nair and Perumal, 2022), and (ii) secondary microplastics form through the degradation of larger plastic materials through the photo–oxidative and mechanical breakdown of plastic materials such as fishing nets, plastic bags, bottles, and clothing fibres released during washing, and fragments present in sewage effluent (Kwon et al., 2022; Ghosh et al., 2024; Mathew et al., 2024). Thus, determining whether microplastics originate from primary or secondary sources is crucial for devising effective mitigation strategies (Reid et al., 2019).

Microplastics, despite their widespread distribution and mobility, are smaller in size than typical prey organisms, increasing the likelihood of ingestion by aquatic organisms (Ma and You, 2025). Microplastics poses a risk to a wide range of species, including invertebrates, birds, fish, turtles, and marine mammals. They can cause harm through injuries, blockages, and restricted feeding while carrying harmful toxins. As microplastics accumulate in fish and mammals, they disrupt reproduction, growth, and immune function, leading to ecological disruption and biodiversity loss (Gatidou et al., 2019; Gola et al., 2021; Issac and Kandasubramanian, 2021). Around the world, microplastics have been extensively observed in aquatic habitats (Sarijan et al., 2021; Onoja et al., 2022; Dalu et al., 2023; Neelavannan and Sen, 2023; Themba et al., 2024), including in distant polar regions (Lacerda et al., 2019; Guerranti et al., 2019).

Despite an estimated 172 million tons of plastic consumption between 1990 and 2007 across 33 African nations, inadequate waste management policies have made the continent one of the highest contributors to mismanaged plastic waste globally (Babayemi et al., 2019; Alimi et al., 2021). With only 9% of the world's freshwater bodies, Africa’s inland water systems are particularly vulnerable to plastic contamination, necessitating urgent and sustainable management strategies. The continent has not yet emerged as the primary source of microplastic emissions, despite South Africa, Morocco, and African nations bordering the Gulf of Guinea being significant contributors to aquatic plastic pollution (Adamma et al., 2024). However, projections suggest that under a "business as usual" scenario, Africa's per capita plastic emissions could surpass those of Latin America and Organization for Economic Cooperating and Development (OECD) countries, approaching East Asian levels by 2050 (Van Wijnen et al., 2019; Misia et al., 2022).

Recent assessments indicate that urban wastewater effluents, stormwater runoff, landfill leakage, and tire wear are among the dominant contributors to microplastic loads in African aquatic systems (Browne et al., 2011; Dris et al., 2018; Babayemi et al., 2019; Alimi et al., 2021). Quantitative source apportionment provides a more practical basis for management interventions than origin-based (primary vs. secondary) distinctions. For example, effluent discharges from wastewater treatment plants can account for up to 80% of microplastic flux into urban rivers (Prata et al., 2020), while runoff and tire abrasion become dominant during rainy seasons (Horton et al., 2017). In sub-Saharan Africa, unlined landfills and open dumping remain major leakage points, exacerbated by limited recycling capacity (Onyari et al., 2023). Ranking these sources by proportional input allows for evidence-based prioritization of mitigation strategies such as upgrading wastewater filtration systems, improving stormwater capture, and promoting extended producer responsibility (EPR) schemes. This integrative approach provides a clearer link between source quantification and policy-relevant actions toward reducing microplastic pollution in freshwater environments.

Freshwater systems, including both water bodies and sediments, play a crucial role in the transport, accumulation, and long–term storage of microplastics (Guo and Abolfathi, 2024). Water is the primary medium for microplastic dispersion, facilitating their movement across vast distances and into different environmental compartments (Jiang et al., 2022). Conversely, sediments act as long–term sinks where microplastics accumulate over time, often reaching concentrations higher than those found in the overlying water column. However, sediments are not permanent storage sites, as environmental disturbances, such as floods, bioturbation, and human activities, can resuspend microplastics back into the water column, thereby prolonging their environmental persistence and increasing their bioavailability (Waldschläger et al., 2022; Faulstich et al., 2022; Chanda et al., 2024). This dynamic exchange between sediments and water can exacerbate microplastic contamination, posing significant ecological risks.

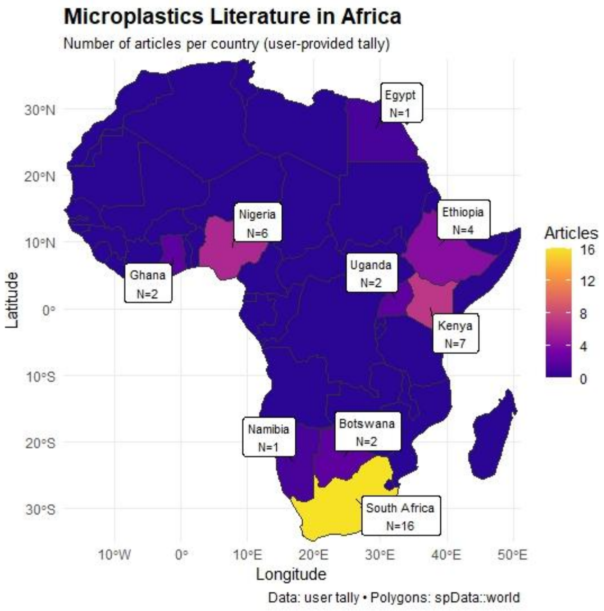
The bioavailability and consumption of microplastics by aquatic organisms are crucial factors influencing their impact on freshwater ecosystems. Microplastics, due to their small size and diverse polymer composition, can be mistaken for food by various aquatic species, including zooplankton, benthic invertebrates, and fish (Benson et al., 2022). Their ingestion may lead to physical blockages in the digestive tract, reduced feeding efficiency, and altered energy allocation. Additionally, microplastics can act as vectors for harmful pollutants, such as heavy metals and hydrophobic organic contaminants, which may be transferred through trophic levels, further exacerbating ecological risks (Botterell et al., 2019). Understanding the mechanisms of microplastic uptake and their subsequent effects on aquatic organisms is crucial for assessing the broader implications of these plastics for biodiversity and ecosystem health (Pitacco et al., 2022; Wang et al., 2022). The study aims to critically assess and synthesize existing research on microplastic contamination in African freshwater ecosystems, with a focus on sediments and water, to provide a comprehensive understanding of their distribution, sources, and potential environmental implications.

2.2 Data acquisition

A comprehensive literature search on microplastics in Africa was conducted in October 2024 using a range of databases, including Google Scholar, Scopus, Web of Science, ResearchGate, Springer, and ScienceDirect. The present study aimed to identify all peer–reviewed articles on inland freshwater systems, with a special focus on water and sediment microplastic abundances, distribution, accumulation, and impacts in African freshwater environments (i.e., rivers, wetlands, lakes, and reservoirs). The keywords used in finding the papers were "microplastics" with a combination/addition of the following terms: *"freshwater", "sediments", "water", "inland water", "river", "lake", "wetlands", "reservoirs", "Africa",* and "the name of each African country". This initial search yielded 312 articles across all databases. After removing duplicates and screening titles and abstracts for relevance, 127 studies were retained for full-text review. Applying the predefined inclusion and exclusion criteria focused on field studies addressing microplastic contamination in water and sediment resulted in a final selection of 41 studies that were systematically analyzed and reviewed.. We followed the Preferred Reporting Items for Systematic Reviews and Meta–Analysis (PRISMA) guidelines to ensure a rigorous selection process (Page et al., 2021). This approach minimized bias and ensured the inclusion of high–quality field studies on microplastic contamination. Specifically, studies were excluded if they were not written in English, focused on biota, social aspects, or general reviews rather than microplastic contamination in water and sediments, had insufficient sample sizes, or lacked validated detection and quantification methods such as FTIR, Raman spectroscopy, or accurate visual sorting with proper quality control. This selection process ensured a specific focus on field studies investigating microplastic dynamics in African freshwater systems and sediment, providing a more in–depth understanding of contamination patterns and methods of analysis.

2.3 Microplastic dynamics in inland systems, fresh waters, and sediment

The table below (Table 1) presents all reviewed studies from eight African countries: South Africa, Ghana, Kenya, Botswana, Nigeria, Ethiopia, Namibia, Egypt and Uganda (Figure 1). Further details on the study sites included system types, microplastic abundances, and references.



Data: user tally • Polygons: spData::world

Figure 1: Microplastic Literature in Africa

Table 2.1. Studies on microplastic contamination in inland systems of freshwater and sediments across African countries

Country	System	Microplastics abundances	Microplastic type	References
South Africa	Nandoni reservoir	Mean 224.1 *vs* 189 particles kg^{-1} dry weight (sediment)	Fibres and beads	Themba et al. (2024)
	Two macadamia orchards and two communal area reservoirs	Densities ranged from 25.3 particles kg^{-1} dwt to 140.6 particles kg^{-1} dwt. hot–dry season (140.6 particles kg^{-1} dwt). Hot–wet and cool–dry seasons, i.e., 22.60 particles kg^{-1} dwt and 16.13 particles kg^{-1} dwt, respectively (sediment).	Fibres (31%) and Fragment (30%) were dominant. All types of microplastics were present.	Mutshekwa et al. (2023a)
	Nandoni reservoir	Hot–dry season (mean range 120–6417 particles kg^{-1} dwt) while the hot–wet season had the lowest densities (mean range 5–94 particles kg^{-1} dwt) (sediment).	Film and fragments were dominant. All types of microplastics were present.	Mbedzi et al. (2020)

	Crocodile River	Abundances: Water samples (mean 1058 particles m^{-3}) and high during the hot–dry season. (mean 568 particles kg^{-1} dwt) in the sediment samples. The hot–wet season had a low particle density in both surface water (mean 625 particles m^{-3}) and sediments (mean 86 particles kg^{-1} dwt) samples	Fibres	Nkosi et al. (2023)
	Crocodile and Luvuvhu Rivers	Water: Crocodile river: microplastic densities of 3.3 and 4.3 particles L^{-1} for the upstream and downstream, downstream (mean 5.4 particles L^{-1}). Luvuvhu: hot–wet (total mean 4.9 particles L^{-1}) and cool–dry (total mean 4.5 particles L^{-1}). Sediments: Crocodile: (total mean 103 particles kg^{-1}dwt) compared to upstream sites (total mean 100.8 particles kg^{-1}dwt). Luvuvhu: densities (total mean 327.0 particles kg^{-1}dwt) observed upstream during the hot–wet season.	Foam, fibres and beads All microplastics type were present.	Dalu et al. (2023)
	Mvudi River	2000 microplastic particles, hot–wet (mean range 76.0 ± 10.0–285.5 ± 44.5 microplastic kg^{-1}) season as compared to the cool–dry (16.5 ± 4.5–27.0 ± 5.0 microplastic kg^{-1}) and hot–dry (13.0 ± 4.0–29.0 ± 10.0 microplastic kg^{-1}) seasons	Fibres	Dalu et al. (2021)

	Vaal River	Abundances of 0.61 ± 0.57 particles/m3and $4.6 \times 10^2 \pm 2.8 \times 10^2$ particles/kg dry weight were recorded for water and sediment samples, respectively	Fragments, fibres and film All microplastics types were present.	Ramaremisa et al. (2022)
	Bloukrans River	Density of 6.3 ± 4.3 (n = 21; ± standard deviation) and 160.1 ± 139.5 particles kg^{-1} (n = 23), respectively for the summer and winter	Not mentioned	Nel et al. (2018)
	Plankenburg River	1235.42 ± 552.23 MP/kg (range 6.3 ± 4.3 and 160.1 ± 139.5 kg^{-1} particles) (Sediment)	Fibres, foam, and pellet	Apetogbor et al. (2023)
	Plankenburg River	Water: Spring (5.13 ± 6.62 MPs/L) and the least in autumn (1.52 ± 2.54 Microplastics/L). sediments: spring at 1587.50 ± 599.32 MPs/kg	Fibres	Apetogbor (2022)
	Vaal River	100% samples with an Average abundance of 463.28 ± 284.08 particles/kg dwt. Small–sized MPs of 2 mm	(PE), (PP), (PEVA), (PES), (PU), and (PEH).	Saad et al. (2022)
	Orange–Vaal River	Water samples contained 505 potential microplastics (mean = 0.23 ± 0.27 items·L^{-1})	Fibres and fragments	Weideman et al. (2019)
	Vaal River	100% prevalent, with a mean numerical abundance of 0.68 ± 0.64 particles/m 3. Small–sized MPs of 1 mm accounted for the largest proportion.	Polyethylene, polypropylene. fragments and fibres over pellets	Saad et al. (2024a)
	Vaal River	Ranging from 29.12 to 1095.89 particles/kg dwt.	Fibres (63%), and pellets (35%)	Saad et al. (2024b)
	Vaal River	Ranged in size from 0.06 – 4.95 mm, with more than 89% less than 2 mm,	Polyethylene, polypropylene	Saad et. (2024c)
	Braamfontein Spruit	Microplastics were detected in water (mean of 705 particles m^{-3})	Fragments (68%), film (19%) pellet (11%) All microplastic types were present.	Dahms et al. (2020)

		and sediment (mean of 166.8 particles kg^{-1} dry weight)		
Ghana	Volta Lake	A total of 398 microplastics	Fibres	Boateng et al. (2024)
	Densu River	Overall, 16 particles of microplastics were recovered per 40 g of sediment from Weija compared to 15 particles per 40 g of sediment from Densu Delta. Similarly, 9 particles of microplastics were observed per 60 ml of water from the Weija Dam compared to 5 microplastic particles per 60 ml of water from the Densu Delta		Blankson et al. (2022)
Kenya	Lake Victoria	80% of the sampled areas, with the highest abundance, 30000MPs m–3, and 3 of the 17 samples recorded 0 MPs.	Fibres:	Onyango et al. (2024)
	Njoro River and Lake Nakuru	In the dry season was recorded as 47–649 MPs $300L^{-1}$ for sampling points in Njoro River and 54–508 microplastics (MPs) $300L^{-1}$ for Fisher's Point in Lake Nakuru; an abundance during the rainy season was measured as 8–389 MPs $300L^{-1}$ and 28–259 MPs $300L^{-1}$ for Njoro River and Lake Nakuru, respectively.	Polyethylene polypropylene polyester and polyethylene terephthalate	Chui et al. (2024)
	Lake Naivasha	0.407±0.135 particles/m 2 and 177.3±87.4 particles/kg in surface waters and surface sediments respectively	polypropylene, polyethylene, and polyester terephthalate, polyvinylchloride and nylon	Migwi (2020)
	Lake Naivasha	Water was 0.183 ± 0.017 to 0.633 ± 0.067 particles/m^2, with the	polypropylene, polyethylene, and polyester.	Migwi et al. (2020)

		mean concentration being 0.407 ± 0.135 particles/m^2.		
	Tudor, Port–Reitz and Mida creeks	Sites averaging 3161.3 ± 363.7 mp m–^{3} in Tudor, 2883.3 ± 485.4 mp m–^{3} in Port–Reitz, and 2523.3 ± 211.8 mp m–^{3} in Mida,	Fibres	Kerubo et al. (2020)
	Tudor, Port Reitz and Mida creeks	Mida 1.24 ± 0.09 particles g–1 d.w, Port–Reitz 1.03 ± 0.01 particles g–1 d.w and Tudor 1.58 ± 0.13 particles g–1 d.w	Fibres	Kerubo et al. (2021)
	Tudor, Port Reitz and Mida creeks	Water: HDPE was more abundant, accounting for 38.3 % (8.29 ± 3.27) compared to LDPE 27.1 % (5.87 ± 2.6) and PP 34.6 % (7.48 ± 4.84) mp. m^3 of the total microplastics extracted. Sediments: HDPE (0.42 ± 0.01 particles g–1 dwt) was more compared to LDPE (0.22 ± 0.002) and PP (0.18 ± 0.01) particles g–1 dwt	Polyethene polypropylene polyethene	Kerubo et al. (2021)
Botswana	Okavango Panhandle	Range between 56.7 and 399.5 particles/kg dwt (dry weight), range between 1075.7 and 1756.3 particles/ kg dwt. One shallow core (15 cm long)	Polyetherne terephthalate polypropylene, polystyrene and polyvinyl chloride	Schneidewind et al. (2023)
	Cubango–Okavango River Basin	MP concentrations (64 µm–5 mm size range) in sediment samples from the Panhandle range between 56.7 and 399.5 particles kg^{-1} (dry weight)	Polyethene terephthalate, polypropylene, polyethene polystyrene, and polyvinyl chloride	Kelleher et al. (2023)
Nigeria	Odo–Ona and Ogun Rivers	Abundances found in the Ogun River sediments was 66.6 ± 12.2 to 311 ± 20.8 particles/kg dwt, while that of the Odo–Ona River ranged from 133 ± 50 to 433 ± 100 particles/kg dwt	Polyethylene, polypropylene, and polyamide	Shokunbi et al. (2024)
	Owe River	MPs in the water samples ranged from 203 ± 50.64 to 724.33 ± 129.89	polyethylene and polypropylene	Olanipekun et al. (2024)

		Items/L with a total of 1898 ± 198.34 Items/L.		
	Osun river	22,079 ± 134 particles/L ranging from 2652 – 17,853 particles/L in the water 344 – 1458 items/kg dwt in the sediments.	Fragments make up 70.6% in water Fragments made up to 87.2% in sediment	Idowu et al. (2024)
	Ox–Bow Lake	1004 to 8329 items·m^3 for dry season. 201–8369 items·m^3 for raining season. Both water and sediments.	Film and Fragment	Oni et al. (2020)
	Borehole	Ranging from 206 to 1691 items m^{-3} and 9–47 items kg^{-1}	Polypropylene	Oni and sanni (2022)
	Ikpoba River	Ranging from 2.67±0.58 particles/m^3 to 8.00±1.00 particles/m^3	Fibres Film (52.0%) Foam and Fragment	Ogbomida and Obazele (2023)
Ethiopia	Hawassa Lake	Range of 11–74 items/m^3	Fiber (90%), fragments (5%) and pellets (5%). polyester (82%), polyethylene (15%) and polystyrene (3%)	Jeevanandam et al. (2022)
	Lake Tana and the Blue Nile River	Out of the total of 239 MP particles, 61.09% were of <0.5 mm and this dominant fraction was transparent and consisted of fragmentary shapes. The mean abundances of <0.5 mm particles were 5 ± 1.00 items/50 g in sediment and 3.00 ± 1.00 items/ml in agglomerated sewage water. Similarly, the abundances of >0.5 mm fractions were 2.33 ± 0.58 items/50 g in sediment and 1.33 ± 0.58 items/50 ml in Agglomerated sewage water.	Polyethylene (PE), Polypropylene (PP), polyethylene terephthalate (PET), Polystyrene (PS), polyamide (PA), and polyvinylchloride (PVC),	Mhiret Gela and Aragaw (2022)
	Lake ziway	Were 30,000 (400–124,000) particles/m^3 and 764 (0.05–36,233) mg/kg_dw	Polyethylene (polypropylene and alkyd–varnish	Merga et al. (2020)

