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Microplastic Concentrations in Sediments and Waters Do Not Decrease in Two Rivers Flowing Through the Kruger National Park, South Africa

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Abstract Plastics are manufactured for various purposes but result in microplastic pollution in aquatic ecosystems. Riverine microplastic occurrence, spatial distribution, and impact have been globally documented but not well understood in Africa. We quantified 36 984 microplastics in riverbed sediment and river water along the Olifants and Sabie rivers, Kruger National Park (KNP), South Africa. These rivers have independent catchments. The microplastic profiles (size, polymer, morphotype, and colour) differed significantly between rivers. Riverbed sediment microplastic (mostly beads) concentrations ranged between 2022 to 9971 n/kg dm, and 2237 to 27 259 n/kg dm, for the Olifants and Sabie rivers respectively. Microplastic (mostly fragments) concentrations in river water ranged between 11 to 50 n/L in the Olifants River, and 4.0 n/L to 41 n/L in the Sabie River. Polyethylene terephthalate (PET) was prevalent in sediment (39%) and water (32%). Concentrations varied along both river stretches but the expected concentration decrease downstream was not observed. This raises transboundary concerns, as all the KNP rivers cross into Mozambique and from there into the Indian Ocean. Given the pervasive plastic pollution already present, there is a need for significant upstream and in-park interventions to reduce the concentration of microplastic in rivers flowing through conservation areas.

Keywords Freshwater · Sediment · Polymers · Olifants River · Sabie River · Transboundary

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1 Introduction

Microplastic particles are defined as plastic particles smaller than 5 mm in their longest dimension (Zhang et al., 2017). They are either manufactured as microplastics or result from the fragmentation of larger plastic particles (Wagner & Lambert, 2018).

Microplastic particles eventually reach the aquatic ecosystem including rivers by wind, illegal dumping of mismanaged solid waste, atmospheric fallout, traffic related activities, stormwater runoff or wastewater treatment plants (WWTPs) effluent, to name but a few (Hanekom, 2020; Iroegbu et al., 2020; Mason et al., 2016; Verster & Bouwman, 2020).

Microplastic pollution has received more attention in marine than in freshwaters (Rios Mendoza et al., 2018; Wagner & Lambert, 2018) as rivers were mostly considered vectors of microplastics to the marine environment (Siegfried et al., 2017). However, freshwater microplastic pollution research, including rivers, has recently garnered attention globally and in South Africa (Bouwman et al., 2018; Burger et al., 2024; Castañeda et al., 2014; Mbedzi et al., 2020; Nel et al., 2018; Nkosi et al., 2023; Saad et al., 2024; Wagner & Lambert, 2018). From a conservation area perspective, even less research has been done on freshwater microplastics in riverine systems of nature-protected areas (Mishra et al., 2021; Zhang et al., 2021).

The occurrence, concentrations, spatial distribution, and impact of microplastic particles in rivers are associated with adjacent soil hydraulic properties, river hydrology, local precipitation patterns, riverbed sediment type, and microplastic properties, to name but a few (Nizzetto et al., 2016; Yan et al., 2021). Soil hydraulic properties control water retention, water flow rate, and the fate of pollutants in soil (Guo, 2022). For instance, plastic-contaminated soil proximate to a river is susceptible to erosion. Inevitably therefore, microplastics will be washed into rivers. Therefore, the receiving water body is likely to accumulate microplastics from soil erosion with pollution hotspots developing near polluted areas (Hurley et al., 2018; Nizzetto et al., 2016). Although microplastics may create concentrated microplastic hotspots in riverbed sediments, flooding events also flush microplastics trapped in riverbed sediment (Hurley et al., 2018; Hurley & Nizzetto, 2018; Tibbetts et al., 2018) transporting them downstream and eventually to the ocean (Kumar & Varghese, 2021).

Riverbed sediment and microplastic characteristics play a role in microplastic retention. Larger microplastic sizes settle in riverbed sediments more quickly than small microplastic particles because some large microplastics are not as buoyant (Wagner & Lambert, 2018). Microplastic concentrations also tend to increase as riverbed sediment particle size decreases because fine sediments retain more microplastics than coarse sediment (Duis & Coors, 2016; Tibbetts et al., 2018). Some of the microplastic particles that are suspended in river water eventually settle in riverbed sediment, depending on microplastic properties and particle size (Van Cauwenberghe et al., 2015; Corradini et al., 2019).

Microplastic abundance in rivers is also associated with human population size and concomitant anthropogenic activities proximate to freshwater bodies (Fu & Wang, 2019; Horton et al., 2017; Mbedzi et al., 2020). Horton et al. (2017) recorded high concentrations (660 particles n/kg dm) of plastic pollution in sediment from a site situated next to an area with a high human population density and located downstream of WWTP effluent. The Yangtze River in China is one of the river systems with high concentrations of microplastic pollution, Fu & Wang (2019) recorded up to 32 947 n/kg dm microplastics in riverbed sediment. Mbedzi et al. (2020) also showed a positive correlation between human population and microplastic particle densities.

The Kruger National Park (KNP) is South Africa's largest protected natural area with five major rivers flowing through it (O'Keeffe & Rogers, 2003). These rivers originate outside the KNP borders flowing west to east and are impacted by inter alia mining, agriculture, residential areas, WWTPs, and transportation activities. These activities are sources of microplastic pollution that may enter the rivers before reaching the KNP. There are also potential microplastic sources within the KNP such as transport and WWTPs. All five rivers flow through Mozambique into the Indian Ocean, potentially transporting microplastics from South Africa across an international boundary and thence onto international waters. In this study, we quantify, characterise, and compare microplastic particles in riverbed sediment and river water within and between two independent major rivers in KNP. The Olifants and Sabie rivers have adjacent but not shared catchments. Due to a presumed lack of any major microplastic sources within the KNP, we predict decreasing microplastic pollution concentrations due to progressive microplastic retention in riverbed sediments and consequently water from where the rivers enter the KNP.