	Lake Tana	Betweenn 4.9 ± 3.9 and 30.5 ± 20.2 items m^{-1} day^{-1} in counts and between 0.32 ± 0.21 and 0.04 ± 0.09 ± 0.03 g m^{-1} day^{-1} in mean weight.	PET, PE, and HDPE	Aragaw (2021)
Namibia	Iishana system	703 particles were visually detected. average of 13.2 ± 16.4 kg^{-1} dry weight.	69.7% fragments, 23.3% films, and 6.2% fibres. polymer types are PE (59.3%), PP (20.7%), and PS (11.5%)	Faulstich et al. (2022)
Egypt	Nile River	MP concentrations in the river ranged from 2.24 ± 0.6 to 3.76 ± 1.1 particles/L, 298 ± 63 to 520 ± 80 particles/kg dry weight,	Fiber (<500–1500 μm) we abundant in all sample.	Khedre et al. (2024)
Uganda	Lake Victoria	Microplastics in all sites (range: 2834–329,167 particles/km^2 or 0.02–2.19 particles/m^3), with the abundance highest in group A (range: 103,333–329,167 particles/km^2 or 0.69–2.19 particles/m^3) and lowest in group C (range: 2834–20,840 particles/km^2 or 0.02–0.14 particles/m^3)	Polyethylene	Egessa et al. (2020a)
	Lake Victoria	Range of 0–1102, 0–218 and 0–100 respectively in shoreline sediment and 0–108, 0–33 and 0–77 respectively in lake sediment. The abundance of micro–, meso– and macro–plastic debris in lake sediment were higher in areas of fish landing beaches (9.5 ± 2.6, 2.1 ± 1.5 and 7.7 ± 4.5 respectively) than what was recorded in areas of recreational beaches (0.7 ± 0.7, 0.2 ± 0.1, and 0 ± 0, respectively)	Films, filaments, fragments, foam and pellets were the plastic types, with the shoreline sediment dominated by films (>54%) while lake sediment was dominated by filaments (>55%). polyethylene, polypropylene, Polyethylene Terephthalate, Polyamide (nylon), and polyvinyl chloride	Egessa et al. (2020b)

2.4 Microplastics in African riverine and wetland waters and sediments

The Vaal River is one of South Africa's most significant and extensively studied freshwater systems, with five articles published between 2022 and 2024 (Table 1). Saad et al. (2024a) recently detected microplastics as small as 0.055 mm in their surface waters, reporting 100% prevalence and a mean abundance of 0.68 ± 0.64. particles kg^{-1}. Microplastics smaller than 1 mm constituted the largest proportion. Raman spectroscopy identified microplastics as high–density polyethylene, low–density polyethylene, and polypropylene. The predominance of fragments (41.6%) and fibres (38.5%) over pellets (8.1%) suggests that most microplastics originate from the breakdown of larger plastic items rather than direct industrial sources. Fragments are typically formed through the degradation of plastic products such as packaging, bottles, and containers, while fibres are commonly shed from synthetic textiles during washing or from fishing gear. In contrast, pellets, which are raw materials in plastic manufacturing, enter the environment directly but were found in much lower proportions. This suggests that secondary sources, including weathering, mechanical abrasion, and textile shedding, significantly contribute to microplastic pollution (Table 1). Similarly, microplastics were detected in all samples from the Vaal River at concentrations ranging from 29.1 to 1095.9 particles kg^{-1}, with particles smaller than 0.5 mm constituting 31.8 % of the total microplastics (Saad et al., 2024b). Furthermore, fragments (63%) and fibres (35%) were significantly more abundant than pellets, and microplastics were observed in various colours, with blue, white, and green being the most dominant (Saad et al., 2024b). Raman analyses of microplastics showed the presence of high–density polyethylene, low–density polyethylene, polyurethane foam, polypropylene, polyethylene co–vinyl acetate, and poly(ethylene–co–1–hexene) (Saad et al. 2024b) Additionally, two pigments (i.e., vine black and smalt), one dye (i.e., saffron), three minerals (i.e., orthoclase, carbon, and microcline), and one additive (i.e., cis–13–docosanol) were also identified. Saad et al. (2024c), working in the Vaal River, identified microplastics in all samples, ranging from 0.13 to 2.52 particles kg^{-1}, from 22 samples collected using a 55 µm plankton net. Microplastics ranged in size from 0.06 to 4.95 mm, with more than 89 being less than 2 mm. Additionally, 81% were fragments (39%) and fibres (42%). Microplastics were observed in various colors, with green, black, and blue being the most dominant, accounting for 22%, 19%, and 18%, respectively (Saad et al., 2024c). Chemical analysis revealed the polymer types as high–density polyethylene (HDPE), polypropylene (PP), and low–density polyethylene (LDPE). The dominance of fragments and fibres, with clear signs of fragmentation, implied that microplastics in the Vaal River are mostly from secondary sources (Saad et al., 2024c). These studies provide new data on the occurrence and characteristics of microplastics in the Vaal River system, offering a baseline for future monitoring.

Blankson et al. (2022) extracted microplastics from samples collected from the Densu River in Ghana, and the results indicated the widespread presence of microplastics in both the water column and sediment compartments studied. Furthermore, the stagnant water system of the reservoir along the Densu River facilitated the accumulation of larger–sized microplastics. In contrast, the flowing waters of the delta did not show any selectivity in the deposition of microplastics between sediment and the water column (Blankson et al., 2022).

In Northern Botswana, Kelleher et al. (2023) conducted the first study on the distribution of microplastic pollution in surface sediments of the Okavango Delta Panhandle. The authors analysed microplastics using fluorescence microscopy and found microplastic (64 µm–5 mm size range) concentrations in sediment samples from the Okavango Panhandle ranging between 56.7 and 399.5 particles kg^{-1} (dry weight). The concentrations of microplastics in the 20 µm to 5 mm grain size range ranged between 1075.7 and 1756.3 particles kg^{-1} (Kelleher et al., 2023). One shallow core (15 cm long) from an oxbow lake suggested that microplastic size decreases with depth, but their concentration increased with depth (Kelleher et al., 2023). Raman Spectroscopy revealed that the compositions of microplastics were dominated by polyethene terephthalate, polypropylene, polyethene, polystyrene, and polyvinyl chloride (Kelleher et al., 2023). The study confirms that an estimated 10.9 to 336.2 billion microplastic particles could be transported into the Okavango Delta annually, making it a significant sink for microplastics. This poses a serious threat to the delta’s biodiversity and disrupts the ecosystem's overall functioning.

In South Africa, Nkosi et al. (2023) found that the Crocodile River and its tributaries serve as temporary sinks for microplastics during periods of low rainfall (i.e., the cool–dry season). Microplastics were more abundant (mean 1058 particles m^{-3}) in the surface water samples during the cool–dry season and higher during the hot–dry season (mean 568 particles kg^{-1} dwt) in the sediment samples. Microplastic shapes were dominated by fibres and fragments, with the colour scheme characterised by transparent, blue, and black colours. The abundance of microplastics was positively correlated with pH and resistivity and negatively with river flow (Nkosi et al., 2023). Similarly, Dalu et al. (2023) assessed the seasonal variation in water and sediment microplastic abundances upstream and downstream of wastewater treatment works across two subtropical river systems (i.e., Crocodile and Luvuvhu) in South Africa. When considered together, the studies by Nkosi et al. (2023) and Dalu et al. (2023) highlight the complex interactions between hydrology, water chemistry, and microplastic behaviour in African riverine systems. The influence of parameters such as pH, flow rate, and resistivity reflects the importance of physicochemical factors in determining microplastic aggregation, buoyancy, and deposition. Furthermore, the predominance of coloured and fibrous particles provides clues to their anthropogenic origins and potential for chemical leaching (e.g., dyes, additives) and biological uptake. Such contextual insights underscore that, beyond mere presence and counts, understanding how environmental conditions modulate microplastic fate is crucial for predicting their persistence and ecological risk in freshwater environments.

Overall, the results showed that the type and distribution of microplastics often did not exhibit clear seasonal or site differences (i.e., upstream and downstream of wastewater treatment works) in water, and microplastics were widespread across the studied systems. The microplastic risk assessments further indicated high pollution loads upstream (Dalu et al., 2023). However, significant differences in sediment microplastic loads across seasons indicated a source sink effect during the hot–wet season. The study noted that the seasonal context influences differences in microplastic concentrations, with the hot–wet season being associated with high pollution loads, particularly within sediments, where this effect was more pronounced, indicating the sink–source effect, which is linked to sediments rather than water.

Shokunbi et al. (2024) examined the abundance and nature of microplastics and potentially toxic elements in the sediments of the Odo–Ona and Ogun Rivers in Southwest Nigeria. Microplastics were extracted from the sediments using the density separation method and categorized according to their size, color, and shape. They ranged between 66.6 ± 12.2 to 311 ± 20.8 particles kg^{-1} in the Ogun River, while in the Odo–Ona River, microplastics ranged from 133 ± 50 to 433 ± 100 particles kg^{-1}. The microplastic polymer analyses revealed the presence of polyethylene, polypropylene, and polyamide particles in the sediments. Polyethylene was the most abundant type in the two rivers, constituting 72.8% and 59.7% of the microplastics recovered from the Odo–Ona and Ogun Rivers, respectively (Shokunbi et al., 2024).

2.5 Microplastics in African lakes/reservoirs water and sediments

Mbedzi et al. (2020) assessed microplastics in sediment along Nandoni reservoir shoreline and found microplastic densities of a mean range of 120–6417 particles kg^{-1} dwt (hot–dry season)) and mean range 5–94 particles kg^{-1} dwt (hot–wet season). Microplastic abundances were positively correlated with population density, demonstrating the direct effects of human activity on microplastic contamination. Similarly, Themba et al. (2024) assessed the abundance and distribution of microplastics in benthic sediments of the Nandoni reservoir using a combination of geospatial techniques and multivariate statistics across two seasons (i.e., hot–wet and cool–dry) at 17 sites. High densities of microplastics were found during the cool–dry season (mean 224.1 ± 189 particles kg^{-1} dry weight). Mbedzi et al. (2020) and Themba et al. (2024) studies revealed high densities of microplastics in the Nandoni reservoir during the dry season (i.e., hot–dry and cool–dry) compared to the rainy (i.e., hot–wet) season. These findings provide insights into the role of reservoirs as microplastic retention sites and highlight the need to further explore microplastic distribution patterns in freshwater ecosystems, particularly in lakes and reservoirs. Furthermore, findings from these studies suggest a risk for fauna during low rainfall periods and the potential for microplastic uptake and transfer from lower trophic groups (Mbedzi et al. 2020; Themba et al. 2024).

Mutshekwa et al. (2023a) assessed the seasonal differences in microplastic density in the sediments from two South African recreational reservoirs associated with low (macadamia orchards) and high (communal areas) human activities. Microplastics were recovered from all the reservoirs assessed, indicating their extensive occurrence and densities. Microplastic numbers were significantly high in reservoirs associated with high anthropogenic activities during the hot–dry season (140.6 particles kg^{-1} dwt) and low in reservoirs associated with low anthropogenic activities during the hot–wet (22.6 particles kg^{-1} dwt) and cool–dry (16.13 particles kg^{-1} dwt) seasons (Mutshekwa et al., 2023a). Overall, polypropylene (31%) and polystyrene (30%) were identified as the dominant microplastic polymer types in both reservoir types. Moreover, no significant relationships were found between environmental parameters and microplastic densities across reservoirs and seasons, indicating a widespread and largely context–independent level of pollution (Mutshekwa et al., 2023).

Egassa et al. (2020a) investigated the occurrence, abundance, and distribution of micro, meso, and macroplastic debris along the shores and sediments of northern Lake Victoria. The abundance of micro, meso, and macroplastics ranged from 0–1102, 0–218, and 0–100 particles/kg dry sediment, respectively, in shoreline sediment and 0–108, 0–33, and 0–77 particles/kg dry sediment, respectively, in lake sediment. Similarly, the mean abundance of micro, meso, and macroplastic debris in lake sediment were high in areas of fish landing beaches (9.5 ± 2.6 particles/kg dry sediment (microplastic), 2.1 ± 1.5 particles/kg dry sediment (mesoplastic) and 7.7 ± 4.5 particles/kg dry sediment (macroplastic) than what was recorded in areas of recreational beaches (0.7 ± 0.7 particles/kg dry sediment, 0.2 ± 0.1 particles/kg dry sediment, and 0 ± 0 particles/kg dry sediment respectively) (Egassa et al., 2020a). The shoreline sediment was dominated by films (>54 %), while the lake sediment was dominated by filaments (>55 %), across the size groups (micro, meso, and macroplastics). Spearman's rank correlation indicated a strong and significant correlation between the abundance of micro- and mesoplastics for total, film, and fragment plastics in shoreline sediment (Egassa et al., 2020a). Together, the studies conducted by Egessa et al. (2020a,b) and Onyango (2023) provide a cohesive picture of the pervasive and heterogeneous nature of microplastic pollution in Lake Victoria, Africa's largest freshwater body. Despite the lake's vast size and dynamic hydrology, microplastics were detected in nearly all sampled sites, underscoring that spatial immensity does not dilute contamination risk—a pattern consistent with observations from large marine and lacustrine systems worldwide. Across these investigations, fibres and filaments emerged as dominant forms, indicating persistent inputs from domestic and textile-related sources, while the prevalence of low-density polymers such as polyethylene and polypropylene points to land-based origins and buoyant particle transport.

The collective evidence reveals clear spatial variability linked to human settlement intensity: higher concentrations were found near fish-landing beaches and densely populated shorelines, whereas macrophyte-rich or less disturbed areas exhibited comparatively reduced levels, suggesting the potential retention or filtration capacity of aquatic vegetation. This indicates that the distribution and fate of microplastics in the lake are governed not only by proximity to pollution sources but also by ecological and hydrodynamic factors such as vegetation cover, sedimentation, and water circulation.

From a broader perspective, these findings demonstrate that large inland waters, much like oceans, are not immune to microplastic accumulation despite their scale and mixing potential. Lake Victoria thus serves as a sentinel ecosystem highlighting how anthropogenic pressures, inadequate waste infrastructure, and hydrological connectivity combine to sustain plastic contamination in African freshwater systems. Consequently, the integrative message from these studies transcends local management implications: effective mitigation requires catchment-wide waste governance, transboundary collaboration, and long-term ecological monitoring to understand how microplastics interact with biota and sediment processes within such extensive lake networks. Recent studies indicate that aquatic macrophytes can influence the spatial distribution of microplastics by acting as biological filters**.** Microplastics can become entangled within root networks**,** adsorbed onto biofilms**, or** settle within vegetated sediment zones where hydrodynamic energy is reduced (Lusher et al., 2017; Mateos-Cárdenas et al., 2019). In this context, the findings by Onyango (2023) suggest that plant communities in Lake Victoria may reduce the transport of suspended microplastics, thereby curbing their spatial spread rather than degrading them. This ecological function underscores the importance of conserving riparian vegetation as part of effective microplastic management strategies in freshwater ecosystems.

2.6 Sources of microplastics in African freshwater environments

The breakdown and degradation of plastics in African freshwater ecosystems remain an underexplored topic with limited research. Various factors, including river currents, turbulence, high solar radiation, fluctuating temperatures, and the chemical makeup of plastics, influence the rate of plastic degradation in these environments (Fotopoulou and Karapanagioti, 2017). While freshwater systems may experience weaker physical forces compared to oceans, plastic degradation lacks persistent large-scale wave action, tidal movements, and deep-water mixing (Andrady, 2011). In contrast, marine environments experience continuous high-energy motion driven by tides, currents, and wave turbulence that physically abrade and fragment plastics more rapidly. Rivers and lakes, however, often have localized, low-energy zones, especially in shallow, slow-moving, or stagnant waters**,** where plastics may remain trapped in sediments or among vegetation for extended periods (Kedzierski et al., 2018). Nonetheless, the intensity of sunlight exposure in many African regions, ultraviolet (UV) radiation, significantly contributes to the deterioration of plastics, causing cracking and surface pitting (Zbyszewski et al., 2014). Africa's unique climatic and environmental conditions may accelerate these degradation processes, particularly in shallow, slow–moving water bodies where plastics are exposed to sunlight and temperature fluctuations.

Microplastic contamination in African freshwater environments is primarily driven by human activities; however, its distribution, abundance, and polymer composition vary according to the dominant local activities and land-use patterns (Lechner et al., 2014; Dalu et al., 2023). In rapidly urbanizing catchments, high population densities and inadequate waste-management systems lead to greater concentrations of fibres and fragments derived from household wastewater, textile washing, and packaging debris. In contrast, industrial zones contribute higher proportions of pellets and resin granules associated with plastic manufacturing, recycling, and transport losses. The sources of microplastics differ across regions, with urban wastewater, industrial effluents, and surface runoff being among the main contributors. Studies from other parts of the world have shown that microplastics from personal care products are prevalent in lakes, whereas industrial regions contain higher concentrations of industrial resin particles (Eriksen et al., 2013). In Africa, microplastics from cosmetic products remain a significant concern, particularly in densely populated cities where wastewater treatment infrastructure is often inadequate or lacking. In many areas, untreated or inadequately treated sewage is directly discharged into rivers and lakes, further exacerbating microplastic contamination (Browne, 2015).

Another major contributor to microplastic pollution is surface runoff, particularly in regions with highly variable rainfall. During heavy rains, microplastics from road markings, tire wear, and discarded plastics are carried into rivers and lakes (Horton et al., 2017a, 2017b). This is particularly problematic in major cities such as Lagos, Nairobi, and Johannesburg, where waste management systems are struggling to cope with rapid population growth. In semi–arid and arid regions, microplastics may accumulate in seasonal rivers and be transported downstream by heavy rains through runoff.

The textile industry is a large problem in many countries across Africa, mostly Ghana (with the largest second-hand textile market) and also Kenya and Tanzania, where the textile waste is a big issue (Aboagyewaa-Ntiri et al., 2016; Sarwar, T. and Khan, 2022). The washing of synthetic fabrics releases significant amounts of microplastic fibres into wastewater (Browne, 2015; Peng et al., 2017). In areas where people wash clothes by hand in rivers and lakes, microplastics are directly introduced into the environment. Additionally, the widespread use of second–hand synthetic clothing contributes to microplastic pollution as these materials degrade over time. The complexity of microplastic pollution sources in African freshwater environments is worsened by deficiencies in waste disposal and wastewater treatment facilities. Although some studies have explored microplastics in Africa's marine environments, research on freshwater systems remains limited. Further studies are needed to assess the extent of various microplastic sources and to develop effective strategies for mitigating plastic pollution in African freshwater systems.

2.7 Types of polymers found in African inland systems waters and sediments

Most studies have reported polyethylene, polypropylene, polystyrene, polyvinyl chloride, and polyester as the most common types of plastic polymers (Lusher et al., 2017; Yang et al., 2021). For example, Lake Victoria had polyethylene as the primary polymer, contributing 60% of the analyzed microplastic particles (Egessa et al., 2021a). In the Owe River, polyethylene and polypropylene accounted for 82% of the plastic particles (Olanipekun et al., 2024). Synthetic compounds in the Cubango–Okavango River Basin included polyethylene terephthalate, polypropylene, polyethylene, polystyrene, and polyvinyl chloride (Kelleher et al., 2023). In Lake Naivasha, 83% of microplastics were predominantly composed of polypropylene, polyethylene, and polyester in surface waters, whereas polyethylene terephthalate, polyvinyl chloride, and nylon polymers were the most dominant in surface sediments (Migwi, 2020). In contrast, the Vaal River had high–density polyethylene, low–density polyethylene, and polypropylene as the dominant polymers (Saad et al., 2022, 2024a-c). These variations in polymer types and compositions between surface water and sediment samples are not fully understood. However, this could underscore the influence of polymer density in determining the spatial distribution of plastic polymers between the two samples (i.e., surface waters and sediments). Thus, further research is needed to determine whether system type (i.e., river or lake/reservoir), sample type (i.e., water or sediment), and location (i.e., urban or rural) influence polymer composition. The widespread presence of polyethylene, polypropylene, and polystyrene in African freshwater systems indicates a significant pollution issue, endangering aquatic life and ecosystem stability (Saad et al., 2022). Effective plastic waste management programs, stronger regulations, and the adoption of biodegradable alternatives are crucial for reducing contamination. Enhancing waste collection, treatment, and public awareness can help minimize plastic pollution.

2.8 Challenges and research directions for water and sediment plastic research

The presence of microplastics in the environment, along with their potential hazardous effects on humans and ecosystems, is garnering increasing scientific attention (Barbosa et al., 2020). Although research on microplastics in the aquatic environment encompasses a wide range of research fields (e.g., analytical chemistry, ecotoxicology, health risk assessments, and trophic studies), it is still in its early stages (Waldschläger et al., 2022). Most previous research on plastic contamination (across all size fractions) has focused on marine environments, with only a few studies examining freshwater habitats (Blettler et al., 2018). In addition, differences in methodological approaches, analytical techniques, and research priorities in freshwater microplastic research have masked the underlying patterns of microplastic distribution and behavior in freshwater environments (Blettler et al., 2018). Microplastic data from some of the most polluted and large freshwater environments (such as the Orange River, Niger River, and Grand Ethiopian Renaissance Dam) is either limited or nonexistent, and for the little available data, it mostly focuses on microplastics rather than macroplastics.

High microplastic pollution has been reported in rivers (Faulstich et al., 2022; Dalu et al., 2023), reservoirs (Guo et al., 2021; Themba et al., 2024; Mutshekwa et al., 2025), lakes (Egessa et al., 2020; Fuschi et al., 2022; Oyege et al., 2024), and creeks (Kerubo et al., 2021; Forrest et al., 2022). Such increased abundances of microplastics will lead to adverse effects on those ecosystems. Furthermore, most freshwater plastic research appears to be intrinsically skewed toward a country's level of development and disconnected, as most studies were designed and carried out with specific goals in mind (Blettler et al., 2018). Table 1 reveals that data on freshwater microplastics in Africa are fragmented across countries, with most countries lacking any data. Most studies on the continent are from South Africa (n = 16), followed by Kenya (n = 7) and Nigeria (n = 7). Only a few studies were detected in Egypt, Namibia, Ghana, and Botswana (fewer than 5 in each country). Although Nigeria and Kenya are the second most dominant countries in terms of scientific production (*n* = 7), their scientific efforts remain inadequate, considering their large human populations and the number of freshwater ecosystems in those countries. According to reports published by the United Nations (United Nations Human Settlements Programme, 2016) and the World Bank (Hoornweg and Bhada–Tata, 2012), the solid waste management systems in the least developed countries are inadequate to handle current and future waste generation. This is especially true in urban informal communities, which are often located in the most hazardous areas, such as river floodplains. Open uncontrolled dumping remains the most common way of solid waste disposal in such countries, allowing plastics to enter aquatic bodies (Blettler et al., 2018). In short, just 9 of Africa's 54 countries have examined plastic pollution in freshwater systems. The current information is still biased by country development levels rather than environmental demands.

2.9 Collection, tools used, and methods used in inland water and sediment samples

Recently, inland water and sediments have been widely studied to trace microplastic contamination and predict future ecological consequences. For sediment sampling, common tools include trowels, spoons, scoops, shovels, buckets, and spatulas (Dalu et al., 2023; Nkosi et al., 2023; Mbedzi et al., 2020). These are primarily used to collect shoreline and surface sediment along the banks of rivers and reservoirs. For riverbed or sub-surface sediments, studies have employed grab samplers such as the Van Veen or Ekman samplers (Themba et al., 2024), which allow sampling at controlled depths while minimising disturbance.

For water sampling, techniques range from simple manual collection using glass bottles or metal buckets (Olanipekun et al., 2024; Dahms and Greenfield, 2025) to more advanced Teflon pumping systems (Oni et al., 2020) or manta nets for surface water microplastic retrieval (Egessa et al., 2020b). Despite these advances, no globally standardized method currently exists for the collection, storage, or reporting of microplastic samples from freshwater environments (Adomat and Grischek, 2021). As a result, protocols vary in sampling depth, volume, and mesh size, leading to difficulties in comparing datasets across regions.

According to Adomat and Grischek (2021), sampling river or inland sediments is not difficult, as numerous devices, such as shovels and standardized samplers or corers, are available. The goal is to develop a consistent sampling technique that prevents secondary contamination and loss of low–density microplastics while ensuring representative data at a reasonable cost. Such a standard requires additional refinement, particularly in terms of establishing a unit for reporting microplastic outcomes. To minimize contamination to a minimum, avoid contact with plastic equipment when sampling. Typically, stainless steel or glass equipment should be used to account for this (Adomat and Grischek, 2021).

2.10 Ecological implications and management relevance

Rivers exhibit wet-season pulses that elevate water-column particle loads, increasing encounter rates for drift-feeding invertebrates and larval fishes. Reservoirs and wetlands accumulate particles in sediments, creating chronic exposure for benthic invertebrates and demersal fishes and enabling periodic remobilization during drawdown or floods. Microplastics provide substrates for microbial biofilms; conditioned particles can alter buoyancy/settling and may vector sorbed contaminants (hydrophobics, metals). While sorption alone does not prove risk, the co-occurrence of MPs with urban/agricultural contaminants strengthens the case for integrated controls at known sources. Field studies document ingestion of fibres/fragments by benthic macroinvertebrates and fishes common to African inland waters. In basins with higher loads, this supports plausible trophic transfer and sub-lethal outcomes (reduced condition, reproduction interference). We flag this as a priority for targeted mesocosm/field experiments using locally relevant taxa and field-realistic mixtures. The spatial alignment of higher MP loads with urban/agricultural corridors implies potential impacts on small-scale fisheries, raw-water abstraction for drinking, and wetland regulation services (flood buffering, habitat). Consequently, basin-scale interventions (first-flush stormwater capture, WWTP tertiary polishing, landfill containment, fibre controls) offer ecological and public-health co-benefits.

2.11 Conclusion

Microplastic contamination in African inland freshwater systems is now a clearly established environmental threat, with consequences for aquatic ecosystems, biodiversity, and human well-being. This review, based on 47 studies across eight countries, revealed consistent patterns: (i) fibres and fragments dominate microplastic types, (ii) sediments act as major sinks while waters serve as transport pathways, and (iii) seasonality and proximity to human settlements are major drivers of variability in abundance.

Across these findings, several lessons emerge. First, source apportionment studies show that wastewater effluents, landfill leakage, and surface runoff remain the dominant microplastic inputs, underscoring the urgent need to improve waste and wastewater infrastructure. Second, standardization of sampling and analytical methods is essential to ensure cross-comparability of data and regional synthesis. Third, the limited geographical distribution of research dominated by South Africa, Nigeria, and Kenya highlights critical data gaps across Central and North Africa, where freshwater systems remain largely unassessed.

To bridge these gaps and enhance data accessibility, we propose the establishment of an African Microplastics Research and Data-Sharing Platform (AMRDP) a collaborative, open-access initiative to standardize methodologies, share datasets, and build analytical capacity across nations. Such a platform would empower local researchers and policymakers with region-specific evidence to inform management strategies within the means of local communities. In conclusion, this review demonstrates that African inland waters are both repositories and conveyors of plastic pollution, reflecting broader socio-economic and infrastructural challenges. The key take-home message is clear: tackling microplastic pollution requires integrated, cross-border actions combining improved waste governance, harmonized monitoring protocols, and community-driven initiatives. Only through collaborative knowledge-sharing and sustained investment in environmental management can Africa mitigate the growing burden of microplastic contamination in its vital freshwater ecosystems.

CHAPTER 3: SILENT INTRUDERS: MICROPLASTIC DISTRIBUTION IN WATER AND SEDIMENT OF RAMSAR–DECLARED WETLANDS

This chapter is currently under review by: ***Nelisiwe Ngomane***, *Linton F Munyai, Pule Mpopetsi, Collins Oduro, Farai Dondofema, and Tatenda Dalu. Silent intruders: Microplastic distribution in water and sediment of Ramsar–declared wetlands. Environmental Monitoring and Assessment.*

ABSTRACT

Microplastics have become ubiquitous contaminants in aquatic ecosystems, yet their distribution and ecological implications in freshwater wetlands remain poorly understood. This study examines the abundance, composition, and seasonal variation of microplastics in the water and sediment of two Ramsar–declared wetlands in South Africa, the Makuleke and Nylsvley, during the dry and wet seasons. Microplastics were identified using density separation and filtration methods based on zinc chloride, visually identified under stereomicroscopy, and particles confirmed using the Fourier Transform Infrared Spectroscopy. Both wetlands exhibited substantial microplastic contamination, with sediments serving as major sinks for microplastics. Fibres, fragments, and beads were the dominant morphotypes, while black, transparent, and white were the most prevalent colours in both wetlands across seasons. Seasonal trends revealed significantly high microplastic densities during the wet season, primarily driven by hydrological transport. The Nylsvley Wetlands exhibited higher microplastic abundances and ecological risk (PLI = 1.39–21.85) than the Makuleke Wetlands (PLI = 1.0–1.95), reflecting a high anthropogenic influence from nearby agricultural and peri–urban areas. Although both wetlands are located in protected areas, these results suggest that diffuse and long–range inputs continue to threaten these sensitive ecosystems. These findings reveal that microplastic contamination is pervasive in both Makuleke and Nylsvley wetlands, with higher levels in areas impacted by surrounding human activities and during the wet season. The study emphasizes the importance of monitoring microplastic inputs at the catchment level and implementing strategies to mitigate plastic pollution from agricultural runoff and urban sources, thereby protecting the ecological integrity and biodiversity of these sensitive wetland ecosystems.

Keywords: microplastics, freshwater wetlands, sediments, hydrological transport, Ramsar sites, ecological risk

3.1 Introduction

Wetlands serve as transitional ecosystems, supporting biodiversity and acting as natural filters for contaminants (Long et al., 2022; Hamidian and Dalvand, 2023). Their unique vegetation and sediment structures often trap microplastics, transforming these zones into hotspots for accumulation (Sruthy and Ramasamy, 2017; Li et al., 2018; Abidli et al., 2019). Despite increasing evidence of microplastic contamination across environments (Wong et al., 2020), freshwater wetlands remain particularly understudied (Helcoski et al., 2020; Qian et al., 2021). Most existing investigations focus on estuarine and tidal wetlands, which serve as transitional filters between land and sea (Duan et al., 2020, 2021; Ibrahim et al., 2021; Ouyang et al., 2022). In contrast, natural and constructed freshwater wetlands, excluding lakes and rivers, have received limited scientific attention (Townsend et al., 2019; Rasta et al., 2020; Abbasi, 2021; Sarkar et al., 2021).

Plastics are indispensable across various domains, ranging from household items and marine–related industries to construction, tourism, and machinery, due to their strength, low weight, and durability (Cole et al., 2011; Hidalgo–Ruz et al., 2012; Eerkes–Medrano et al., 2015; Zobkov and Esiukova, 2017; Mashamba et al., 2024). Over twenty years have passed since microplastic particles less than 5 mm in size were first identified as pollutants of significant global concern. These particles have since been documented on every continent, including the polar regions (Andrady, 2017; Auta et al., 2017; Chen et al., 2018).

Microplastics originate from both primary sources, such as microbeads, plastic pellets, and industrial abrasives designed for specific uses, and secondary sources, which are fragments formed through the breakdown of larger plastic debris like fishing gear or packaging (Thompson, 2004; Arthur et al., 2009; Cole et al., 2011; Hidalgo–Ruz et al., 2012). These particles vary in shape, ranging from filaments to fragments, pellets, and granules, depending on their source and the environmental degradation processes (Wagner et al., 2014; Zhao et al., 2018). Their physical structure and chemical composition are closely linked to their potential toxicity (Zhang et al., 2021). Aquatic microplastic pollution is primarily driven by land–based human activities such as industrial production, agriculture, and the mismanagement of waste (Driedger et al., 2015; Vandermeersch et al., 2015). Because their complete removal from affected ecosystems is almost impossible, effective waste management and upstream pollution control remain essential strategies for mitigating the impact (Anderson et al., 2016; Estahbanati and Fahrenfeld, 2016).

Plastics also play a pivotal role in economic development, particularly in the export, recycling, and innovation sectors, by generating employment, driving technological advancement in material science, and contributing significantly to trade revenues (Mbedzi et al., 2020). (Mbedzi et al., 2020). Despite regulatory measures encouraging proper disposal and recycling, South Africa remains the eleventh–most–significant global contributor to marine plastic waste (Verster et al., 2017). High production rates have significantly impacted aquatic habitats, as microplastics enter waterways through the degradation of consumer products, wastewater discharge, and littering (Barnes et al., 2009). Although microplastics are widespread, their relationship with human population density remains unclear (Hale et al., 2020). Although considerable research has been conducted on marine systems, studies examining freshwater environments, such as rivers, lakes, and reservoirs, are still limited (Biginagwa et al., 2016; Horton et al., 2017; Nel et al., 2018; Hurley et al., 2018; Tibbetts et al., 2018). Microplastics enter water systems through stormwater runoff (Silva Cavalcanti et al., 2017; GESAMP, 2019), sewage effluents (Nel et al., 2019; GESAMP, 2019), and direct littering (Dris et al., 2017; GESAMP, 2019).

Microplastic pollution thus poses serious global threats to environmental integrity, food safety, and human health (Dalu et al., 2023). Aquatic organisms, such as crustaceans and fish, as well as amphibians and birds, can ingest microplastics, leading to physical blockages, reduced feeding efficiency, stunted growth, and lower reproductive success, often resulting in increased mortality (Nel et al., 2018; Mbedzi et al., 2020; Nkosi et al., 2023). Moreover, microplastics can absorb and transport harmful pollutants such as Polychlorinated biphenyls (PCBs), Polycyclic aromatic hydrocarbons (PAHs), and Dichlorodiphenyltrichloroethane (DDT) (Kinigopoulou et al., 2022). These pollutants may settle within sediments, aggregate with organic materials, and accelerate sedimentation processes (Long et al., 2015; Nel et al., 2019).

The Makuleke and Nylsvley Wetlands are both protected areas under the Ramsar Convention, providing valuable case studies for examining the occurrence of microplastics in relatively undisturbed freshwater systems. Although shielded from direct urban and industrial influences, these wetlands may still receive microplastics through indirect pathways such as atmospheric deposition, upstream catchment activities, and tourism–related inputs. Studying these systems provides insights into long–range or diffuse sources of pollution. This study aims to assess water and sediment microplastic pollution in terms of composition and distribution across two seasons (i.e., dry and wet) in the Makuleke and Nylsvley Wetlands. The study hypothesised that: (1) Microplastics are present in both the water and sediment of the Makuleke and Nylsvley wetlands, with high microplastic density expected in sediment due to long-term particle accumulation. (2) Microplastic densities differ significantly between the two Wetlands, with Makuleke Wetlands exhibiting a higher microplastic density than Nylsvley Wetlands, influenced by differences in hydrology, vegetation cover, and indirect catchment inputs, despite Makuleke Wetlands' protected status.

3.2 Materials and methods

3.2.1 Permit consideration

Before sampling, the necessary research permits were obtained from SANParks (Permit No. SS1424) and the Limpopo Department of Economic Development, Environment and Tourism (Permit No. CPM 01753).

3.2.2 Study area

The Makuleke wetlands are located in the northernmost region of the Kruger National Park in South Africa's Limpopo Province (Figure 1a). This region receives a mean annual rainfall of 731 mm, with an annual mean temperature of approximately 23–26 °C (Munyai et al., 2023). Summer maximum temperatures can reach up to 40 °C, while minimum temperatures between January and July range from 20 °C to 21°C (Roos et al., 2025). According to the Köppen–Geiger climate classification, this region is classified as a moist subtropical zone, characterized by summer rainfall (Dyamond, 2017). Makuleke's lush wetlands and woodlands thrive under this precipitation regime, supporting a variety of habitats and wildlife species. According to Mucina and Rutherford (2006), the region's vegetation is categorized as an open tree savanna, characterized by species such as Digitaria eriantha, Combretum apiculatum, and Colophospermum mopane. The land area is approximately 2400 hectares. The Makuleke Wetlands were certified as a Ramsar Wetland on May

22, 2007 (Dzurume, 2021). These wetlands are categorized as a floodplain vlei, indicating that they undergo seasonal flooding and support a diverse array of wildlife (Munyai et al., 2023).