2 Materials and Methods

2.1 Study Area

The KNP is a semi-arid protected area in the north-east of South Africa where it borders Mozambique to the east, and Zimbabwe to the north. Five perennial rivers, each with their own catchments, flow west to east through the KNP (O'Keeffe & Rogers, 2003). The rivers' catchments have different sizes and land use activities. Here, we selected two of the five rivers, the Sabie and Olifants rivers. The Olifants River has a large catchment surrounded by mining, agriculture, and forestry whilst the Sabie River has agriculture and forestry as the main activities (Biggs et al., 2017). Both rivers are surrounded by growing human populations. However, the Olifants River catchment has a high human residential density stretching from the Highveld before it reaches the KNP (Statistics South Africa, 2019). The catchment length for the Olifants and Sabie rivers is 840 km and 189 km, respectively. Approximately 90% of the Olifants river-length and 37% of the Sabie River river-length (within South Africa) falls outside the KNP (O'Keeffe & Rogers, 2003; Pollard et al., 2011). Within the KNP, there are tourist camps, traffic, and construction activities that are likely microplastic sources (Supplemental Figs. S1 and S2).

2.2 Sample Collection

2.2.1 Riverbed Sediment Sample Collection

Riverbed sediment sampling was conducted during low flow conditions (0.9 m^3/s flow for the Olifants River, and 2.2 m^3/s flow for the Sabie River), from 6 to 21 September 2018 at the same sites (Table 1 and Supplemental Fig. S1). Low-flow conditions are better suited for sediment sampling because the sediment is less disturbed. Sediment samples were collected using an unpainted stainless-steel hand trowel. Sub-samples of approximately 500 g of the top 5 cm river sediment were collected at five points from the shoreline at each sample site, 0.5 m apart. All five sub-samples were then mixed into a single sample per site. The sediment was stored in aluminium foil, labelled, and then transported to the research laboratory at Skukuza, the main camp in the KNP.

2.2.2 River Water Sample Collection

Water samples were collected after a high rainfall event (56.3 m^3/s flow in the Olifants River, and 47.6 m^3/s flow in the Sabie River) from 9 to 15 January 2019 at nine sites in each river (Fig. 1, Table 1, and Supplemental Fig. S1). Sample sites are numbered from S1 to S9 (Sabie River) and O1 to O9 (Olifants River) located from the west (upstream of KNP) to the east (KNP boundary with Mozambique). Sample site selection at each river was mainly guided by accessibility and proximity to tourist camps, staff residential areas, or WWTPs. Both tourist camps and residential areas were considered during sample site selection because they are potential sources of microplastic pollution such as mismanaged waste, paint chips, and stormwater runoff (Hernandez et al., 2017; Horton et al., 2017; Nel et al., 2018; Wang et al., 2017). River water samples were collected from both Olifants (O1) and Sabie (S1) rivers upstream outside of the KNP boundary to quantify the concentrations of microplastic particles entering the KNP.

A stainless-steel bucket was used to collect river water at < 50 cm depth. Ninety litres of river water were sieved through a 25 µm sieve. The residue on the sieve was then decanted into a pre-rinsed 500 ml SIMAX glass bottle. Sampling equipment was rinsed with river water before each sample collection to minimize contamination.

2.2.3 Microplastic Sample Contamination Control

Procedural precautions were taken to minimize laboratory microplastic contamination. A cotton laboratory coat was worn, and the laboratory air conditioner was switched off during extraction and analysis. Deionized water used for microplastic extraction was prefiltered through a 47 mm diameter, 0.45 µm pore size cellulose filter paper using a 47 mm Merk Millipore glass vacuum filtration system. Extraction solutions were prepared in glass containers. Samples were extracted using glass flasks and test tubes. Additionally, test sieves were thoroughly rinsed with prefiltered deionized water before sieving each sample. Procedural blanks (petri dishes left open during procedures) were included with all sample batch. Following the microplastic extraction process, the samples and procedural blanks were kept in glass petri dishes until counted and characterised.

Table 1 Sample site location, catchment size, and adjacent land use description along the Olifants and Sabie River

River	Sample site	Location	Adjacent	Catchment Size (km^2)
Olifants	O1	4.7 km upstream from the KNP western boundary	Private game reserves, urban, mining, and KNP natural vegetation	54570
Olifants	O2	4.0 km downstream from KNP border	Urban, private game reserves, and KNP natural vegetation	54570
Olifants	O3	35 km downstream from KNP western boundary	KNP natural vegetation	54570
Olifants	O4	8.5 km downstream from the tourist road	KNP natural vegetation, tourist tar road	54570
Olifants	O5	Olifants high water bridge	KNP natural vegetation, viewpoint, and Satara–Olifants tourist road	54570
Olifants	O6	Balule low water bridge	KNP natural vegetation, Balule trails camp, and tourist road	54570
Olifants	O7	1 km upstream from the Olifants tourist camp	KNP natural vegetation, Olifants tourist camp, and water abstraction site	54570
Olifants	O8	5.2 km downstream from Olifants tourist camp	KNP natural vegetation, WWTP, and Tourist camp	54570
Olifants	O9	6.0 km upstream from KNP eastern boundary	KNP natural vegetation, Klein Letaba River, and KNP Eastern boundary	54570
Sabie	S1	5.0 km upstream from KNP western boundary	Semi urban area, Mkhuhlu main road, small-scale crops, and WWTP	7096
Sabie	S2	0.5 km downstream from KNP western boundary	KNP natural vegetation, tourist gravel road, rural residence, and small-scale crops	7096
Sabie	S3	5.0 km upstream from a private lodge	KNP natural vegetation and private lodge	7096
Sabie	S4	0.4 km upstream from the centre of Skukuza staff village	KNP natural vegetation, Skukuza staff village and water abstraction site	7096
Sabie	S5	5.0 km downstream from Skukuza tourist camp	KNP natural vegetation, tourist camp, WWTP, Lower Sabie—Skukuza main road, and WWTP	7096
Sabie	S6	Sand and Sabie River confluence	KNP natural vegetation, Sand River, high water bridge, and Lower Sabie-Skukuza main road	7096
Sabie	S7	5.0 km upstream from Lower Sabie tourist camp	KNP natural vegetation, Lower Sabie tourist camp, and Lower Sabie-Skukuza main road	7096
Sabie	S8	Lower Sabie low water bridge	KNP natural vegetation, low water bridge, tourist camp, and WWTP	7096
Sabie	S9	1.5 km upstream from KNP eastern boundary	KNP natural vegetation, Corumana dam, and trails camp	7096