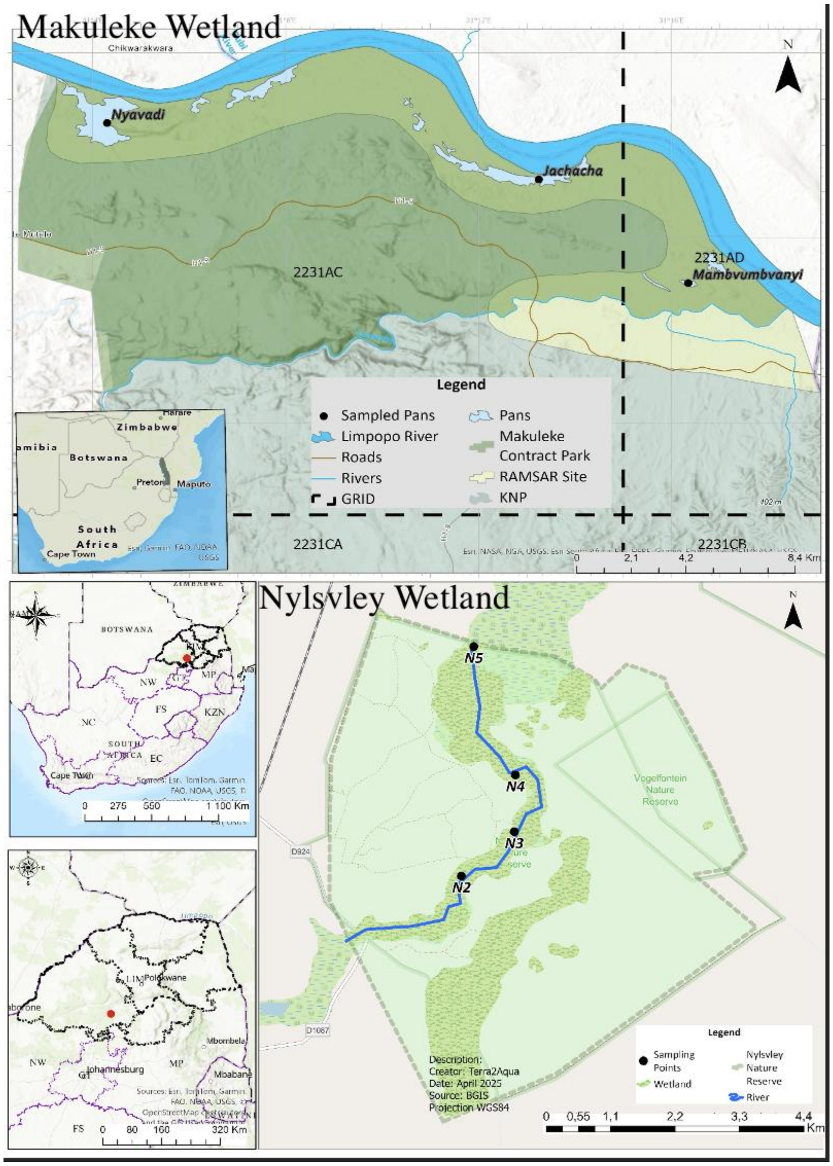


Figure 3.1. Study area map of Makuleke and Nylsvlei wetlands in the Limpopo Province of South Africa

The Nylsvley Wetlands are situated in South Africa's Limpopo Province within the Waterberg District Municipality (24º39’17” S, 28º42’28” E) (Figure 1b), gained global recognition as a Ramsar wetland site in 1998 (Dzurume et al., 2022). Characterised by vast reed beds and grassy plains, it is surrounded by expansive savanna woodlands. Positioned between 1080 and 1155 meters above sea level, Nylsvley Nature Reserve receives average annual rainfall of 620 mm, with a yearly mean temperature of 19 ºC. The maximum temperature in summer ranges from 21 °C to 29 °C, whereas the minimum temperature in summer varies between 17 °C in January and 4 °C in July (Dzurume, 2021). The Nylsvley Nature Reserve protects the floodplain from Middelfontein to Moorddrift towns (Dzurume et al., 2021; Makhuvha, 2021; Dzurume, 2022). The Nyl River floodplain consists of small grassy plains, large stands of rice grass, open water fields, reed beds, marshes, and forests. Nearly 600 plant species have been identified at the Nylsvley Nature Reserve (Stuart and Stuart,2018). Nylsvley Nature Reserve is a critical habitat for both wildlife and species that depend on wetlands. It is home to the roan antelope (Hippotragus equinus) and the rare tsessebe (Damaliscus lunatus), underscoring its conservation importance (Makhuvha, 2021).

3.2.3 Sampling

The sampling of surface water and sediments was carried out from five different sites in Makuleke and Nylsvley, with three samples taken from each site over two seasons, cool–dry (May, 2024) and hot–wet (March, 2025). Makuleke sites were selected to reflect gradients from areas near river inflows (with likely higher hydrological connectivity and potential pollutant transport) to interior, less–disturbed zones. At the same time, Nylsvley Wetlands sites were selected based on proximity to agricultural fields, reed–dominated areas, and open floodplain regions to capture spatial variability in potential microplastic deposition. This stratified selection enabled a more comprehensive assessment of microplastic distribution across various wetland conditions.

3.2.4 Microplastics in water

These steps were repeated for all samples collected at each location, and the samples were subsequently transported to the laboratory for further analysis. Samples were filtered through filter paper to retain medium– to crystalline particles. The paper was then partially dried and inspected under a Nikon DS–L3 camera head microscope with magnification ranging from 10 to 80, and a field of view calculated at ×20 magnification (Masura et al., 2015). Visual counting was used to classify particles based on shape, colour, and size (Wang et al., 2017). To address the presence of organic material, transparent and black particles underwent hardness and 3D testing (Long et al., 2022). Following counting, characteristics of microplastics (shapes, colours, and size) were documented, and samples were securely sealed in glass vials (Masura et al., 2015).

3.2.5 Microplastics in sediments

A quadrat was randomly placed at each site to collect riverbed silt. At each location, an aggregated sediment sample weighing 2 kg was collected from the upper 5 cm layer and stored in Ziploc bags for further laboratory analysis. Sediment samples were dried in a laboratory oven at 50°C for 48–72 hours, until a consistent weight was achieved (Hidalgo–Ruz et al., 2012). A 0.5 kg subsample was sieved through a 2 mm mesh steel sieve to remove large pebbles and debris. The residual silt was weighed to determine the number of microplastic particles per kilogram of dry weight (dwt). Large microplastics (2–5 mm) were detected in the material left on the sieve and were included in the overall microplastic count (Galgani et al., 2013). Each 0.5 kg sieved sediment subsample was placed in a clean 5 L beaker, and 100 g L^{-1} hyper–saturated zinc chloride (ZnCl) solution, filtered through a 63 μm mesh, was added. The mixture was vigorously stirred to suspend microplastics, then allowed to settle for 24 hours, allowing denser sediment to sink (Lusher et al., 2015). Hyper–saturated ZnCl is commonly used in density separation because its density allows microplastics to float while sediment settles. No chemical digestion was applied; microplastics were isolated solely through physical separation using the ZnCl solution.

3.2.6 Microplastic quantification

Microplastics were classified into the following commonly used morphological shapes: fibre, fragment, film, foam, and bead (Norén and Linell, 2007). Colours were also classified into the following categories: black, blue, white, green, yellow, red, colourless, and other, which are representative of the colours commonly observed in most microplastic–aquatic studies (Barrows et al., 2018). Particles were considered microplastics if they had unnatural colour (e.g., bright colour, multi–coloured) and/or unnatural shape (e.g., sharp edges, perfectly spherical; Hidalgo–Ruz et al., 2012). Because visual inspection alone was insufficient for characterizing and quantifying microplastics, we further subjected microplastic particles to vibrational Platinum–ATR Fourier transform infrared spectroscopy (FTIR). This method makes available libraries for identifying microplastic polymers and is more efficient for dense samples (Pico and Barceló, 2019). All sample processing was conducted under clean laboratory conditions to ensure accuracy and prevent external contamination. Cotton laboratory coats were worn, tools were rinsed with filtered distilled water between samples, and procedural blanks were included to detect any airborne or handling–related contamination.

3.2.7 Data analysis

The data were assessed for homogeneity of variance and normality using Levene's test and Shapiro–Wilk's W test, respectively, and were found to conform to the parametric assumptions. A three–way analysis of variance (ANOVA) was used to analyse the differences in total microplastic ‘species’ (i.e., different particle types – fragments, beads, fibre, foam, film) and diversity indices among sites (i.e., Makuleke and Nylsvley wetlands) and seasons (i.e., cool–dry, hot–wet), with significant variables being further assessed for pairwise differences using Tukey's post–hoc analysis. All statistical analyses were performed using PAST 4.13. Diversity analysis (i.e., Shannon–Wiener diversity, α-diversity, β-diversity, Simpson diversity, and evenness indices) was calculated using the modified methods of Battisti et al. (2018) and Dalu et al. (2019).

3.2.7.1 Sediment microplastic risk assessment

Microplastic indices, adapted from the Pollution Load Index (PLI) proposed initially by Tomlinson et al. (1980) for assessing metal pollution in sediments, were utilized to evaluate and compare the potential impacts of microplastics on aquatic ecosystems (Kabir et al., 2021). The contamination factor for microplastics measures concentrations relative to baseline levels and is classified into four categories: low (<1), moderate (1–3), high (3–6), and very high (>6).

$$\text{Contamination factor} = \frac{Asample}{Bbackground}$$

Where A represents the concentration of microplastics at a given site, while B refers to the background concentration obtained from a pristine control site with minimal or no human influence (e.g., 20 particles·kg^{-1}), the Microplastic Pollution Load Index (MpPLI) offers a standardized method for accurately assessing microplastic concentrations in river sediments across various systems. Sites with an MpPLI value greater than 1 are classified as polluted or in poor condition, whereas values below 1 indicate no pollution. The *MpPLI* for each wetland system was determined using modified equations from Tomlinson et al. (1980), as adapted by Kabir et al. (2021).

$$MpPLI_{\text{river}} = (CF_1 \text{ x } CF_2 \text{ x } \ldots \text{x } \mathrm{CF_n})^{1/n}$$

Where *i* represents the site, *n* is the number of sites in a wetland system, *and CFn* is the contamination factor at site n. Therefore, the *MpPLIrive*r is the riverine microplastic pollution load index.

3.4 Results

3.4.1 Microplastics in water

Microplastic types in Makuleke Wetlands water samples varied between seasons, indicating differences in hydrological and pollution dynamics. During the dry season, fibres were the dominant type (mean 35.6 particles L^{-1}), followed by beads (mean 12.8 particles L^{-1}) and films (mean 10.6 particles L^{-1}). Fragments (6.1 particles L^{-1}) and foams (mean 4.4 particles L^{-1}) were the least observed (Figure 2a). In the wet season, a shift in microplastic particles was observed, with beads becoming the most abundant type (mean 30.0 particles L^{-1}), followed by fibres (mean 25.6 particles L^{-1}) and films (mean 21.7 particles L^{-1}), whereas fragments (mean 10.6 particles L^{-1}) and foams (3.9 particles L^{-1}) were least observed (Figure 2b).

Nylsvley Wetland exhibited higher microplastic abundances than Makuleke Wetland, with clear dominance of certain types across both seasons. In the dry season, fibres (mean 72.2 particles L^{-1}) and fragments (mean 54.4 particles L^{-1}) were the most abundant types, followed by beads (mean 37.2 particles L^{-1}) and foams (mean 28.3 particles L^{-1}), while films were least observed (mean 19.4 particles L^{-1}) (Figure 2a). During the wet season, fibres remained dominant (mean 47.2 particles L^{-1}), followed by fragments (mean 38.3 particles L^{-1}) and foams (mean 26.1 particles L^{-1}). Beads (mean 22.8 particles L^{-1}) and films (mean 18.3 particles L^{-1}) were present in lower quantities compared to other types (Figure 2b).

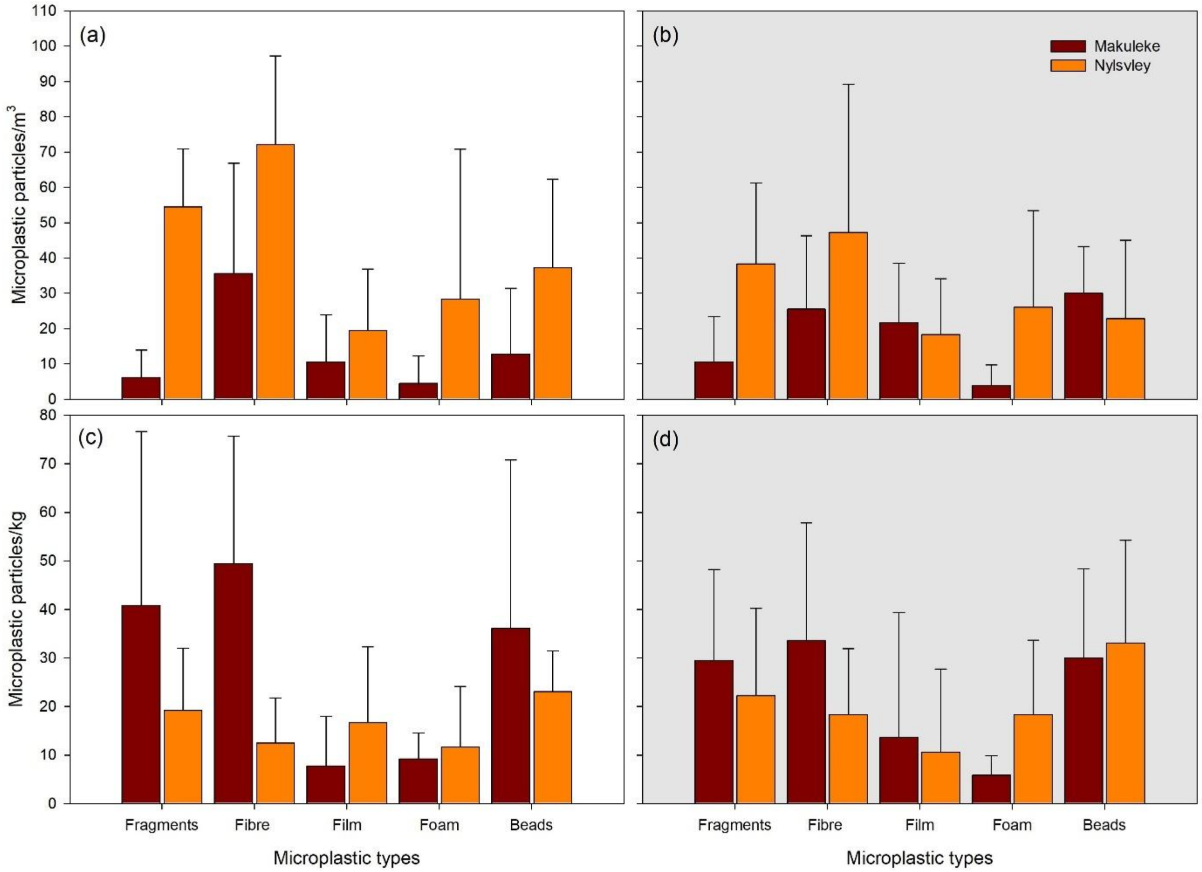


Figure 3.2: Microplastic type (a) dry season (white shade) and wet season (grey shade): (a, b) microplastic collected in water, and (c, d) microplastic collected in sediments collected in Makuleke and Nylsvley Wetlands.

Microplastic colours in water samples from Makuleke and Nylsvley wetlands varied between the dry and wet seasons, reflecting both site–specific and seasonal differences in plastic sources (Figure 3). Microplastic colour composition in the Makuleke Wetland varied between dry and wet seasons, reflecting seasonal differences in plastic inputs and hydrological conditions. During the dry season, black particles dominated the samples (mean 18.8 particles L^{-1}), followed by transparent (mean 12.7 particles L^{-1}) and blue (mean 12.2 particles L^{-1}) microplastics (Figure 3a). White (mean 5.5 particles L^{-1}) and yellow (mean 5.0 particles L^{-1}) were present in moderate quantities, while red (mean 2.7 particles L^{-1}) and green (mean 1.6 particles L^{-1}) were the least abundant; other colours accounted for a mean of 7.2 particles L^{-1}. In the wet season, overall microplastic abundance increased, with black (mean 26.1 particles L^{-1}) and white (mean 20.5 particles L^{-1}) emerging as dominant colours. Transparent and blue particles each contributed a mean of 13.3 particles L^{-1}, while yellow (mean 7.7 particles L^{-1}) and red (mean 5.0 particles L^{-1}) were moderately represented. Green (mean 3.3 particles L^{-1}) and other colours (mean 2.2 particles L^{-1}) were least abundant (Figure 3b). Nylsvley Wetlands exhibited higher overall microplastic abundances than Makuleke Wetland, with colour variability across seasons. During the dry season, black particles were dominant (mean 66.6 particles L^{-1}), followed by white (mean 36.6 particles L^{-1}) and transparent (mean 35.0 particles L^{-1}). Green (mean 23.3 particles L^{-1}), blue (mean 16.1 particles L^{-1}), yellow (mean 13.8 particles L^{-1}), and red (11.1 particles L^{-1}) also occurred in substantial quantities, while other colours contributed a mean of 8.8 particles L^{-1} (Figure 3a). In the wet season, black (mean 47.2 particles L^{-1}) and transparent (mean 38.3 particles L^{-1}) microplastics remained dominant. White (mean 21.1 particles L^{-1}) and green (mean 13.3 particles L^{-1}) were moderately abundant, whereas yellow (mean 10.5 particles L^{-1}), red (mean 8.3 particles L^{-1}), and blue (mean 5.0 particles L^{-1}) were present in lower density. Other colours contributed a mean of 8.8 particles L^{-1} (Figure 3b).

We observed that seasonality significantly influenced most microplastic types, particularly fragments ($F = 73.85$, $p < 0.001$), fibres ($F = 13.78$, $p < 0.001$), foams ($F = 18.98$, $p < 0.001$), and transparent particles ($F = 13.84$, $p < 0.001$) (Table 1). This suggests that seasonal variations have a significant influence on the abundance of these microplastics in aquatic systems. At the same time, Location showed insignificant effect, with only fibre being significantly influenced ($F = 4.96$, $p = 0.030$). However, microplastic types, such as beads ($F = 7.22$, $p = 0.009$) and fragments ($F = 5.39$, $p = 0.024$), exhibited significant interaction effects between season and location, indicating that both temporal and spatial factors influence their distribution. The interaction was primarily driven by high fragment density during the wet season in Nylsvley Wetlands compared to Makuleke Wetlands, indicating that hydrological flooding and increased surface runoff enhanced fragment transport in this site. In contrast, bead abundance was more sensitive to dry-season accumulation at Makuleke, implying local inputs from human activity surrounding the wetlands.

Regarding colour, black ($F = 30.15$, $p < 0.001$), green ($F = 19.95$, $p < 0.001$), white ($F = 7.08$, $p = 0.010$), red ($F = 5.70$, $p = 0.020$), and transparent ($F = 13.84$, $p < 0.001$) microplastics varied significantly across seasons. Although location alone had a limited influence on colour composition, significant season × location interactions were detected for black ($F = 4.52$, $p =$

0.038) and white particles (F = 6.59, p = 0.013). This indicates that seasonal changes were the primary driver. Still, their magnitudes varied across sites, suggesting that site-specific factors, such as hydrology, land use, and sediment characteristics, control how seasonal dynamics influence microplastic colour distribution.

3.4.2 Microplastics in sediments

Microplastic abundances in sediment samples were assessed in the Makuleke and Nylsvley Wetlands during both the dry and wet seasons (Figure 2). Microplastic abundances in Makuleke Wetlands sediments showed apparent seasonal variation. During the dry season, fibres (mean 49.4 particles kg^{-1}) were the dominant type, followed by fragments (mean 40.8 particles kg^{-1}) and beads (mean 36.1 particles kg^{-1}). Foam (mean 9.1 particles kg^{-1}) and films (mean 7.7 particles kg^{-1}) were the least observed microplastic types (Figure 2c). In the wet season, fibres (mean 33.6 particles kg^{-1}) continued to dominate, followed by beads (mean 30.0 particles kg^{-1}) and fragments (mean 29.4 particles kg^{-1}), whereas film (mean 13.6 particles kg^{-1}) and foam (mean 5.8 particles kg^{-1}) were the least observed microplastic type compared to other types (Figure 2d).

Nylsvley Wetlands sediments exhibited lower microplastic abundances than those of Makuleke Wetlands, but showed distinct seasonal compositional patterns. During the dry season, beads were the most abundant type (mean 23.0 particles kg^{-1}), followed by fragments (mean 19.1 particles kg^{-1}) and films (mean 16.6 particles kg^{-1}). Foam (mean 11.6 particles kg^{-1}) and fibre (mean 12.5 particles kg^{-1}) were less common (Figure 2c). In the wet season, beads remained dominant (mean 33.0 particles kg^{-1}), while fragments (mean 22.2 particles kg^{-1}) were the second most abundant. Fibres and foams occurred at similar levels (mean 18.3 particles kg^{-1}), and films (mean 10.5 particles kg^{-1}) were the least represented microplastic type (Figure 2d).

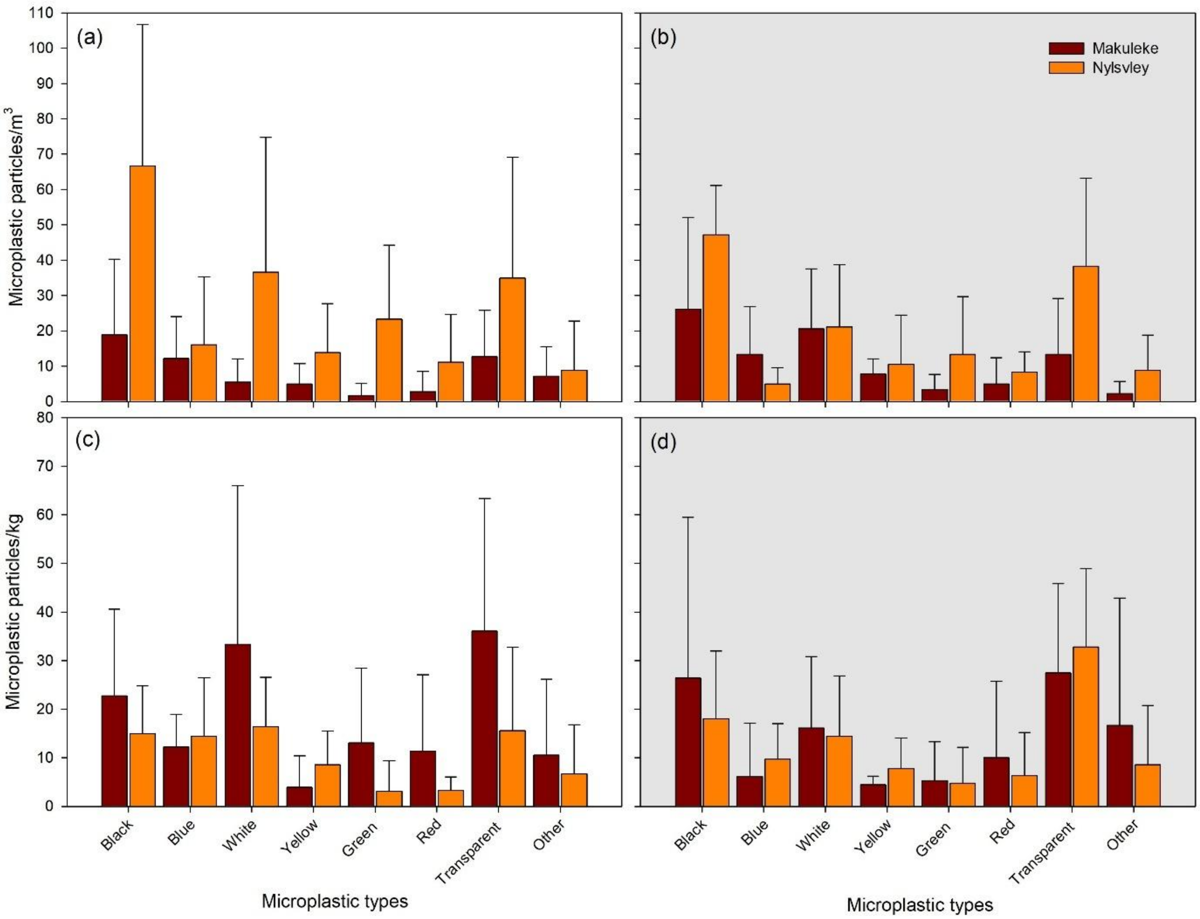


Figure 3.3: Microplastic colours (a) dry season (white shade) and wet season (grey shade): (a, b) microplastic collected in water, (c, d) microplastic collected in sediments collected in Makuleke and Nylsvley Wetlands

Table 3.2: Two-way ANOVA results for water microplastic densities across different seasons (i.e., dry and wet), and location (Makuleke and Nylsvley wetlands).

	Seasons		**Location**		**Seasons x Location**	
Variables	**F**	***p***	**F**	***p***	**F**	***P***
Microplastic type						
Fragment	**73.85**	**<0.001**	1.74	0.193	5.39	0.024
Fibre	**13.78**	**<0.001**	**4.96**	**0.030**	0.91	0.344
Film	0.46	0.500	1.50	0.227	2.23	0.141
Foam	**18.98**	**<0.001**	0.07	0.794	0.02	0.875
Beads	2.14	0.150	0.06	0.815	**7.22**	**0.009**
Microplastic colour						
Black	**30.15**	**<0.001**	0.95	0.334	4.52	0.038
Blue	0.52	0.476	2.61	0.112	3.90	0.053
White	**7.08**	**0.010**	0.00	0.963	6.59	0.013
Yellow	3.46	0.068	0.01	0.930	0.95	0.334
Green	**19.95**	**<0.001**	1.38	0.245	2.71	0.105
Red	5.70	0.020	0.01	0.910	1.05	0.311
Transparent	**13.84**	**<0.001**	0.09	0.760	0.05	0.828
Other	1.58	0.213	0.57	0.453	0.57	0.453

Microplastic colour composition in Makuleke Wetlands sediments exhibited seasonal variation. During the dry season, transparent particles (mean 36.1 particles kg^{-1}) were most abundant, followed closely by white (mean 33.3 particles kg^{-1}) and black (mean 22.7 particles kg^{-1}) particles. Blue (mean 12.2 particles kg^{-1}) and green (mean 13.0 particles kg^{-1}) microplastics occurred in moderate quantities, while red (mean 11.3 particles kg^{-1}) and yellow (mean 3.8 particles kg^{-1}) were less observed. Other colours contributed a mean of 10.5 particles kg^{-1} (Figure 3c). In the wet season, a shift in dominance was observed, with black (mean 26.3 particles kg^{-1}) and transparent (mean 27.5 particles kg^{-1}) particles emerging as the most abundant colours. White (mean 16.1 particles kg^{-1}) and red (mean 10.0 particles kg^{-1}) followed, while blue (mean 6.1 particles kg^{-1}), green (mean 5.2 particles kg^{-1}), and yellow (mean 4.4 particles kg^{-1}) occurred in lower concentrations. Other colours accounted for a mean of 16.6 particles kg^{-1} (Figure 3d).

Nylsvley Wetlands sediments contained fewer microplastic particles compared to those of Makuleke Wetlands, exhibiting distinct seasonal patterns (Figure 3). During the dry season, white (mean 16.3 particles kg^{-1}) and transparent (mean 15.5 particles kg^{-1}) particles dominated, followed by black (mean 15.0 particles kg^{-1}) and blue (mean 14.4 particles kg^{-1}). Yellow (mean 8.1 particles kg^{-1}), green (mean 3.0 particles kg^{-1}), and red (mean 3.3 particles kg^{-1}) were less abundant, while other colours had a mean of 6.7 particles kg^{-1} (Figure 3c). In the wet season, transparent particles (mean 32.7 particles kg^{-1}) became dominant, followed by black (mean 18.0 particles kg^{-1}) and white (14.4 particles kg^{-1}). Red (mean 6.3 particles kg^{-1}), blue (mean 9.7 particles kg^{-1}), yellow (mean 7.7 particles kg^{-1}), and green (mean 4.7 particles kg^{-1}) were least observed, with other colours contributing a mean of 8.6 particles kg^{-1} (Figure 3d).

We observed fewer significant seasonal differences, although fibres ($F = 15.86$, $p < 0.001$), foams ($F = 9.45$, $p = 0.003$), fragments ($F = 5.78$, $p = 0.020$), and yellow particles ($F = 5.59$, $p = 0.022$) showed notable seasonal variation (Table 2). This highlights that seasonal input of microplastics still affects sediment load, but the effect is less intense than that of water. Location alone did not significantly influence any microplastic type or colour, suggesting relatively uniform sediment accumulation across Makuleke and Nylsvley Wetlands. However, the significant season × location interactions for foam ($F = 4.20$, $p = 0.045$) and transparent microplastics ($F = 5.17$, $p = 0.027$) indicate that seasonal effects on microplastic accumulation differ among sites, suggesting that both seasonal hydrology and sediment characteristics influence microplastic retention.

Table 3.3: Two-way ANOVA results for sediment microplastic densities across different seasons (i.e., dry and wet), and location (Makuleke and Nylsvley wetlands).

Variables	**Seasons**		**Location**		Seasons *x* **Location**	
	F	***p***	**F**	***p***	**F**	***p***
Microplastic types						
Fragment	**5.78**	**0.020**	0.48	0.491	1.45	0.234
Fiber	**15.86**	**<0.001**	0.58	0.449	2.73	0.104
Film	0.33	0.566	0.00	0.978	1.40	0.242
Foam	**9.45**	**0.003**	0.47	0.497	**4.20**	**0.045**
Beads	0.60	0.443	0.09	0.765	1.55	0.219
Microplastic colour						
Black	1.15	0.287	0.20	0.658	0.00	0.971
Blue	0.92	0.341	3.18	0.080	0.05	0.820
White	2.17	0.146	2.31	0.134	1.47	0.231
Yellow	**5.59**	**0.022**	0.01	0.935	0.17	0.685
Green	3.26	0.076	1.09	0.300	2.61	0.112
Red	2.20	0.144	0.04	0.833	0.32	0.574
Transparent	1.81	0.184	0.57	0.452	**5.17**	**0.027**
Other	1.68	0.200	0.77	0.385	0.21	0.652

3.4.3 Microplastic diversity indices

3.4.3.1 Water microplastics

In the Makuleke Wetlands, α–diversity for water microplastics was lower in the dry season (mean 2.92) but increased notably in the wet season (4.26), suggesting an influx of diverse microplastic types and colors during higher flow conditions (Figure 4a). The Simpson diversity index also reflected this pattern, with higher values in the wet season (mean 0.68), indicating greater evenness and reduced dominance by a single microplastic type (Figure 4c). Similarly, the Shannon–Wiener index showed higher diversity in the wet season (mean = 1.26), reflecting increased richness and potentially greater heterogeneity in microplastic types during periods of increased hydrological activity (Figure 4e). Evenness values were moderately high across both seasons, though high in the wet season, with a mean of 0.86 (Figure 4g). In contrast, the Nylsvley Wetlands exhibited relatively stable diversity patterns across seasons, with minimal variation in α–diversity, Simpson's, and Shannon's indices. This stability indicates consistent sources and types of microplastics throughout the year. The β–diversity (Figure 4i) showed that Makuleke Wetlands water samples were more heterogeneous in the dry season, while Nylsvley Wetlands exhibited low and uniform β–diversity across both seasons.

3.4.3.2 Sediment microplastics

For sediment microplastics, Makuleke Wetlands showed greater seasonal fluctuation than Nylsvley Wetlands. The α–diversity index was low in the dry season (mean 0.42) but increased (mean 0.45) during the wet season (Figure 4b), reflecting a broader range of deposited microplastic types. Simpson with a mean of 0.64 during the dry season and 0.71 during the wet season, whereas Shannon–Wiener indices had a mean of 1.19 during the dry season and 1.36 during the wet season (Figure 4d, f), followed a similar trend, with higher values in the wet season, suggesting enhanced diversity and evenness due to sediment resuspension and redistribution. Evenness indicated balanced community structures, although Makuleke Wetlands displayed slightly more seasonal variability, with a mean of 0.78 during the dry season and 0.86 during the wet season, compared to Nylsvley Wetlands (Figure 4h). Within the Nylsvley Wetlands, sediment diversity indices remained stable across both seasons, showing consistent composition and low heterogeneity. Correspondingly, β–diversity values were low, with a mean of 0.27 during the dry season and a mean of 0.15 during the wet season, indicating uniformity in sediment–associated microplastics between seasons (Figure 4j).

In Makuleke Wetlands, α–diversity was lower in the dry season, with a mean range of 4.26, but increased in the wet season, with a mean range of 4.53, whereas Nylsvley Wetlands remained relatively stable across both seasons. In the Simpson diversity indices, the Makuleke Wetlands exhibit greater seasonal fluctuations, with a mean range of 0.071 during the wet season, whereas the Nylsvley Wetland demonstrates diversity across seasons. Similarly, Shannon–Wiener indices indicate that the Diversity of water microplastics in Makuleke Wetlands is higher during the wet season than during the dry season, whereas sediment diversity in Nylsvley Wetlands remains constant and steady across seasons (Figure 4f). The Makuleke wetland showed evenness mean values of 0.789 during the dry season and 0.860 in the wet season, while Nylsvley Wetlands have a mean of 0.811 and 0.829, respectively (Figure h). Finally, β–diversity values (Figure 4j) reveal clear seasonal effects: Makuleke Wetlands sediment microplastics are highly heterogeneous in the dry season compared to the wet, while Nylsvley Wetlands maintains low and uniform β–diversity across both seasons (Figure 4j).

3.4.4 Fourier transform infrared spectroscopy (FT-IR)

The FT-IR spectra of both water and sediment samples showed distinct absorption bands associated with different polymeric materials. Strong C–H stretching vibrations appearing between 2950–2850 cm^{-1}, along with bending modes at 1465–1375 cm^{-1}, were indicative of aliphatic hydrocarbons commonly found in polyethylene (PE), polypropylene (PP), and vaseline. An additional band observed near 1715 cm^{-1}, corresponding to C=O stretching, signified the presence of polyethylene terephthalate (PET). These spectral features demonstrate a mixture of polyolefin and polyester compounds combined with petroleum-derived hydrocarbons. The detection of PE, PP, PET, and Vaseline in both matrices suggests inputs from packaging debris, textile fibres, and cosmetic residues, most likely transported into the wetland system through runoff, human activity, and tourism-related waste.

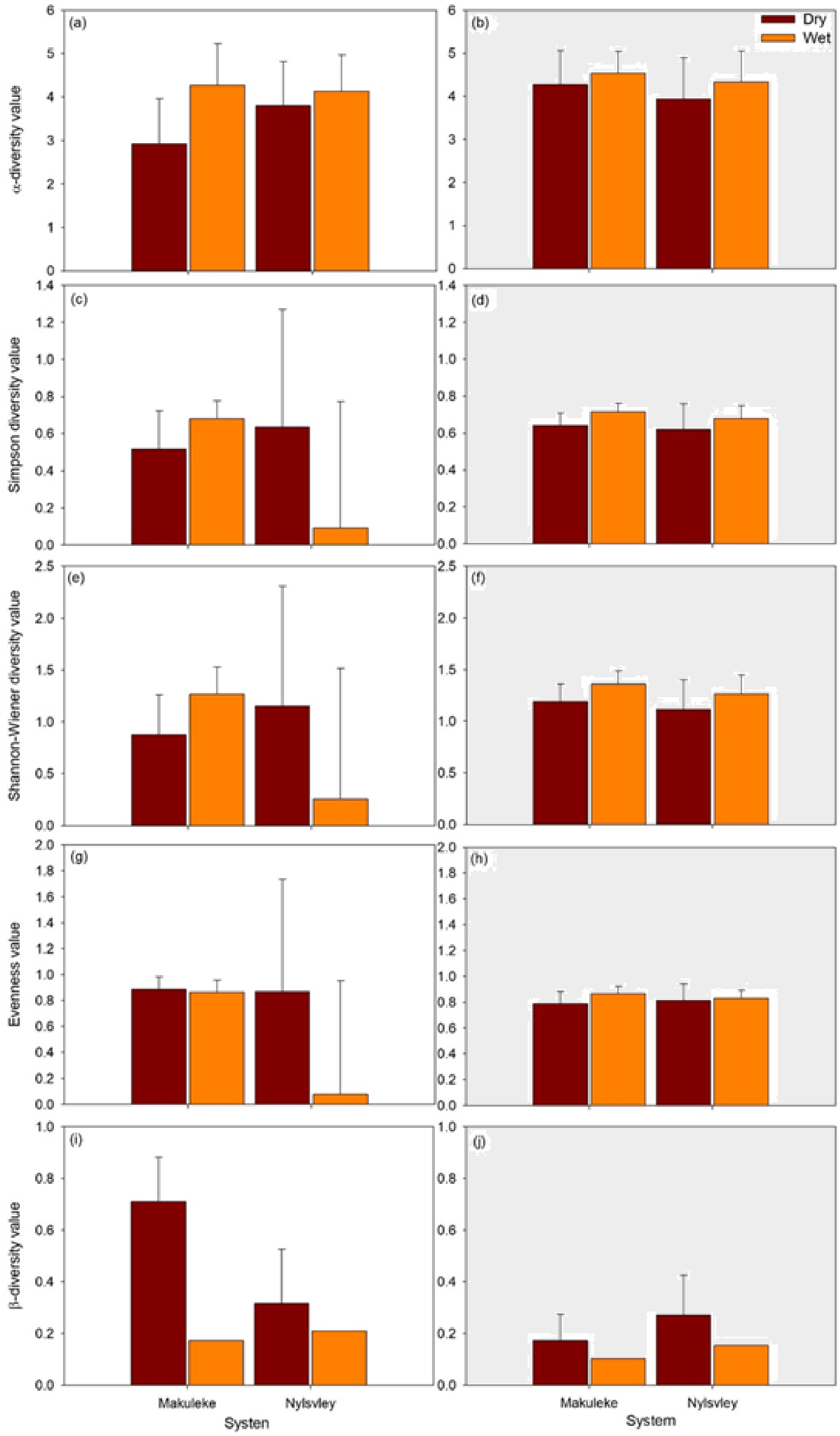


Figure 3.4: Microplastic diversity indices water (white shade) and sediment (grey shade): (a, b) α–diversity, (c, d) Simpson diversity, (e, f) Shannon–Wiener diversity, (g, h) evenness, (i, j) β–diversity value collected in Makuleke and Nylsvley Wetlands

3.4.5 Sediment microplastic risk assessment

The risk assessment of the Makuleke and Nylsvley wetlands revealed distinct differences in ecological vulnerability, shaped by environmental variability and human impact. In the Makuleke Wetlands, microplastic contamination was relatively consistent across sampling sites during the dry season (mean = 102.02 ± 78.77; PLI = 1.0), indicating reduced variability compared to the wet season (mean = 43.80 ± 25.69; PLI = 1.95), posing a moderate risk. This suggests that rainfall may dilute and redistribute microplastics rather than intensify contamination. Conversely, Nylsvley Wetlands showed greater variability in microplastic concentrations, especially during the dry season (mean = 98.67 ± 123.24; PLI = 1.39), indicating a moderate risk, suggesting an uneven distribution among sites. During the wet season, concentrations increased substantially (mean = 53.53 ± 28.45; PLI = 21.85, very high risk), reflecting intensified runoff and anthropogenic inputs. These findings suggest that Nylsvley Wetlands is more ecologically vulnerable to microplastic pollution, underscoring the need for site-specific, seasonal monitoring strategies to mitigate contamination risks.