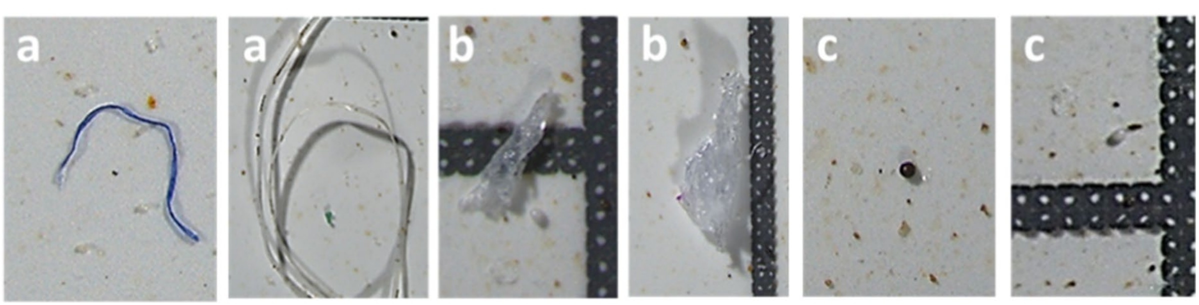

Fig. 1 Microscope images of different microplastic shapes: **a** fibres, **b** fragments, and **c** beads

2.3 Microplastic Isolation and Characterisation

2.3.1 Riverbed Sediment Samples

Microplastics were isolated from sediment according to Wang et al. (2019), with minor modifications regarding timing and sieve sizes. In the laboratory, sediment samples were dried at 65° C overnight. Each sample was sieved through a 2 mm mesh size test sieve, and then 200 g of the sieved sample was weighed into a 1000 ml Erlenmeyer flask. Samples were subjected to 150 ml of oxidising solution of 1:3 nitric acid and hydrogen peroxide for 2 to 3 h to digest organic matter before adding 400 ml of 1.6 g/cm^3 NaI solution. The sediment sample in the floatation solution was shaken on an orbital shaker at 250 rpm for 10 min. The sample was left on the lab desk for another 10 min to allow the sediment to settle. The floatation solution containing the microplastics was then transferred into glass vials and centrifuged at 3000 rpm (0.978 × g) for 5 min. The supernatant was poured through five test sieves with different mesh sizes (300 µm, 150 µm, 100 µm, 75 µm, and 25 µm) to separate microplastics into different size classes. The residue from each sieve was transferred and filtered through a 0.45 µm cellulose filter paper using a 47 mm glass vacuum filtration system. To maximize microplastic extraction, the extraction process was repeated three times per sample. The filter paper with retained microplastic particles was transferred into a glass petri dish using forceps. The petri dish remained closed and allowed to dry at room temperature before the microplastics were identified and counted using an EZ4 Leica stereo microscope at 35 X magnification and classified according to colour and size classes. Concentrations are expressed as n/kg dm (dry mass). Photographs were captured with EZ4 Leica camera fitted on the microscope and stored for further analysis.

2.3.2 River Water Microplastic Samples

Microplastics were isolated from river water according to Wang et al. (2019), with minor modifications regarding timing and sieve sizes. In the laboratory, samples were dried at 60° C without ventilation until dry. Each oven-dried sample was treated with a 30 ml oxidising solution of 1:3 nitric acid and hydrogen peroxide for 2 to 3 h to digest organic matter from the sample. Fifty ml of 1.6 g/cm^3 sodium Iodide (NaI) floatation solution was added to float microplastic particles. Thereafter, samples were decanted into glass tubes that were pre-rinsed with deionized water filtered through a 0.45µm cellulose filter using 47 mm Merk Millipore glass vacuum filtration system and then subjected to centrifugation for 5 min at 2500 rpm (0.978 × g) using a Z383K centrifuge. To separate microplastic particles into classes, mesh test sieves of 300 µm, 150 µm, 100 µm, 75 µm, and 25 µm were stacked in descending order. Samples retained on each sieve was then filtered through a 0.45 µm gridded cellulose filter using a 47 mm glass vacuum filtration system and allowed to dry at room temperature in a glass petri dish before the examination. Glass petri dishes were kept closed to avoid microplastic particles contamination. Using a EZ4 Leica stereo microscope at 35 X magnification, microplastic particles were identified, counted, and classified according to colour and size classes. Concentrations are expressed as n/L. Photographs were taken with an EZ4 Leica camera fitted on the microscope and stored for further analysis.

2.3.3 Microplastic Polymer Identification

Microplastic polymer identification done on microplastics from water and sediment. Microplastic particles (100 particles greater than 250 µm for river water and sediment, each) were selected randomly for plastic polymer identification using an attenuated total reflectance, Fourier-transform infrared spectrometer (ATR-FTIR; Agilent 630). Microplastic particles were carefully picked up from the cellulose filter using forceps and placed on the ATR-FTIR diamond crystal to determine the microplastic sample spectrum. The spectrum obtained from each microplastic particle was compared with the spectra of known plastic polymers from the ATR-FTIR library (Supplemental Fig. S4).

3 Results

Microplastics were absent in all procedural blanks. Within and between batch microplastic profiles (colour, morphotype, size classes, and polymer compositions) were very different (Fig. 1, Tables 2, 3,

Table 2 Microplastic counts and concentrations in riverbed sediment along the Olifants and Sabie River

	Concentration n/kg dm		Microplastic particles count per morphotype					
			Fibres		Fragments		Beads	
	Olifants	Sabie	Olifants	Sabie	Olifants	Sabie	Olifants	Sabie
Minimum	447	404	374	143	656	492	1207	1088
Median	1786	1322	719	544	3150	1892	5242	2958
Maximum	6565	1994	1895	937	5676	2906	25,252	7815
Range	6117	1590	1521	794	5020	2414	24,045	6727
Mean	2682	1139	925	530	2944	1577	9539	3588
Std. Deviation	2393	570	573	334	1808	797	9732	2319
% CV	89	50	62	63	61	50	102	65
Geometric mean	1740	985	778.6	420.9	2339	1360	5291	2916

Table 3 Microplastic concentrations morphotype counts in river water of the Olifants and Sabie rivers

	Concentration (n/L)		Microplastic particle counts per morphotype					
			Fibres		Fragments		Beads	
	Olifants	Sabie	Olifants	Sabie	Olifants	Sabie	Olifants	Sabie
Minimum	111	4	40	14	588	295	240	37
Median	29	16	88	48	1992	1256	496	142
Maximum	49	41	142	124	3494	3443	836	620
Mean	27	18	80	58	1863	1394	510	199
Std. Deviation	12	13	36	44	971	1117	198	190
% CV	42	73	45	76	52	80	39	95
Geometric mean	25	14	77	44	1619	988	475	134

Section 3.5, and Supplemental Fig. S2–S3), confirming a negligible procedural background.

3.1 Overall Water Microplastic Counts and Concentrations

Overall river water microplastic particles were classified according to microplastic morphotype (Fig. 1), size classes, and colour. A total of 22 080 and 14 868 microplastic particles were counted in Olifants and Sabie river water, respectively. The total microplastic particles counted translated to microplastic particle concentrations of 49 n/L and 41 n/L, respectively (Fig. 2 and Table 2). The Olifants River water had higher microplastic counts (Fig. 2a, e, and g) and microplastic concentrations (Fig. 2c) than the Sabie River water. Overall, the Olifants River water accounted for 60%, and the Sabie River for only 40% of the total detected microplastics in river water. However, microplastic concentrations were not significantly different between the two rivers (Fig. 2c; $p = 0.1615$). Fisher's exact tests showed statistically significant differences ($p < 0.0001$) in proportions of microplastic particle morphotype, size classes, and colour categories between the Olifants and Sabie rivers (see Table 2).

3.2 Microplastic Pollution in Riverbed Sediment

Riverbed sediment microplastic concentrations ranged from 2022 to 9971 n/kg dm, and 2237 to 27 259 n/kg dm, for the Olifants and Sabie rivers respectively (Table 2). Beads were the highest recorded morphotype, followed by fragments, and fibres along both rivers and sample sites (Fig. 4). The highest microplastic concentration (27 596 n/kg) in riverbed sediment along the Olifants River was at site O1 (Fig. 2a), located 4.7 km upstream from KNP western boundary. Although all five microplastic size classes occurred at site O1, two

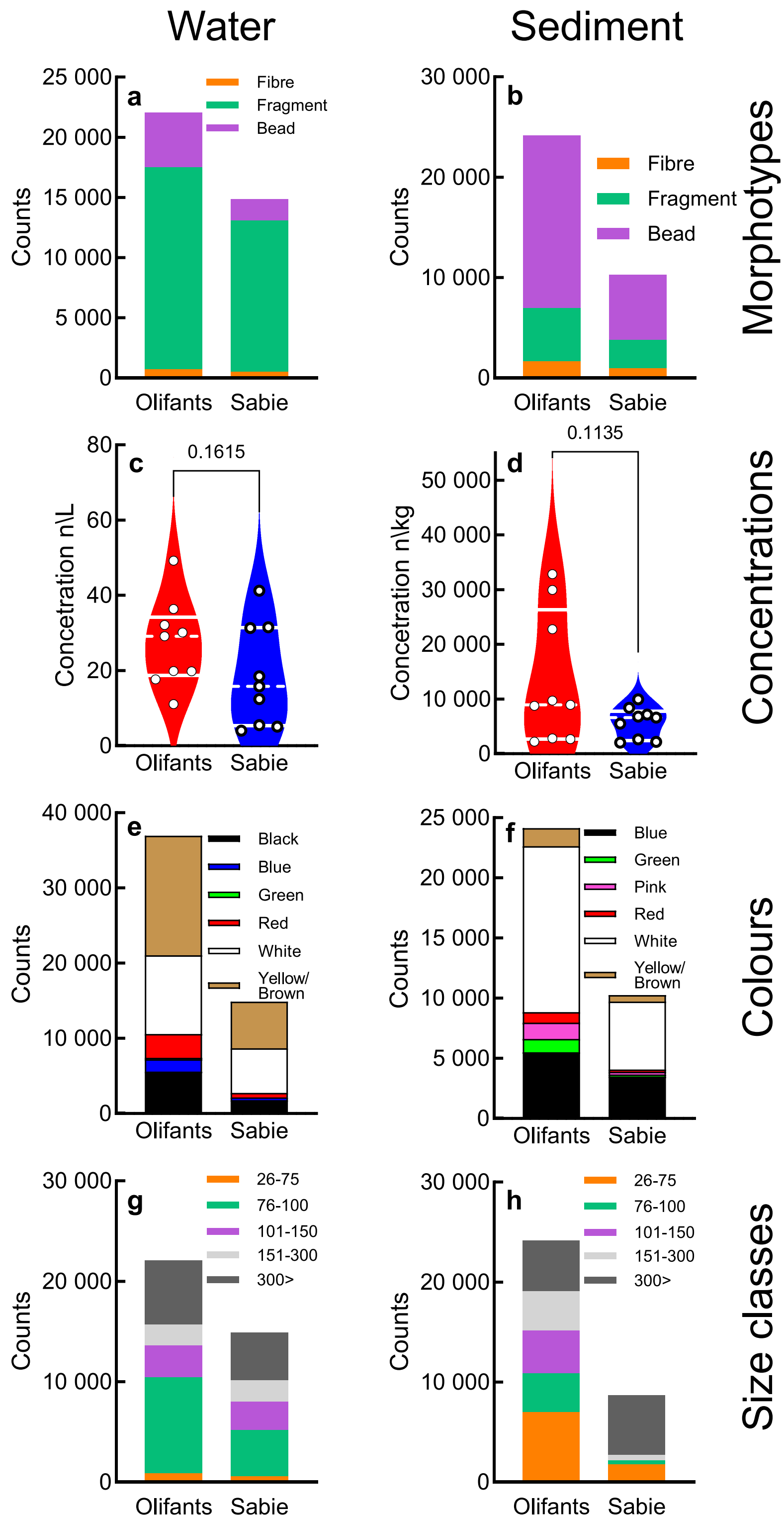

Fig. 2 Bar and violin graphs illustrating overall microplastic particle counts and concentration in river water and riverbed sediment along Olifants and Sabie rivers according to, (**a** and **b**) microplastic morphotype, (**c** and **d**) concentrations, (**e** and **f**) microplastic colour, and (**g** and **h**) microplastic size classes. Microplastic count proportions were statistically different ($p < 0.0001$; Fisher's exact) for microplastic morphotype, size classes, and colour, between the Olifants and Sabie. The violin graphs (**c** and **d**) illustrate the difference in microplastic concentration frequency distributions between Olifants and Sabie rivers water, which was not significant ($p = 0.1615$ and $p = 0.1135$); unpaired, two-tailed, Mann–Whitney test). Horizontal lines in the violins are the median, 25%, and 75% quartiles