3.5 Discussion

The study confirms that microplastics are widespread in both water and sediment samples from the Makuleke and Nylsvley wetlands. Despite their protected status, these ecosystems are vulnerable to diffuse pollution, particularly from microplastics, which are recognised as persistent contaminants in freshwater environments. As hypothesized, sediments consistently contained higher particle densities than water, reflecting the settling and accumulation of particles over time. Microplastic levels also varied between wetlands and among sampling sites, influenced by local hydrology, vegetation cover, and inputs from surrounding catchments. These findings support all the study hypotheses and are consistent with Hurley et al. (2018), who demonstrated that sediments act as long–term sinks, particularly following flood events that redistribute particles within aquatic systems. Distinct spatial and seasonal variations were observed between the wetlands. Makuleke Wetlands had lower overall microplastic abundances, with fibres dominating in the dry season and beads in the wet season, while Nylsvley Wetlands consistently showed higher loads, with fibres and fragments prevalent across both seasons. Seasonal increases were recorded at both sites, likely due to rainfall, flooding, and runoff transporting plastics from surrounding catchments (Hurley et al., 2018; Nkosi et al., 2023). The prevalence of fibres and fragments suggests contributions from textiles and degraded packaging (Biginagwa et al., 2016; Horton et al., 2017).

Seasonal variation emerged as the primary factor influencing the distribution of microplastics in water. High abundances of fragments, fibres, foams, and transparent particles during the wet season reflect increased runoff and hydrological transport, which enhance the movement and mixing of plastics within the wetlands. Site–related differences were less consistent, although variations in fibre abundance suggest that local environmental or anthropogenic factors contribute to microplastic inputs (Hurley et al., 2018). The combined effects of season and location on beads, fragments, and certain colours, notably black and white, indicate that both hydrological conditions and site–specific characteristics shape microplastic patterns. Overall, waterborne microplastics are largely governed by seasonal hydrodynamics, while local factors exert secondary, context–dependent influences (Zhang et al., 2021).

In sediments, seasonal differences were less pronounced but still evident for fibres, foams, fragments, and yellow particles. These trends suggest that deposition and resuspension respond to seasonal shifts in water flow, influencing particle persistence. Although sediments act as more stable sinks compared to water, they still reflect seasonal variations linked to hydrodynamic activity and changing pollution inputs. Foam and transparent particles exhibited significant season × location interactions, indicating that hydrological conditions affected their deposition differently between wetlands. This resulted in enhanced foam accumulation in Makuleke Wetlands during the wet season, but reduced sediment retention in Nylsvley Wetlands due to higher flow. Sediments thus function as stable sinks, yet seasonal runoff and turbulence periodically resuspend or introduce specific microplastic types (Wicaksono et al., 2021; Saarni et al., 2023).

Sediment composition and colour patterns revealed clear spatial and seasonal contrasts between the two wetlands. In Makuleke Wetlands, fibres and fragments were more abundant across both seasons, indicating contributions from textiles and the breakdown of larger plastic debris—a trend consistent with previous findings that link synthetic fibres to laundry and sewage effluents (Browne et al., 2011; Napper and Thompson, 2016). In contrast, Nylsvley Wetland sediments were dominated by beads, reflecting inputs from personal care products and domestic wastewater, as microbeads typically originate from cosmetic and household sources (Bashir et al., 2021; Habib et al., 2022). This persistent bead dominance aligns with regional reports of elevated microplastic loads in the Nyl River system, suggesting ongoing contamination driven by local wastewater discharge and catchment activities (Dahms, 2025).

The colour composition of microplastics further supports these spatial patterns and their underlying sources. Black particles were the most abundant, especially at Nylsvley Wetlands, likely derived from anthropogenic sources such as tire wear debris and open waste burning. In contrast, transparent and white fragments were associated with discarded packaging and bottle materials (Sruthy and Ramasamy, 2017; Zhang et al., 2021). Seasonal differences likely reflect variations in plastic sources and hydrological transport. In Makuleke, the dominance of black and white particles during the wet season suggests runoff-driven inputs from road debris, tire wear, and nearby settlements. In contrast, the consistently high proportion of black and transparent particles in Nylsvley Wetlands points to continuous domestic and vehicle-related sources. In sediments, the high microplastic abundance in Makuleke Wetlands indicates greater deposition due to slower flow and sediment trapping, whereas the more dynamic hydrology in Nylsvley Wetlands limits settling, keeping particles suspended. The increase in transparent items during the Nylsvley Wetlands' wet season likely results from the enhanced transport of lightweight polyethylene and polypropylene films (e.g., plastic bags) washed into the wetland during rainfall events.

Nylsvley Wetland sediments contained fewer microplastics overall because water flow and higher flushing rates during rainfall reduce particle settling, keeping most plastics suspended in the water column. The increase in transparent items during the wet season likely reflects the increase in transport of lightweight materials, such as films (e.g., plastic bags and packaging), that are easily mobilized by runoff from surrounding human activities. Similar patterns have been reported in other rivers and wetlands, where hydrological factors such as flooding, resuspension, and seasonal changes in water flow influence both abundance and colour composition (Ramaremisa et al., 2022; Bordós et al., 2019; Li et al., 2018). These results suggest that differences between the two wetlands are shaped by seasonal hydrology, which together determine the transport and accumulation of microplastics.

The microplastic PLI of the Makuleke and Nylsvley wetlands revealed notable differences in ecological vulnerability, reflecting variations in environmental conditions and anthropogenic pressures. The results show that Makuleke Wetlands experienced low contamination during the dry season but moderate contamination during the wet season, driven by rainfall and flooding that increased plastic transport. Nylsvley Wetlands consistently exhibited higher contamination, with extreme wet-season levels resulting from runoff and human activities, indicating stronger hydrological and anthropogenic influences. The extreme wet-season risk highlights the combined influence of sediment-associated microplastics and diffuse pollution from agricultural and peri-urban activities. During heavy rainfall, runoff from the surrounding catchment transports plastics from soil surfaces and agricultural areas into the wetland, increasing contamination levels. This process reflects the high runoff carrying capacity of microplastics, which enables their transfer from terrestrial to aquatic systems during storm events (Li et al., 2021; Horton and Dixon, 2018).

The detection of PE, PP, PET, and Vaseline in both matrices suggests inputs from packaging debris, textile fibres, and cosmetic residues, most likely transported into the wetland system through runoff, human activity, and tourism-related waste. Despite both wetlands being Ramsar–listed and protected from direct industrial discharge, clear disparities emerged. Nylsvley Wetlands is influenced by nearby agriculture and peri–urban settlements, which contribute plastic debris through soil erosion, irrigation return flows, and waste leakage (Townsend et al., 2019; Kabir et al., 2024). The Makuleke Wetlands, situated within the Kruger National Park, face few direct anthropogenic pressures; however, atmospheric deposition and tourism remain potential sources of concern.

These findings indicate that the Nylsvley Wetlands are more heavily impacted by microplastic pollution, particularly during the wet season, emphasizing the need for site–specific monitoring and management strategies (Saikia and Handique, 2024). Conversely, Makuleke Wetlands, while impacted, remain relatively resilient, with lower contamination and risk overall. The assessment highlights the importance of considering both seasonal dynamics and local anthropogenic pressures when assessing the risk of microplastic pollution in wetlands.

This research is distinctive in its focus on wetlands within protected areas, whereas most studies target urban rivers and estuaries. The findings from the Makuleke and Nylsvley wetlands highlight that conservation sites are also affected, demonstrating the extensive spread of plastic pollution and the challenge of managing diffuse land–based inputs (Zhang et al., 2021). The results highlight the importance of integrated catchment–based management. Priority measures include improving solid waste management, regulating plastic use, and restoring riparian vegetation to reduce runoff. Similar interventions have been shown to reduce microplastic and contaminant loads in wetlands (Rasta et al., 2020; Duan et al., 2021). Long–term monitoring is essential for capturing seasonal variability and strengthening the basis for risk assessment and conservation planning.

3.6 Conclusion

This study demonstrates that microplastics are widespread in both water and sediment of the Makuleke and Nylsvley Wetlands, with sediments acting as major sinks. Seasonal patterns showed significantly higher abundances during the wet season, highlighting the role of rainfall, flooding, and runoff in mobilising and depositing plastics into wetland systems. The contrast between the two sites was pronounced: Nylsvley Wetland recorded higher concentrations and ecological risk levels than Makuleke Wetland, reflecting greater exposure to tourism pressures. Fibres, fragments, and beads were the most prevalent across both wetlands, while black, transparent, and white particles were the most common, suggesting inputs from textiles, packaging materials, and degraded consumer plastics. The microplastic PLI revealed that Makuleke Wetland posed a low to moderate ecological risk, while Nylsvley Wetlands exhibited a moderate to very high risk, particularly during the wet season when hydrological transport intensified. These findings confirm that even protected Ramsar wetlands are not immune to microplastic contamination and that indirect pathways, such as catchment runoff and atmospheric deposition, significantly influence pollution loads. Addressing these challenges requires catchment–scale management strategies. Improving waste management, regulating plastic use in agriculture, and restoring riparian buffers are critical interventions. Equally important is the establishment of long–term monitoring programs to track spatiotemporal trends and assess ecological impacts. Protecting wetlands, such as the Makuleke and Nylsvley wetlands, is vital not only for biodiversity conservation but also for sustaining their role as ecological filters and refuges in an increasingly plastic–contaminated world.

CHAPTER 4: MICROPLASTIC DYNAMICS IN SEDIMENT LAYERS OF TWO RAMSAR–DESIGNATED WETLANDS IN SOUTH AFRICA

This chapter is has been published**:** ***Nelisiwe Ngomane****, Linton F. Munyai, Ross N. Cuthbert, Pule Mpopetsi, Farai Dondofema, Rabelani Mudzielwana, Philippa Huchzermeyer, and Tatenda Dalu. Microplastic dynamics in sediment layers of two Ramsar–designated wetlands in South Africa.* ***Water, Air, and Soil Pollution.***

ABSTRACT

Little is known about the vertical and spatial dynamics of microplastics in relation to hydrology and land use, particularly in African contexts. This study aimed to assess the abundance, type, colour, and vertical distribution of microplastics in sediment cores from two Ramsar–designated South African wetlands, Makuleke and Nylsvley. Sediment core samples were collected from five depth intervals for microplastic quantification. Overall, microplastics were detected across all depth profiles, with slight variation throughout the substrate, particularly in fibres and beads. Makuleke exhibited significantly higher concentrations of fragment and film microplastics than Nylsvley, driven by hydrological connectivity and anthropogenic inputs. These findings reveal that wetland protection status alone does not shield against microplastic contamination, which can persist in deep substrate layers for extended periods. The study highlights the importance of integrated wetland management, enhanced plastic waste policies, and ongoing research on the fate of microplastics in freshwater sediment systems.

Keywords: Microplastics, wetland sediments, Ramsar sites, hydrological connectivity, sediment core analysis

4.1 Introduction

Plastics are a significant component of the Anthropocene, mainly due to their durability and usefulness since mass manufacture began in the 1940s (Mashamba et al., 2024). Their durability and versatility make plastics among the most common types of man–made aquatic debris found in marine, estuarine, and freshwater ecosystems (Andrady, 2011; Galgani et al., 2015; Wang et al., 2022). If current disposal methods are not improved, plastic waste entering the world's aquatic systems, including oceans, rivers, coastlines, and wetlands, is predicted to increase dramatically, reaching millions of tonnes by 2025 (Jambeck et al., 2015).

Wetlands are unique transitional ecosystems that bridge terrestrial and aquatic environments, playing vital roles in biodiversity conservation, water purification, flood mitigation, and nutrient cycling (Long et al., 2022; Swartz et al., 2019). Their structural complexity, vegetative cover, and slow–moving waters allow them to retain pollutants, including sediments, nutrients, and increasingly, microplastics (Li et al., 2018; Sruthy and Ramasamy, 2017). Sediments in wetlands can act as both hotspots and sinks for microplastic accumulation (Abidli et al., 2019). Still, research on microplastic dynamics in wetland sediments remains sparse, particularly compared with other aquatic systems, such as lakes, reservoirs, and rivers (Helcoski et al., 2020; Dahms and Greenfield, 2024).

Over time, plastics in aquatic systems degrade through photochemical and mechanical processes, breaking down into microplastic particles smaller than 5 mm (Browne et al., 2007; Dalu et al., 2022; Mashamba et al., 2024). Microplastics are emerging contaminants of concern due to their persistence, potential to adsorb pollutants, and adverse effects on aquatic organisms and ecosystem functions (Dalvand et al., 2023; Rodrigues et al., 2018). Microplastics enter freshwater and wetland environments via various pathways, including the breakdown of larger plastic items, wastewater discharge, river inflows, stormwater runoff, atmospheric deposition, and improper waste disposal (Browne et al., 2010; Cole et al., 2011; Woodall et al., 2014). Their fate in the environment is primarily influenced by density; low–density particles tend to float, while high–density ones sink and accumulate in sediments (Ma and You, 2025). Processes such as biofouling and chemical leaching further influence particle behaviour, often leading to the submersion of initially buoyant plastics (Long et al., 2015; Cole et al., 2016).

Globally, microplastics have been detected in a wide range of aquatic environments from urban rivers and wetlands to remote polar regions and even groundwater (Ajith et al., 2020; Hale et al., 2020; Ziani et al., 2023; Dalu et al., 2023; Neelavannan and Sen, 2023; Lacerda et al., 2019; Guerranti et al., 2019; Mutshekwa et al., 2025a). Once ingested, microplastics can disrupt growth, reproduction, and immune function in aquatic species, threatening biodiversity (Gatidou et al., 2019; Gola et al., 2021; Issac and Kandasubramanian, 2021). Inhaled microplastics have also been linked to respiratory illnesses in humans and animals due to their ability to penetrate lung tissue and carry harmful pollutants, such as heavy metals (Thakur et al., 2022; Nel and Froneman, 2015; Qian et al., 2021; Eerkes–Medran et al., 2015).

Despite their ecological importance, wetlands are increasingly threatened by human activities, including land-use changes, mining, urban expansion, and agricultural runoff (Bhowmik, 2022; Wasserman and Dalu, 2022). In wetland ecosystems, microplastics can alter sediment texture by reducing porosity and oxygen diffusion, disrupting microbial activity, nutrient cycling, and habitat availability for benthic organisms (Rillig and Lehmann, 2020; Zhang et al., 2021). They may also be ingested by wetland biota, threatening food web stability (Qian et al., 2021; Xia et al., 2022). While past research has primarily focused on larger wetland fauna, such as birds and reptiles (Batzer and Boix, 2016; Hu et al., 2017; Xu et al., 2019), there is growing recognition of the need to assess microplastic accumulation in abiotic components that underpin ecosystems. Microplastic accumulation in the substrate of such environments is therefore a growing concern. Studies on microplastics in wetland sediments remain limited, particularly in African contexts, where land use and hydrological variability may influence microplastic transport and deposition in unique ways. This study aimed to assess the distribution and dynamics of microplastics across sediment depths (0–100 cm) in the Makuleke and Nylsvley wetlands, in Limpopo Province, South Africa. We hypothesized that (1) microplastic concentrations differ significantly between the two wetlands, with higher concentrations expected in Makuleke due to greater hydrological connectivity and anthropogenic inputs; and (2) deeper sediment layers contain higher microplastic concentrations, reflecting long–term deposition and sediment accumulation processes.

4.2 Materials and methods

4.2.1 Permit consideration

Before sampling, the necessary research permits were obtained from SANParks (Permit No. SS1424) and the Limpopo Department of Economic Development, Environment and Tourism (Permit No. CPM 01753).

4.2.2 Study area

The Makuleke wetlands are in the northernmost area of the Kruger National Park in South Africa's Limpopo Province (Figure 1a). The Makuleke wetlands receive a mean annual rainfall of 31 mm (Munyai et al., 2023), with an annual mean temperature of approximately 23–26 °C. Summer maximum temperatures can reach 40°C, while minimum temperatures between January and July range from 20°C to 21°C (SANParks, 2024). According to the Köppen–Geiger climate classification, this region is classified as a moist subtropical zone, characterized by a summer rainfall pattern (Dyamond, 2017). Makuleke's diverse wetlands thrive under this precipitation regime, supporting a variety of habitats and wildlife species. According to Mucina and Rutherford (2006), the region's vegetation is categorised as an open tree savanna, characterized by species such as *Digitaria eriantha*, *Combretum apiculatum,* and *Colophospermum mopane*. Though both grass species are present in the sandstone pans, *C. mopane* trees predominated in most of the pan wetland areas in the present study. The land area is approximately 2400 hectares. The Makuleke Wetlands were certified as a Ramsar Wetland on May 22, 2007 (Dzurume, 2021). These wetlands are classified as floodplain vleis, indicating that they experience seasonal flooding and support a diverse array of wildlife (Keates et al., 2022; Munyai et al., 2023).

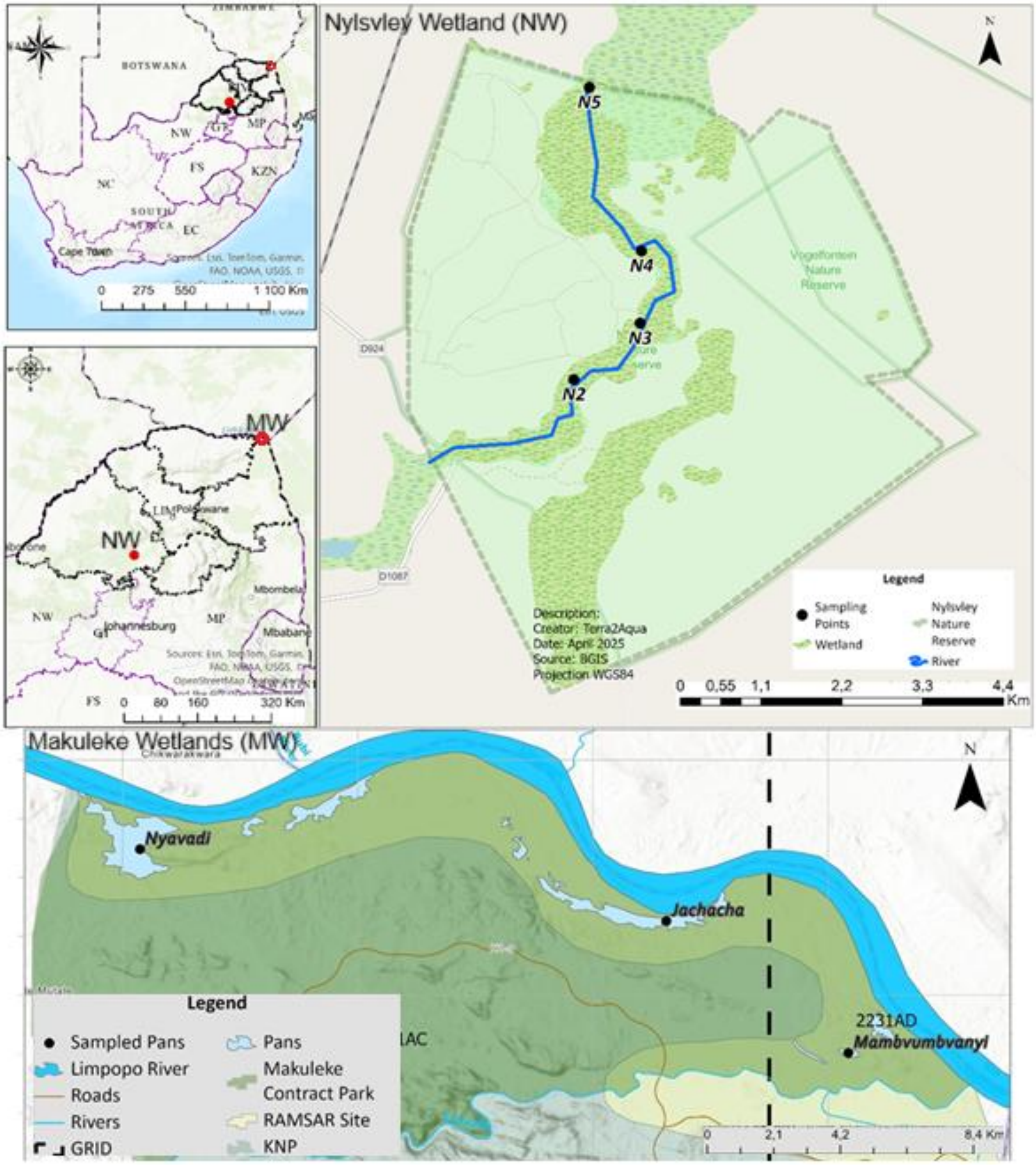


Figure 4.1. Study area map of Makuleke and Nylsvley wetlands in the Limpopo Province of South Africa

The Nylsvley Wetlands, situated in South Africa's Limpopo Province within the Waterberg District Municipality (24º39’17” S, 28º42’28” E) (Figure 1b), were classified as a Ramsar wetland site in 1998 (Dzurume et al., 2022). Characterized by vast reed beds and grassy plains, it is surrounded by expansive savanna woodlands. Positioned between 1080 and 1155 meters above sea level, Nylsvley Nature Reserve receives average annual rainfall of 620 mm, with a yearly mean temperature of 19ºC. The maximum temperature in summer ranges from 21 °C to 29 °C, whereas the minimum temperature in summer varies between 17 °C in January and 4 °C in July (Dzurume, 2021). The Nylsvley Nature Reserve protects the floodplain from Middelfontein to Moorddrift towns (Dzurume et al., 2021; Makhuvha, 2021; Dzurume, 2022). The Nyl River floodplain consists of small grassy plains, large stands of rice grass, open water fields, reed beds, marshes, and forests.