size classes 25–75 µm (7921 n/kg) and 151–300 µm (6462 n/kg), accounted for 50% of the total microplastics counted here. The highest microplastic particle concentration for the Sabie River was at sample site S7 (Fig. 2b). Sample site S7 is 4 km upstream from the Lower Sabie tourist camp.

Overall, the Olifants River sediment accounted for 70% of the total detected microplastics. The Sabie River accounted for only 30% total detected sediment microplastic concentration. The lowest microplastic concentration for the Sabie riverbed sediment was at sample site S5 (Fig. 2b), 5.0 km downstream from the Skukuza tourist camp. Microplastic size classes 25–75 µm (368 n/kg), 76–100 µm (334 n/kg), and 150–300 µm (210 n/kg) accounted for approximately 70% of the total microplastic concentration at the same site; the other 30% of the detected microplastics was in the 101–150 µm class (420 n/kg; Fig. 2b). In general, high concentrations of microplastics occurred at the three easternmost sample sites (S7, S8, and S9) along the Sabie River (Fig. 3). Sample site S9 is 15.8 km downstream from the Lower Sabie tourist camp and 1.5 km upstream of the Mozambique border. However, the Olifants River riverbed sediment reflected high microplastic concentration at the first two westernmost sample sites (O1 and O2) and the last most eastern sample sites (O9) (Fig. 3).

3.3 Overall Riverbed Microplastic Counts and Concentrations

Overall, microplastic particles in riverbed sediment along the Olifants and Sabie rivers were classified according to microplastic particle morphotype, size classes, and colour (Tables 2, 3, Supplemental Fig. S3 and S4). A total of 24 136 and 10 252 microplastic particles were counted in riverbed sediment along the Olifants and Sabie, respectively (Fig. 2b, f, h and Table 2). The total microplastic particles counted translated to microplastic particle concentration that ranged from 2237 to 32 823 n/kg for the Olifants, and 2022 to 9971 n/kg dm for the Sabie (Fig. 2d and Table 4). Figure 3d illustrates that microplastic particle concentrations were not significantly different ($p = 01135$) between the two rivers. The Olifants riverbed sediment had higher microplastic counts (Fig. 2b, f, and h) and microplastic particle concentrations than the Sabie riverbed sediment (Fig. 2d). Fisher's exact tests reflected a statistically significant difference ($p < 0.0001$) in proportions for microplastic particle morphotype (Fig. 2b) and size classes (Fig. 2h) between the Olifants and Sabie rivers (Tables 2 and 3).

3.4 River Water Microplastics

Microplastic concentrations in river water ranged from 11 to 50 n/L, and 4.0 to 41 n/L for the Olifants

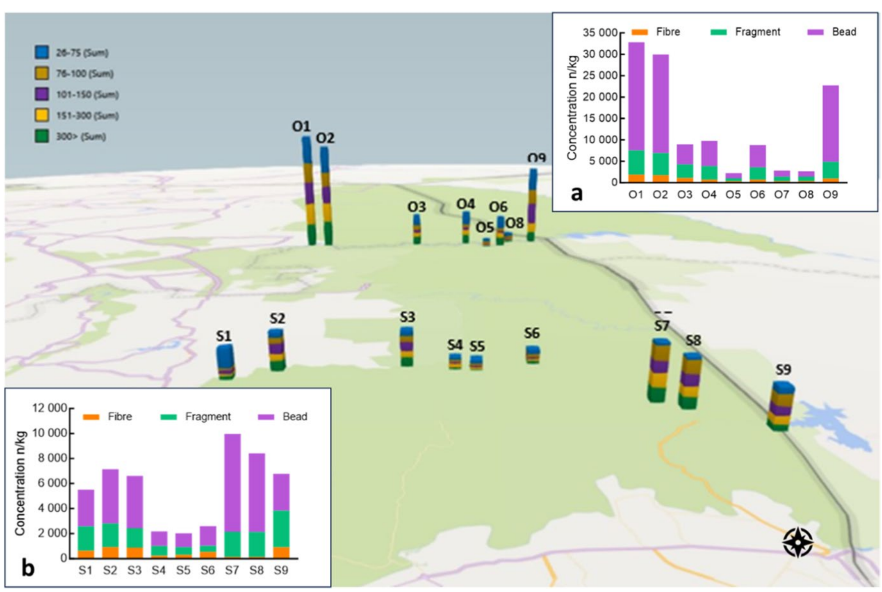

Fig. 3 A 3D map showing riverbed sediment microplastic particle distribution across different sample sites along the Sabie (O1 to O9) and Olifants (S1 to S9) rivers. Bar graphs illustrating riverbed sediment microplastics per morphotype at different sample sites along the Olifants (**a**) and Sabie (**b**) rivers

Table 4 Percentage distribution of microplastic polymer types in river water and riverbed sediment of the Olifants and Sabie rivers

Polymer	Acronym	Ratio water (%)	Ratio sediment (%)
Butyl	BTL	2	4
Chlorobutyl	CIIR	9	7
Cellulose	CLL	2	0
Chitosan	CHT	0	4
Ethylene–vinyl acetate	EVA	7	2
Polyisoprene	IR	0	2
Polyacrylamide	PA	0	2
Polyethylene	PE	12	15
Polyethylene Terephthalate (Polyester)	PET	32	39
Poly (4-methyl-1-pentene)	PMP	2	0
Polypropylene	PP	10	11
Polystyrene	PS	6	3
Polytetrafluoroethylene	PTFE	2	0
Poly(vinyl)alcohol	PVA	14	3
Polyvinyl chloride	PVC	0	8
Thermoplastic Elastomer	TPE	2	0

and Sabie rivers respectively (Fig. 3 and Table 2). However, the distribution of microplastic particle morphotypes seemed to follow a similar pattern along both rivers. Fragments were the highest recorded microplastic particle type, followed by beads and fibres along both rivers and within sample sites (Fig. 3). However, at some sample sites in the Sabie River beads and fibres were not detected. The highest microplastic particle concentration (49 n/L) (Fig. 3a) amongst the nine sample sites along the Olifants River was the easternmost sample site O9, 10 km downstream of the Olifants tourist camp and 6.5 km before crossing the Mozambique border (Figure S1 and Table 1).

Amongst the nine sites (S1 to S9) sampled along the Sabie River within the KNP, sample site S9 had the highest microplastic particle concentration (Fig. 2b). This site is also the easternmost sample site, located 1.5 km upstream of the KNP boundary with Mozambique (Table 1 and Supplemental Fig. S1). The lowest concentration (11 n/L) microplastic particle concentration along the Olifants River (Fig. 4a) was still more than double the lowest (4.0 n/L) microplastic particle concentration recorded along the Sabie River (Fig. 4b). Additionally, the highest microplastic particle concentration detected in the Olifants River (50 n/L) was almost 10 n/L more than the highest microplastic concentration recorded in the Sabie River water.

The lowest microplastic concentration (11 n/L) for the Olifants River was at sample site O6, 5.3 km upstream from the Olifants tourist camp (Table 1 and Supplemental Fig. S1). Four of the five microplastic classes were observed at sample site O6, however, the 25–75 µm size class was not detected. Microplastic size class 150–300 µm (10 n/L) accounted for more than 50% of the detected microplastics at the sample same site (Table 1, Fig. 4 and Supplemental Fig. S1). The highest microplastic particle concentration in water along the Sabie River (41 n/L) (Fig. 4b) was at the easternmost sample site (S9), 15.8 km downstream from the Lower Sabie tourist camp and 1.5 km upstream of the Mozambique border (Table 1, Fig. 4, and Supplemental Fig. S1). All five microplastic size classes occurred at sample site S9. Microplastic size classes 26–75 µm (15 n/L) and 76–100 µm (13 n/L) accounted for more than 35% of the total microplastics detected. Size class 25–75 µm (1.5 n/L) accounted for approximately 40% of the combined river water microplastic particles distributed across both rivers (Fig. 4).

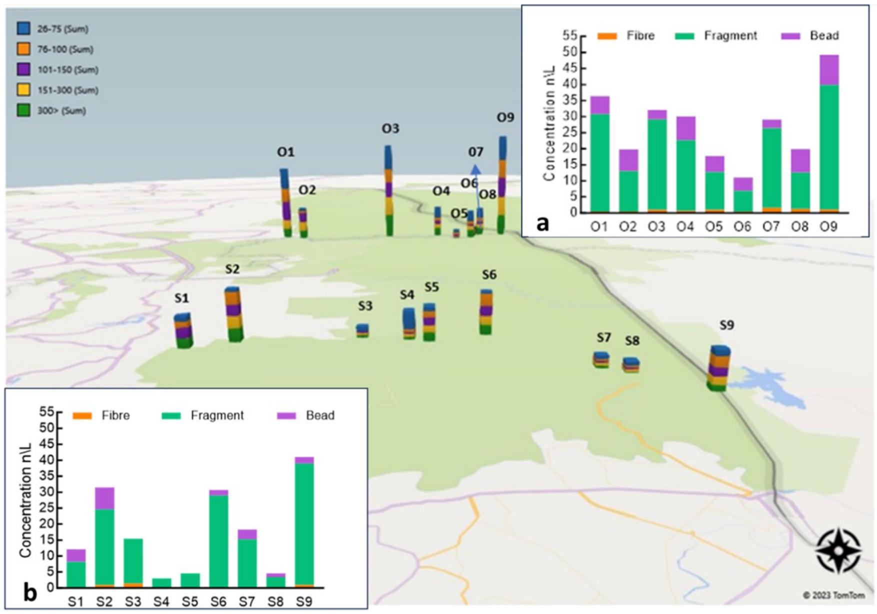

Fig. 4 A map showing river water microplastic particle concentration and morphotype distributions along the Sabie and Olifants rivers. Bar graph insets illustrate river water microplastic particles per size class at different sample sites along the Olifants (**a**) and Sabie (**b**) rivers, while the bars on the map reflect particle size class distributions

3.5 Microplastic Polymer Composition in River Water and Riverbed Sediment

Twelve microplastic polymer types were found in river water and sediment, but there was not a complete correspondence between polymer composition in the water and in the sediment (Table 3 and Supplemental Fig. S5). The following polymers were detected: Butyl (BTL), chlorobutyl (CIIR), cellulose (CLL), chitosan (CHT), ethylene–vinyl acetate (EVA), polyisoprene (IR), polyacrylamide (PA), polyethylene (PE), polyethylene terephthalate (polyester) (PET), poly (4-methyl-1-pentene) (PMP), polypropylene (PP), polystyrene (PS), polytetrafluoroethylene (PTFE), poly(vinyl)alcohol (PVA), polyvinyl chloride (PVC) and thermoplastic elastomer (TPE).

The dominant polymer was PET (32%), followed by PVA (14%), PE (12%), PP (10%), CIIR (9%), EVA (7%), PS (6%), and the least polymer types (PMP, PTFE, CLL, thermoplastic elastomer (TPE) and butyl (BTL)) contributed only 2% each. Microplastic polymer PET contributed 39% of the observed microplastic particles polymer type in riverbed sediment. Microplastic polymers PE, and PP contributed 15% and 11%, respectively. PVC and CIIR contributed 8% and 7%. A lower contribution of microplastic polymer type at 4% each were BTL and CHT, followed by PS and PVA at 3% respectively. The microplastic polymers found in the least amount were PA, EVA, and IR.