4.2 Data collection

Sediment core samples were collected from 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm using a hand auger after clearing surface debris following methods described by Dalu et al. (2020) and Mutshekwa et al. (2023). Within each wetland, three representative sampling sites were purposively selected based on varying degrees of anthropogenic influence and hydrological characteristics. In Makuleke Wetlands, sites were selected to reflect gradients from areas near river inflows (with higher hydrological connectivity and potential pollutant transport) to interior, less-disturbed zones. In the Nylsvley Wetlands, site selection was considered in relation to proximity to agricultural fields, reed-dominated areas, and open floodplain regions to capture spatial variability in potential microplastic deposition. This stratified selection enabled a more comprehensive assessment of microplastic distribution across various wetland conditions.

The hand auger was inserted vertically into the soil to extract undisturbed sediment layers, ensuring consistent depth and minimal cross-contamination between layers. To prevent cross-contamination between successive cores, the auger was thoroughly decontaminated after each sampling event. This involved rinsing with distilled water, washing with laboratory-grade detergent, followed by a second rinse with distilled water. The equipment was then wiped with 70% ethanol and air-dried before the next core was collected. All cleaning materials were non-plastic, and procedural blanks were included to account for potential airborne contamination during sampling. Background samples (*n* = 10 per site) were randomly collected from nearby wetlands with minimal human activity for comparison. Each sample was stored in polyethylene Ziploc bags and transported to the University of Mpumalanga laboratory, where it was oven–dried at 50°C for 48–72 hours to remove moisture.

The dried sediment was crushed with a porcelain mortar and sieved through a 0.05 mm mesh to remove plant roots and debris. A portion of 250 g per sample was measured and stored in a 2 2-litre glass jar. The sediment was subjected to density separation for microplastic analysis using zinc chloride to isolate microplastics (Rodrigues et al., 2020). The sediment solution was left undisturbed for 24 hours to allow heavier particles to settle, and the floating material, which contained suspected microplastics, was filtered through filter paper. The filter paper was stored in petri dishes and allowed to dry before being identified under a stereo microscope at magnifications ranging from 10 to 80, with the field of view calculated at ×20 magnification (Wang and Wang, 2018; Kutralam–Muniasamy et al., 2018; Dalu et al., 2023).

4.2.1 Microplastic quantification

Microplastics were classified into the following commonly used morphological shapes: fibre, fragment, film, foam, and bead (Norén and Linell, 2007). Colors were also classified into the following categories: black, blue, white, green, yellow, red, transparent, and other, which are representative of the colours commonly observed in most microplastic–aquatic studies (Barrows et al., 2018). Particles were considered microplastics if they had unnatural coloration (e.g., bright coloration, multi–coloured) and/or unnatural shape (e.g., sharp edges, perfectly spherical; Hidalgo–Ruz et al., 2012). Because visual inspection alone was insufficient for characterizing and quantifying microplastics, additional physical analyses were performed (Mintenig et al., 2017). As such, selected microplastic particles were subjected to vibrational Platinum–ATR FTIR using a Bruker Alpha model (Germany). This method makes available libraries for identifying microplastic polymers and is more efficient for dense samples (Pico and Barceló, 2019). All sample processing was conducted under clean laboratory conditions to ensure accuracy and prevent external contamination. Cotton laboratory coats were worn, tools were rinsed with filtered distilled water between samples, and procedural blanks were included to detect any airborne or handling–related contamination.

4.3 Data analysis

Generalized linear mixed models were used to analyze microplastic counts based on types and colors across depths (i.e., 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm) and between wetland locations (i.e., Makuleke and Nylsvley wetlands), as well as for the two–way depth–location interaction. Sites within locations were included as a random effect to account for repeated measurements by depth within each core. Using simulation tests, residuals were checked for overdispersion and zero inflation (Hartig, 2024). A negative binomial error family was suitable for addressing residual diagnostic issues. Separate models were fitted for total microplastic loads and for each particle type and color, with a significance level of 0.05.

4.4 Results

4.4.1. Microplastic abundances between the two wetlands

Sediment cores collected from the Makuleke and Nylsvley wetland systems revealed variation in microplastic distribution, including abundance, type, and color (Figure 2). A mean count of 31.84 particles kg–1 microplastics was found in the Nylsvley Wetlands, while 49.04 particles kg–1 was found in the Makuleke Wetlands microplastic samples. Fragment and film particles drove the overall significant differences between locations (Figure 2a), with fragments almost twice as prevalent in Makuleke Wetlands (mean 12.48 particles kg^{-1}) compared to Nylsvley Wetlands (mean 6.4 particles kg^{-1}). Film particles were similarly approximately doubled in Makuleke Wetlands (mean 8.56 particles kg–1) compared to Nylsvley Wetlands (mean 3.28 particles kg–1) (Figure 2a). Black particles were the most common (mean 8.68 particles kg^{-1}), followed by white (mean 8.2 particles kg^{-1}), yellow (mean 7.52 particles kg–1), transparent (mean 6.4 particles kg–1), green (mean 3.48, particles kg^{-1}), blue (mean 3.04 particles kg^{-1}), and red (mean 3.12 particles kg^{-1}) (Figure 2b). For yellow particles, abundances were significantly greater at Makuleke Wetlands (mean = 9.92 particles kg^{-1}) than Nylsvley Wetlands (mean 5.12 particles kg^{-1}).

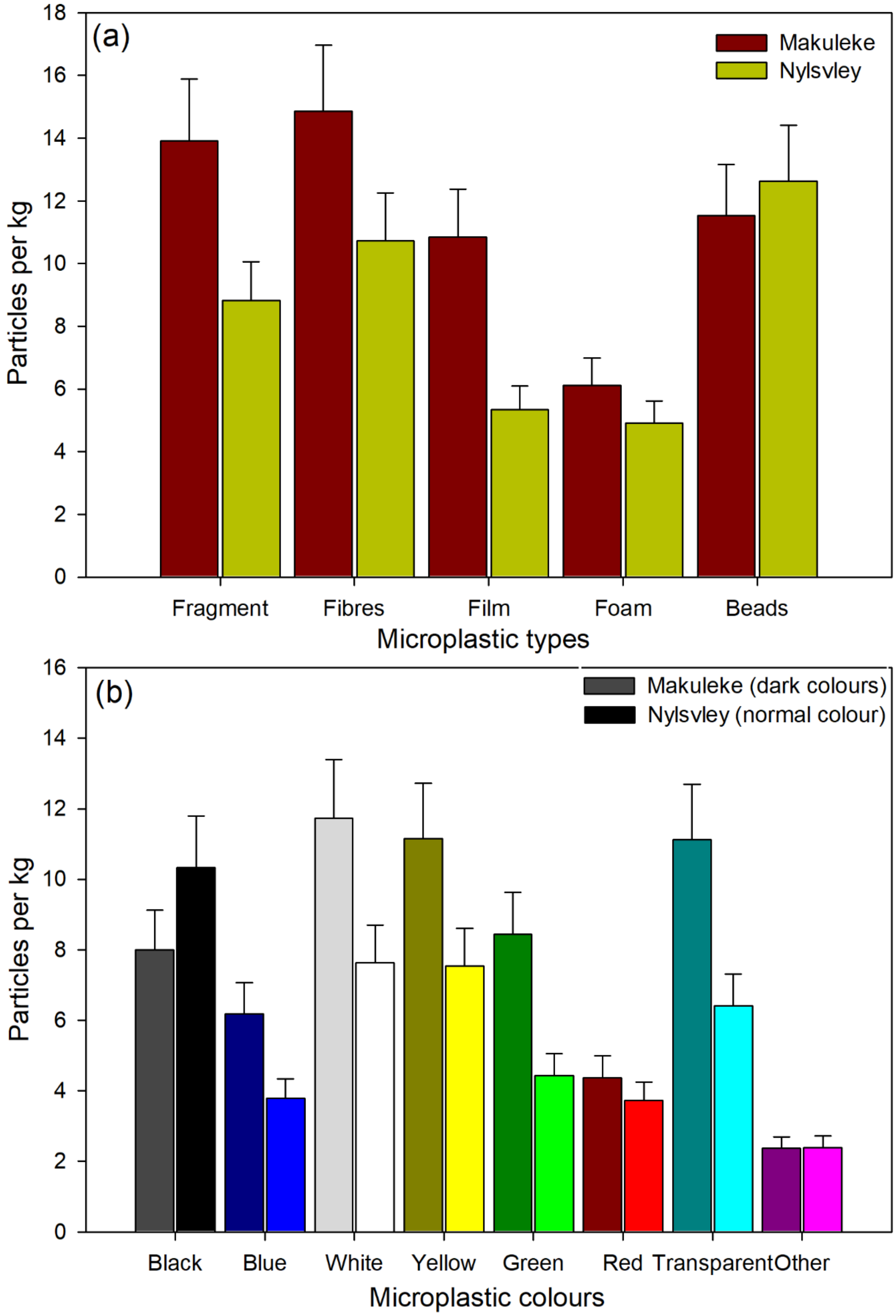


Figure 4.2. Microplastic abundance in Makuleke and Nylsvley wetlands (a) Microplastic type (b) Microplastic colours.

4.4.2 Microplastic abundance across sediment depths between the wetlands

At Makuleke Wetlands, microplastic counts were generally high, with the 0–20 cm depth averaging around 20 particles and the 20–40 cm depth showing a peak of up to 45 particles (Figure 3). The deepest layers at Makuleke Wetlands (80–100 cm) also exhibited some variation, with counts ranging from 10 to 15 particles, suggesting the potential for past deposition or sediment disturbance. In contrast, Nylsvley Wetlands exhibited consistently lower and more stable microplastic levels across sediment depths, with counts averaging between 5 and 10 particles at all layers, except at 20–40 cm and 80–100 cm, where a slight increase was observed (up to 12 particles) (Figure 3). A significant difference was found between the wetland locations in total microplastic counts ($z = 2.915$, $p = 0.004$), with Makuleke Wetlands having significantly higher microplastic concentrations than Nylsvley Wetlands. Although mean microplastic counts varied from 8.70 to 11.85 across depths, no significant differences were observed by depth ($z = 1.431$, $p = 0.152$), and the interaction between location and depth was also not significant ($z = 1.813$, $p = 0.07$). However, at the shallowest layer, the Makuleke Wetlands exhibited notably higher concentrations (mean = 13.5) than the Nylsvley Wetlands (mean = 5.7), although the difference narrowed at deeper layers.

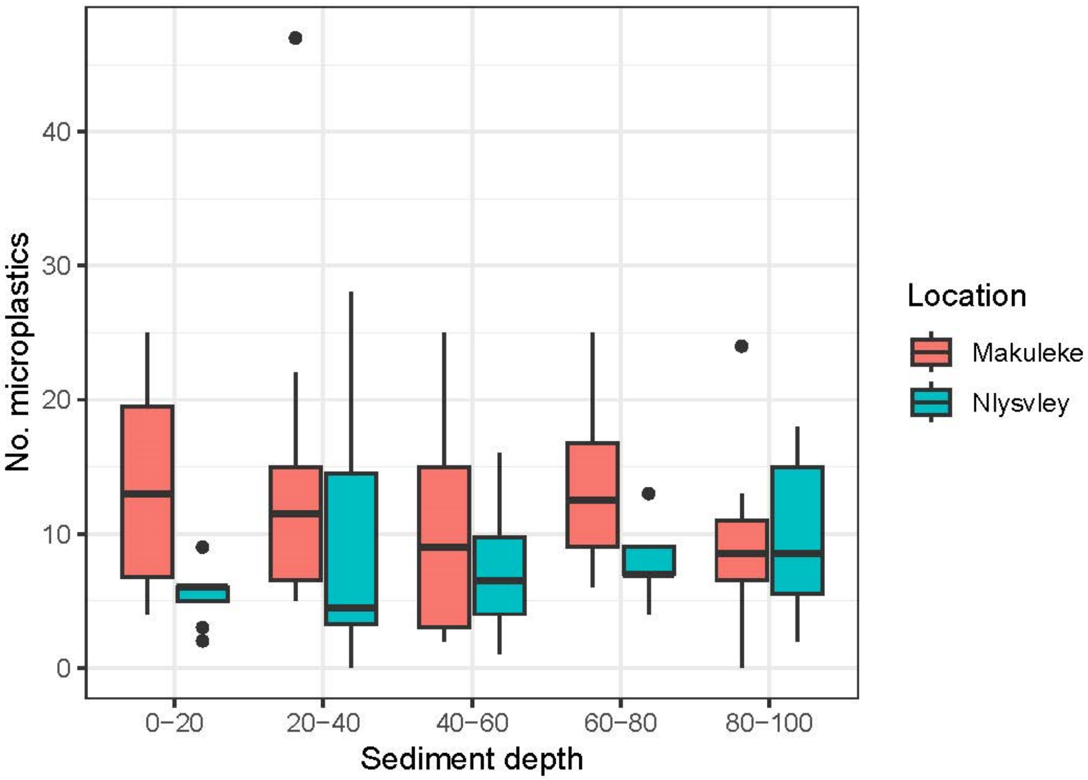


Figure 4.3. Microplastic abundance from sediment per depth (0–100 cm) from Makuleke and Nylsvley Wetlands.

Differences between the two wetlands were further mediated by microplastic type and colour (Table 1). Fragment counts revealed a significant difference between locations (p = 0.039), indicating that site–specific factors, such as land use or pollution sources, influence their abundance, whereas depth had no effect. Film–type microplastics were significantly influenced by both location ($p = 0.002$) and the interaction between location and depth ($p = 0.038$), indicating that their vertical distribution varies between wetlands, possibly due to differences in deposition patterns or hydrodynamics (Table 1). In contrast, fibers, foams, and beads did not show significant variation with either depth or location, suggesting a more uniform or random distribution across sediment profiles and sites. These findings highlight the heterogeneous nature of microplastic contamination and suggest that each plastic type has distinct sources or transport mechanisms within wetland environments. However, it is important to interpret marginally significant results with caution. Because multiple statistical tests were conducted across several variables (microplastic types, colours, locations, and depths), the probability of Type I errors increases.

Consequently, p-values close to the 0.05 threshold (e.g., $p = 0.039$ and $p = 0.038$) may reflect potential false positives if adjustments for multiple comparisons, such as Bonferroni or Benjamini–Hochberg corrections, are not applied. Future analyses could incorporate these correction methods to further validate the robustness of the observed patterns.

Table 4.1. Generalised linear mixed model results (negative binomial) considering counts of microplastics by type among wetland locations and sediment core depths. Significant variables are highlighted in bold font.

Model	**Variable**	***z*–value**	***p*–value**
(a) Fragment	Depth	0.035	0.972
	Location	**2.066**	**0.039**
	Location × Depth	1.148	0.251
(b) Fibre	Depth	1.167	0.243
	Location	0.908	0.364
	Location × Depth	0.144	0.886
(c) Film	Depth	1.450	0.147
	Location	**3.089**	**0.002**
	Location × Depth	**2.076**	**0.038**
(d) Foam	Depth	0.491	0.624
	Location	0.544	0.586
	Location × Depth	0.518	0.604
(e) Bead	Depth	0.491	0.624
	Location	0.544	0.586
	Location × Depth	0.518	0.604

For most microplastic colors, namely black, blue, white, green, red, and transparent, there were no statistically significant effects of depth, location, or their interaction on particle counts ($p > 0.05$) (Table 2). This finding suggests a consistent distribution pattern across the two wetland sites and depth layers for these colors. In contrast, yellow microplastics exhibited statistically significant differences across variables. The effect of location was substantial, indicating that particle abundance differed between the Makuleke and Nylsvley wetlands (Table 2). Additionally, the interaction between location and depth was also significant, indicating that the influence of sediment depth on yellow microplastic counts varies across different wetland sites. Although depth alone was insignificant, the significant interaction underscores a complex, site–specific pattern of yellow microplastic deposition. These findings underscore the importance of spatial context and depth in understanding the distribution of specific microplastic types in freshwater environments.

Table 4.2. Generalised linear mixed model results (negative binomial) considering counts of microplastics by type among wetland (Makuleke and Nylsvley) locations and particle color. Significant variables are highlighted in bold font.

Model	Variable	z–value	p–value
(a) Black	Depth	1.638	0.101
	Location	0.700	0.484
	Location × Depth	0.478	0.633
(b) Blue	Depth	1.017	0.309
	Location	1.084	0.278
	Location × Depth	0.850	0.395
(c) White	Depth	0.182	0.855
	Location	1.545	0.122
	Location × Depth	1.122	0.262
(d) Yellow	Depth	1.611	0.107
	Location	**3.140**	**0.007**
	Location × Depth	**2.579**	**0.010**
(e) Green	Depth	0.383	0.702
	Location	0.454	0.650
	Location × Depth	0.094	0.925
(f) Red	Depth	1.831	0.067
	Location	1.315	0.188
	Location × Depth	0.738	0.461
(g) Transparent	Depth	1.636	0.102

	Location	1.353	0.176
	Location × Depth	0.716	0.474

4.5 Discussion

This study assessed the distribution and dynamics of microplastics across sediment depths (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm) in two Ramsar–designated wetland systems, Makuleke and Nylsvley, in South Africa. The results indicate that pollutants are widespread through these depth profiles, while identifying certain significant differences in microplastic abundance, type, and colour between the study systems. Makuleke wetland exhibited generally higher microplastic concentrations than Nylsvley wetland, with more pronounced vertical variation in sediment layers, likely due to increased anthropogenic pressures and stronger hydrological connectivity. The site's proximity to and interaction with the Limpopo River likely facilitate the influx and deposition of microplastics from upstream sources, such as urban runoff, agricultural inputs, and waste discharge (Browne et al., 2010; Waldschläger et al., 2020). This enhanced connectivity transforms Makuleke into a microplastic sink, especially during high–flow events, allowing for the accumulation of diverse particle types. In contrast, Nylsvley Wetlands' relative hydrological isolation could limit external microplastic input, resulting in lower, more uniform concentrations throughout its sediment profile. These observations highlight how localised land use and hydrological features directly influence microplastic pollution patterns in wetland systems.