4 Discussion

4.1 Overall Microplastic Concentration

Protected areas are generally expected to have fewer pollution challenges because they are often relatively remotely located and presumably less disturbed by anthropogenic activities (Napper et al., 2020). Microplastic pollution has been detected across many environments that were perceived to be relatively pristine including Mount Everest, the Antarctic, and Tibetan Plateau glaciers (González-Pleiter et al., 2020; Horton & Barnes, 2020; Zhang et al., 2021). Here, we show that microplastic pollution is present in high concentrations in Olifants and Sabie river water and riverbed sediment, with higher concentrations in the Olifants River. In a pilot study in 2018, a low concentration of microplastic particles was found in the Olifants River sediment (480 n/kg) and none along the Sabie River (Shikwambana et al., 2019).

To the best of our knowledge, the microplastic concentrations in the sediment of the present study are the highest yet recorded in South Africa. In Braamfontein Spruit, 170 n/kg dm was found (Dahms et al., 2020), 500 microbeads/kg from Grahamstown (Nel et al., 2019), 160 n/kg along the Bloukrans River (Nel et al., 2018), and 570 n/kg along the Crocodile River (Nkosi et al., 2023) However, these studies employed different microplastic sampling and extraction methods. Additionally, Nel et al. (2019) showed that the microbead detection method currently used may not be efficient considering that there is possibly a 79% underestimation in some methods. The predominant morphotype in our study was beads suggesting that we were using a robust and efficient extraction and detection process.

The high levels of microplastic pollution detected along the Olifants River could be because its catchment size, and intense land use types such as mining, WWTPs, inefficient solid waste management, agriculture, and residential areas (Estahbanati & Fahrenfeld, 2016; Klein et al., 2015; Ziajahromi et al., 2016). The Olifants River's catchment is extensive; it covers approximately 54 750 km^2, (Pollard et al., 2011). This suggests that the Olifants River is more vulnerable to microplastic pollution, and this we found. Also, the high concentrations of microplastics detected at the westernmost site from upstream of the KNP border before the river enters the park, shows that there is microplastic input from areas upstream of the KNP boundary. In the KNP however, we also found high concentrations of microplastics at the easternmost sample site before the KNP border. Meanwhile, the Sabie River has a small catchment size (6 320 km^2) but flows through both rural and urban Mpumalanga (Pollard et al., 2011; Riddell et al., 2019). We detected a high concentration of microplastics at the westernmost sample site outside the KNP boundary before the river enters the park, confirming that the Sabie River had microplastics originating outside the KNP boundary.

4.2 Decreasing Concentrations?

Our expectation was decreasing microplastic pollution from the upstream of the KNP border to downstream as the rivers exit the park. However, we found distinctive microplastic hotspots within the KNP for both rivers. Microplastic particles seem to be dispersed at different concentrations at different sample sites across both the Olifants and Sabie rivers. Riverbed sediment grain size may be a factor in the development of microplastic particle hotspots (Gola et al., 2021; Hurley & Nizzetto, 2018; Hurley et al., 2018; Kumar & Varghese, 2021).

The largely similar patterns we found between two independent rivers can be driven by several factors upstream and within the KNP border such as urban areas, villages, streams or tributaries, industries, WWTPs, solid waste management at the KNP rest camps, and motor vehicles. For instance, the Olifants River alone has six tributaries before it reaches the KNP border (O'Keeffe & Rogers, 2003). There are additional potential microplastic sources within the KNP border including, WWTPs, streams or tributaries, plastic woven sandbags, dams and weirs slowing river flow, tourist camps, and roads (Supplemental Figures S1 and S2). Moreover, annual flows, floods, droughts, resuspended sediments, reshuffled sand banks, and different sediment particle sizes are likely to create or redistribute microplastic hotspots, or transport microplastics downstream (Gola et al., 2021; Hurley & Nizzetto, 2018; Hurley et al., 2018; Kumar & Varghese, 2021).

Riverbed sediment in the Olifants River had high microplastic concentrations at the most upstream sample site within the KNP. The sample site O1 is located after the Olifants-Selati River confluence (Selati River (not shown) is a tributary of the Olifants). Site O1 is about 950 m after the confluence with the Olifants River. Therefore, there could be some microplastic input from the Selati River tributary. There was also an increase in microplastic concentration at the sample site (site O6) located next to a water abstraction site, upstream of the Olifants tourist camp. The process of water abstraction includes digging and sometimes the use of plastic woven sandbags to create seasonal damming when river water levels are low (Supplemental Figure S2). Sediment scouring could also expose microplastic particles that have been in the river system for many years.

4.3 Microplastic Colour and Size Class Distribution

Although all microplastic morphotypes were detected in water along the Olifants and Sabie rivers, microplastic fragments within the size classes of 25–76 μm and 151–300 μm were dominant (Figs. 1, 2, 3, and 4). Microplastic fragments mainly result from bigger plastic pieces that mechanically break down into smaller plastic pieces (Klein et al., 2015). Therefore, inefficient solid waste management, or the lack of solid waste management, is likely the main source of the microplastic fragments we found. Also, microplastic fragments are likely to float in water due to their shape and density (Duis & Coors, 2016). Yellow–brown microplastic particles were the most prevalent followed by white microplastic particles in both the Olifants and Sabie river water (Fig. 3c). White microplastic particles were more dominant in the Sabie than the Olifants River, suggesting that river water microplastic pollution sources is different between the two rivers. However, white microplastic particles contributed to more than 50% of the observed microplastic particles in riverbed sediment for both rivers.

4.4 Microplastic Morphotype Distribution

Fragments were the highest recorded microplastic type, followed by microbeads, and fibres in water along both rivers. This observation is comparable with surface water microplastics observed in the Vaal River (Saad et al., 2024). However, riverbed sediments were dominated by microbeads, followed by fragments, and fibres were the least prevalent. A study by Nel et al. (2019) highlighted an observer error of approximately 79% underestimation of microbeads during quantification. However, we have minimized observer error by including centrifugation to increase sample clarity and dividing each sample into five size groups to minimize sample impediment. Thus, we were able to effectively isolate and identify microbeads in riverbed sediment. Personal care products (facial scrubs and toothpaste) and detergents are the main sources of microbeads (Chang, 2015; Mason et al., 2016), and WWTPs are the most common pathway for microbeads to reach rivers and other water bodies (Estahbanati & Fahrenfeld, 2016; Verster & Bouwman, 2020; Ziajahromi et al., 2016).

Countries such as the US, the UK, and Canada instituted microbead bans between 2017 and 2019 (Kentin & Kaarto, 2018), following the initial microbead bans by the Netherlands and South Korea in personal care products (Xanthos & Walker, 2017). However, South Africa has not done so despite the ongoing WWTPs challenges highlighted in the Green Drop National Report (2022). The average national Green Drop score for 2021 was recorded as poor at 37% with Limpopo province scored at 31% (Department of Water & Sanitation, 2022).

4.5 Microplastic Polymer Types

Microplastic polymer composition differed between water and sediment (Table 4), with IR, PA, CHT, and PVC only in sediment and TPE, CLL, PTFE, and PMP only in water. The most common and dominant polymer was PET in both matrixes. The observed 39% PET polymer distribution in sediment might be because PET density ranges between 1.34 and 1.39 g/cm^3 (Oni et al., 2020; Wagner & Lambert, 2018). It is expected that PET sinks in sediment because of its higher density relative to most of the other polymers. This result corresponds with a study by (Huang et al., 2020); they observed PET as the most common polymer in sediments. PET is one of the most common plastic polymers used for packaging, textiles, plastic bottles, containers, and generic plasticware, insulation, and sometimes in the manufacturing of microbeads (GESAMP, 2015; Siegfried et al., 2017). Approximately 32 million tons of PET waste is generated annually on a global scale. However, only 3% is recovered (Geyer et al., 2017; Yuan et al., 2022). WWTPs and solid waste management plants could be the common sources of PET (Hernandez et al., 2017; Wang et al., 2019). Therefore, the observed PET in the study area could result from tourism activities, domestic solid waste, transport, and WWTPs before and within the KNP borders.

Other common (> 10% distribution) polymers observed for both riverbed sediment and river water were PVA, PE, and PP. Polymer-type PET, PVA, PE, and PP have common sources and are thermoplastics (GESAMP, 2015). Therefore, their introduction into the river systems might not be different depending on use and waste management on adjacent land. Other less common (< 5% distribution) polymers such as CIIR, BTL, EVA, PA, PVC, PVA, IR, PS, PMP, PTFE, CLL, TPE, and CHT in riverbed sediment and river water were also observed. It has been estimated that 42% of microplastic transported via rivers to seas are synthetic polymers from tyre and road wear particles (Siegfried et al., 2017). BTL and CIIR are natural rubber copolymers that are used in vehicle tyres (Paduvilan et al., 2021) and conveyor belts (Masrangi et al., 2020). The presence of both BTL and CIIR indicates that both the Sabie and Olifants rivers are exposed to traffic-related microplastic pollution.

Based on significant differences in microplastic morphotypes, colours, size classes, and polymer compositions, we conclude that microplastic sources differ markedly between the two rivers. This finding affects the identification of mitigation interventions on a catchment basis.

5 Conclusions and Recommendations

Rivers are complex, dynamic systems. The microplastic pollution detected during the study likely reflects microplastic pollution accumulation over an extended period from different geographical locations and various sources. Although the concentrations between the rivers did not differ significantly, all other variables did, showing that the two catchment-independent rivers have distinctly different microplastic sources. Indeed, this may be true for the other rivers in the KNP.

The concentrations of microplastics in water and sediment did not decline with distance downstream for both rivers (Figs. 1 and 4). This may be ascribed to two factors. The first is that there are microplastic sources within the KNP, inputs from the tourist camps, and traffic and construction (Supplemental Figure S2), that keep concentrations at an even concentration throughout the river courses. However, it is unlikely that the scale of the within-park sources is near that of the combined contributing sources before the rivers enter the KNP. The second likely factor is that over the decades of pollution, from sources both before and within the KNP, reservoirs of microplastics have accumulated to such an extent that geography, weather, and temporal influences are hardly discernible nor conclusive. This has implications for mitigation and biotic exposure.

The high microplastic concentrations observed in this study (the highest yet recorded for South Africa) show that microplastic pollution in the KNP river systems is substantial. This study presents a baseline for future research and monitoring. It also provides a baseline for the South African National Parks policymakers to plan towards the IUCN World Conservation Congress 2020 announcement of eliminating plastic pollution in protected areas by 2025 (IUCN et al., 2020). There is a need for KNP management to include microplastic sampling as part of the freshwater annual surveys. This study shows the importance of continued monitoring of microplastic concentration, polymer, morphotype, and size in all the major KNP rivers to identify trends, threats to biota and ecosystem functioning, and the response to any mitigation. For future surveys, it would be advised to sample water and sediments at the same time to better understand the relationships and dynamics between the two matrixes.

The microplastic pollution concentrations recorded in this study highlight the need to address pollution challenges in protected areas in South Africa. As we have shown here it should preferably be on a catchment basis. Policymakers in South Africa need to prioritize the elimination of single-use plastic products within and beyond protected areas. The reduction or banning of plastic microbeads, for instance, presents low-hanging fruit. The KNP is a highly important conservation area—the impacts of microplastics on biota, therefore, should be investigated. Given the pervasive microplastic pollution we here illustrated underscores the need for significant upstream and in-park interventions to effect concentration reductions of rivers flowing through conservation areas. Since rivers have no borders, transboundary pollution needs consideration since the five major rivers all flow from the KNP through Mozambique to the Indian Ocean.

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Data Availability The data with which this article has been prepared is part of the MSc dissertation of Purvance

Shikwambana (Microplastic pollution in the rivers of the Kruger National Park). The South African National Parks is the custodian of the data, and they are available upon request at visuser@sanparks.org.

Declarations

Ethical Approval The permission to conduct the research in the Kruger National Park was granted by the South African National Parks (SANParks), Scientific Service Department (SHIP1551). Ethical clearance was granted by the NWU (NWU – 01639–20-A9).

Consent to Participate All authors have given consent to participate in this research.

Consent to Publish All authors have agreed to submit the manuscript in its current form for consideration for publication in the journal.

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