Wetlands often function as natural filtration systems; however, the presence of microplastics in these Ramsar–protected areas highlights the extent of anthropogenic impact, even within conservation zones. Previous studies suggest that microplastic contamination can enter wetland systems through various pathways, including runoff, direct waste disposal, and waterway connectivity (Liu et al., 2018; Qian et al., 2021). In the Makuleke Wetlands, elevated microplastic concentrations in surface sediment layers indicate ongoing inputs, likely linked to upstream sources such as the Limpopo River, which receives waste from urbanized regions. Additionally, increased tourism activity at the Makuleke Wetlands, given its status as a 'Big Five' conservation area, may contribute to microplastic deposition through indirect environmental disturbances (Nel and Froneman, 2015).

Further supporting the first hypothesis, microplastic abundance peaked at the 20–40 cm sediment layer in Makuleke wetlands, reaching up to 45 particles kg^{-1}. This suggests localised accumulation hotspots, potentially influenced by hydrological connectivity and external pollution sources, including urban runoff. In contrast, Nylsvley Wetlands exhibited a more stable microplastic distribution, with values averaging 5-10 particles kg^{-1} across sediment depths. A slight increase at 80–100 cm (up to 12 particles kg^{-1}) suggests gradual deposition or sediment mixing, reinforcing site–specific differences in microplastic retention mechanisms (Browne et al., 2010; Waldschläger et al., 2020). These findings align with previous studies reporting higher microplastic accumulation in wetlands with greater hydrological connectivity to urban and industrial sources (Zhang et al., 2025).

The separation of microplastic types, including fibres, beads, fragments, films, and foams, was undertaken to understand both the sources and environmental behavior of microplastic pollution within the wetland ecosystems studied. This distinction is not merely taxonomic; it plays a critical role in interpreting the ecological dynamics of contamination. Different microplastic forms are associated with different origins, degradation processes, transport behaviours, and potential ecological impacts. For example, fibres, which were the most abundant type found across both wetlands, are typically sourced from synthetic textiles and enter the aquatic environment primarily via wastewater effluent. Similarly, beads that followed closely in abundance are linked to cosmetic products and industrial abrasives. Their near–equal presence across the two wetlands suggests a common regional exposure through similar domestic and municipal wastewater pathways.

The observed abundance of fragments and films in Makuleke Wetlands compared to Nylsvley Wetlands reflects differences in local waste inputs and in the dynamics of environmental degradation. Fragments, resulting from the breakdown of larger plastic items, are more common under conditions that promote physical weathering, such as intense ultraviolet (UV) exposure and hydrological movement, which accelerate polymer embrittlement and fragmentation (Gao et al., 2024; Belone et al., 2021). Films, often originating from agricultural mulches or single–use plastics, tend to accumulate in wetland sediments, where land–use practices adjacent to the Makuleke Wetlands may increase their introduction and persistence (Alimi et al., 2021). Together, these site–specific patterns highlight how both the source material and the environmental context, such as UV–driven photodegradation and land management, influence the spatial distribution of different microplastic types in wetlands.

While microplastic MPs were generally distributed similarly across depths between locations, the study observed a few significant depth–location interaction effects, particularly for film particles, which emphasizes the role of depositional dynamics in influencing microplastic retention and distribution. Wetlands, by nature, are dynamic environments characterized by sedimentation. The interaction suggests that site–specific processes, such as sediment trapping, water flow velocity, or episodic flooding, may influence the vertical and lateral movement of lighter plastic types, including films, which are more likely to remain suspended or be redistributed through resuspension events. This observation aligns with findings from constructed wetland studies, such as those by Lu et al. (2023), which demonstrate that wetlands function as both sinks and transport systems for microplastics.

The observed colour–based variation in microplastic distribution, particularly the prominence of black and white particles, may reflect dominant local sources such as degraded vehicle tyres, road runoff, or domestic plastic waste, aligning with findings from Eerkes–Medrano et al. (2015) and Qian et al. (2021) that associated microplastic prevalence with land–based inputs and differential transport mechanisms. The contrasting depth–dependent trends of yellow microplastics between the Makuleke and Nylsvley Wetlands, decreasing in one and increasing in the other, further support the notion of site–specific deposition dynamics likely driven by distinct hydrological conditions, land–use patterns, or sedimentation processes. Gupta and Pandey (2024) similarly noted that microplastic accumulation in inland wetlands is strongly influenced by agricultural runoff and domestic waste, which may explain the variability in deposition rates and colour profiles observed between the two study sites. These findings highlight the importance of considering both environmental and anthropogenic factors when interpreting the distribution of microplastics in freshwater wetlands.

The second hypothesis, predicting higher microplastic concentrations in deeper sediment layers, was partially supported. Although the Makuleke Wetlands exhibited strong accumulation in surface sediments (0–20 cm and 20–40 cm), the deepest sediment layer (80–100 cm) contained lower microplastic counts (mean 10–15 particles kg^{-1}), suggesting limited vertical transport. In contrast, the Nylsvley Wetlands demonstrated a gradual increase in microplastic abundance at the deepest layer, indicating potential sediment mixing or prolonged retention (Dalu et al., 2019). However, our statistical analysis did not reveal a significant effect of depth on overall microplastic abundance, suggesting that other environmental factors, such as organic matter retention and hydrological variability, may be influencing microplastic deposition (Qian et al., 2021). These findings align with studies on microplastic retention in wetland soils, which highlight the roles of sediment composition and microbial interactions in determining microplastic fate (Zhang et al., 2025).

These findings highlight the complex interactions among anthropogenic activities, hydrological connectivity, and sedimentation processes that affect microplastic retention in wetland systems. Despite their protected status, both wetlands remain vulnerable to external sources of pollution, including agricultural runoff, wastewater discharge, atmospheric deposition, and trophic interactions. The results underscore the need for integrated watershed management approaches that extend beyond conservation boundaries to mitigate broader pollution risks. Further research should investigate the transport mechanisms of microplastics, their interactions with aquatic biota, and potential remediation strategies in wetland ecosystems.

4.6 Conclusions

This study reveals vital information about the dynamics and distribution of microplastics in South African wetland sediment systems, which have been recognized as Ramsar sites. The results highlight how anthropogenic effects and hydrological connectivity shape contamination levels, revealing notable variations in microplastic abundance, type, and color between the Makuleke and Nylsvley Wetlands. The Nylsvley Wetlands exhibited a more consistent accumulation pattern, suggestive of controlled environmental inputs, whereas the Makuleke Wetlands' higher microplastic content indicates greater exposure to pollution sources, possibly influenced by urban runoff and tourism–related activities. The results showed that microplastic load was highest in the surface layers, especially at the Makuleke Wetlands, contradicting the study's hypothesis that deeper sediment layers would have higher concentrations due to long–term deposition. According to this, microplastic retention is impacted by environmental interactions such as sediment turnover and hydrological movement, indicating ongoing input rather than stable burial. Considering the ecological significance of wetlands, more research is needed to examine pollutant transport pathways, mitigation techniques, and the long–term ecological effects of microplastic retention. Furthermore, to successfully reduce microplastic pollution, conservation management must extend beyond protected areas and incorporate more comprehensive watershed protection measures. This study contributes to the broader conversation on freshwater plastic pollution by expanding our understanding of microplastic sediment dynamics, emphasizing the need for sustainable environmental policies.

CHAPTER 5: GENERAL SYNTHESIS

5.1 Introduction

This chapter synthesizes key findings from previous chapters of this research project. This involves summarizing key findings, conclusions, and implications from each part to provide a comprehensive overview of the research findings.

5.2 General discussion

Wetlands are unique ecosystems formed by the interaction of aquatic and terrestrial ecosystems, playing a crucial role in maintaining ecological balance, conserving biodiversity, and reducing pollutants (Hamidian et al., 2016; Long et al., 2022). Their vegetation and sediment structure enable the effective retention of microplastics, making these environments potential reservoirs for plastic particles (Li et al., 2018; de Smit et al., 2021; Yin et al., 2021; Martuscelli et al., 2025). Consequently, wetland sediments act as both sinks for microplastics and hotspots for plastic pollution (Sruthy and Ramasamy, 2017; Abidli et al., 2019). Understanding the mechanisms of microplastic retention and accumulation in wetlands is therefore vital for assessing their ecological vulnerability and their role in global plastic cycling.

Plastic pollution has emerged as one of the most pressing environmental challenges of the 21st century, driven by the exponential increase in global plastic production and consumption. This increase has led to substantial quantities of plastic waste entering natural ecosystems, where it persists and accumulates (Dalvand et al., 2023). Ubiquity and persistence of plastics have made them a central focus of environmental research. Plastics are synthetic organic polymers composed of long-chain molecules with high molecular weights, derived from hydrocarbons sourced from fossil fuels, although bio-based alternatives are now under development (Law, 2017). Their chemical composition, molecular structure, and the presence of manufacturing additives govern their behavior and interactions within the environment (Lambert and Wagner, 2016).

The degradation and weathering of plastics are influenced by environmental factors, including sunlight, temperature, and biological activity. Among these, photooxidation driven by ultraviolet (UV) radiation is the most critical process promoting polymer breakdown (Andrady, 2017).

Additives within plastics can either inhibit or accelerate this process; for example, surface biofilms can reduce UV penetration by up to 99 %, significantly slowing degradation (Weinstein et al., 2016). Conversely, certain additives, such as brominated flame retardants, can enhance UV absorption, increasing the rate of photooxidation (Khaled et al., 2018). As larger plastic items (macroplastics) undergo degradation, they fragment into smaller pieces known as microplastics, which vary in morphology, including fragments, fibres, foams, films, and beads (Lambert and Wagner, 2016; Hartmann et al., 2019). These microplastics, and eventually nanoplastics (<1 μm), exhibit diverse behaviours in aquatic systems, influenced by their size, density, and shape. High-density polymers such as polystyrene (PS: 1.04–1.07 g cm^{-3}), polyvinyl chloride (PVC: 1.20–1.70 g cm^{-3}), and polyethylene terephthalate (PET: 1.36–1.37 g cm^{-3}) tend to sink, while lower-density plastics such as polyethylene (PE) and polypropylene (PP) often remain buoyant (Bond et al., 2018). However, the attachment of biofilms and the formation of heteroaggregates can increase the sinking rate of even low-density plastics, leading to their accumulation in intertidal and sedimentary environments (Paduani, 2020).

The settling dynamics of microplastics depend not only on density and size but also on particle morphology. For example, fibrous and irregularly shaped particles often deviate from the sinking rates predicted by Stokes' Law due to enhanced drag and aggregation effects (Johnson et al., 1996; Khatmullina and Isachenko, 2017). In natural systems, such as wetlands and estuaries, high concentrations of suspended colloids and organic matter facilitate heteroaggregation, promoting microplastic sedimentation (Quik et al., 2014; Zhu et al., 2014). However, further empirical studies are required to elucidate how organic matter content and hydrodynamic conditions influence microplastic deposition and resuspension within these environments (Lo et al., 2018; R. Li et al., 2019). Once deposited, plastic particles may remain buried in sediments or be resuspended by tidal action and bedload transport, thereby redistributing across wetland and estuarine systems. This study aimed to assess and compare the dynamics of microplastic abundance in water and sediment, including sediment cores, of two Ramsar-declared wetlands in South Africa, Makuleke, located in Kruger National Park, and Nylsvley, located in Nylsvley Nature Reserve, in the Limpopo province, during low and high hydroperiods, to determine how hydrological conditions influence their distribution.

Chapter two of this study reveals that there is extensive microplastic contamination in rivers, lakes, and reservoirs across the African continent, with polyethylene, polypropylene, and polystyrene being the most common polymers. Microplastics were more commonly detected in sediments than in water. According to a study conducted by Amrutha and Warrier (2020), the increased prevalence of PE in environmental matrices, such as water and sediments, can be attributed to its global use as a packaging material and its primary use as a plastic raw material. PE and PP are widely used in the packaging sector; their presence in surface waters may indicate the urban origin of microplastics (Sadri and Thompson, 2014). In 7% of studies, polystyrene was identified as the primary polymer in wetland water and sediments, but not in biota. According to Wu et al. (2020), polystyrene foams typically float in water, while polystyrene pieces prefer to sink into wetland sediments.

Chapter three results showed that both Makuleke and Nylsvley Wetlands exhibited substantial microplastic contamination, with sediments serving as major sinks. According to Dalvand and Hamidian (2023), local hydrodynamics influence the dispersion and accumulation of microplastics in the bottom sediments of wetlands, with microplastics tending to accumulate in low-dynamic locations. Fibres, fragments, and beads were the dominant morphotypes, while black, transparent, and white were the most prevalent colours in both wetlands across seasons. McIlwraith et al. (2024) noted that fibres and fragments represent the most frequently reported microplastic morphotypes across all environmental compartments, including water, sediments, and biota, within wetland ecosystems. Among these, the proportion of fibrous microplastics is higher in water and biological samples compared to sediments.

Chapter three results also revealed that seasonal trends were significantly higher microplastic densities during the wet season, primarily driven by hydrological transport. According to Li et al. (2023), the sampling season plays a significant role in influencing the spatial and temporal distribution of microplastics in freshwater systems. Several studies have documented higher microplastic concentrations during wet seasons compared to dry periods (Eo et al., 2019; Ramirez et al., 2019), particularly following rainfall events that enhance surface runoff and riverine transport of plastics from terrestrial sources into aquatic environments.

Chapter four showed that the microplastics collected in sediment depth profiles revealed insignificant variation through the substrate, and with particularly high abundances of fibres and beads. The study conducted by Fu et al. (2020) revealed that the type of microplastic is a critical parameter for understanding its sources, transport dynamics, and bioavailability within aquatic systems. Fiber-shaped microplastics are often associated with textile and fishing-related sources and can be readily transported through water columns due to their low density and elongated form. Their dominance in biotic samples may be attributed to their relatively smaller size and flexible morphology, which enhance ingestion likelihood compared to other particle shapes. The results on the current study revealed that the microplastic counts were generally high, with the 0–20 cm depth, whereas the study by Ball, (2019) observed a decrease in microplastics in the most recent 10 cm of sediments, which might be attributed to reduced sediment availability and ongoing local erosion, and related intense storms to increases in microplastic concentrations where sediments were more variably sorted. Local microplastic inputs clearly interact with the biological processes they are superimposed on, as well as sediment cores.

Chapter four of this study provides critical insights into the occurrence, distribution, and behavior of microplastics in two ecologically significant Ramsar-declared wetlands in South Africa. The findings reveal that even protected ecosystems are not immune to diffuse plastic pollution sources, including atmospheric deposition, upstream runoff, and waste generated by tourism. This highlights that microplastic contamination is a pervasive environmental threat that transcends administrative boundaries. The study highlights the role of wetlands as both sinks and potential secondary sources of microplastics, depending on the dynamics of hydrology and sedimentation. The observed differences between the Makuleke and Nylsvley Wetlands illustrate how local hydrology, organic matter content, and sediment turnover govern the retention and redistribution of microplastics. These findings have broader implications for wetland conservation, indicating that plastic pollution management must be integrated into watershed-level policies. Furthermore, the study contributes baseline data for southern African wetlands, which are underrepresented in global freshwater plastic pollution research. These results can inform environmental monitoring frameworks, guide ecological risk assessments, and support the development of sustainable waste management and conservation policies in developing regions.

The overall research achieved its objectives; several limitations must be acknowledged. First, the sampling was spatially and temporally limited to two wetlands and two hydrological seasons, which may not capture the full spectrum of seasonal variability in microplastic input and transport, although the use of density separation and FTIR analysis provided reliable particle identification, it is possible that very fine nanoplastic particles (<1 μm) were not fully captured due to methodological detection limits. Additionally, the study did not include biological assessments to determine the extent of microplastic ingestion or bioaccumulation within wetland biota. Including such biological components could provide a more holistic understanding of ecological risks. Lastly, the lack of standardized global protocols for microplastic sampling and quantification introduces challenges in directly comparing results with other studies.

Based on the findings from both chapters, several recommendations were made to enhance the understanding, management, and mitigation of microplastic pollution in freshwater wetlands. Firstly, future management efforts should adopt an integrated catchment-based approach, recognizing that wetlands are directly influenced by activities occurring within their surrounding watersheds. Improved waste management, effective control of agricultural runoffs, and enhanced wastewater treatment systems are critical steps in reducing upstream sources of microplastics that eventually accumulate within wetland environments. Secondly, long-term, and seasonally consistent monitoring programs should be established to assess temporal variations in microplastic deposition in both water and sediment. Such continuous monitoring will enable the detection of pollution trends and provide early warnings for ecosystem degradation.

Future research should expand to include biological assessments that investigate the ingestion, accumulation, and potential effects of microplastics on wetland biota. This will provide a more comprehensive understanding of ecological risks, particularly in relation to food web dynamics and the impacts on biodiversity. Furthermore, the standardization of sampling, extraction, and quantification methodologies is urgently needed to ensure the comparability of results across studies and geographical regions. Developing harmonized protocols would improve the reliability and reproducibility of microplastic research within African contexts. Lastly, environmental policy frameworks should explicitly integrate the management of microplastic pollution within national and regional wetland conservation strategies. Public awareness and education campaigns are also essential for promoting behavioural change and reducing plastic use and disposal, particularly in communities and tourism-intensive areas adjacent to Ramsar sites, such as Makuleke and Nylsvley.

5.3 Conclusion

This study demonstrates that microplastic contamination is prevalent in both the Makuleke and Nylsvley Wetlands, despite their protected status as Ramsar sites. Sediments served as major sinks, with fibres, fragments, and beads being the most dominant morphotypes. Seasonal variation was a key factor, with higher concentrations recorded during the wet season, driven by hydrological transport and runoff. Nylsvley Wetland exhibited higher contamination and ecological risk than Makuleke, likely to reflect greater anthropogenic influence from surrounding land uses. These results emphasize that even well-managed conservation areas remain vulnerable to diffuse pollution sources. Overall, the research contributes valuable baseline data for understanding microplastic dynamics in African wetlands and reinforces the urgent need for integrated, cross-boundary management strategies to mitigate plastic pollution. Protecting wetlands such as Makuleke and Nylsvley is essential not only for maintaining biodiversity but also for preserving their function as ecological buffers in the fight against global plastic contamination.

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