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RESEARCH

Spatiotemporal variation in macroplastic abundances along a subtropical Austral river system

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Abstract Plastic pollution is a ubiquitous problem that poses a threat to society and the environment. The issue is especially pervasive in the aquatic environment, where large amounts of plastic debris accumulate from numerous anthropogenic pathways. Relatively little is known about the extent of macroplastics in African subtropical Austral rivers, where management strategies are lacking. This study quantifies and compares the variation in macroplastic abundances along the Mvudi River, South Africa, over four sites and four seasons. We observed a non-significant difference in macroplastic abundance and variation across sites and seasons, with pollution therefore widespread across these contexts. However, the diversity of plastic debris (i.e. γ-diversity value) decreased generally along sites, with most macroplastic items being collected during winter, and fewer macroplastic during autumn. We observed high abundances of macroplastic debris on the shoreline compared to the mainstream, with high proportional abundances of plastic bags and film (> 57.8%) macroplastic physical type across all sites and seasons. We also observed a high proportional abundance of the polymer polypropylene (> 25.3%) across seasons. The information derived from this study serves as the baseline for understanding seasonal variations in plastic debris and their driving factors on this and other subtropical Austral rivers.

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Introduction

Plastic pollution is a major environmental problem that is increasing at an unprecedented rate globally (Galgani et al., 2013). Plastic products are very cheap and extensively used in everyday applications (Dalu et al., 2019). These plastic items vary in size, colour, shape, and polymer type (Piehl et al., 2018). Due to the mismanagement or illegal disposal of plastics, they often end up in the aquatic environment where they pose threat to ecosystems (Cao et al., 2022; Dalu et al., 2019). Plastics are the most prevalent, rapidly increasing, and the most dominant aquatic contaminants (Zhao et al., 2014). Large-sized plastic debris, also known as macroplastics (size > 25 mm), are frequently found in aquatic environments (Krishnakumar et al., 2018). They enter standing waters through a variety of pathways and activities via rivers, aquaculture, shoreline litter, shipping, recreational activities, and fishing, which significantly influence their abundances (Lebreton et al., 2017).

A myriad of natural factors mediate macroplastic abundance and distribution. Accumulation of plastic debris varies from shorelines to the deep pelagic waters (EPA US, 2016). Furthermore, spatial scale, local environmental conditions, and individual plastic polymer characteristics (i.e. the density of polymers) affect the variability in the distribution of macroplastic pollution (Vegter et al., 2014). Vertical variation in macroplastic distribution can occur within the water column due to the interaction between a polymer's buoyancy and water turbulence (Reifferscheid et al., 2017). The density of suspended macroplastic debris tends to increase due to water turbulence caused by storm or flood events (Faure et al., 2015).

Wind further plays a major role in the spatial distribution of macroplastic (Hoffman & Hittinger, 2017). Studies on global macroplastic pollution show that macroplastic debris can diffuse between countries and continents, float on or below the water's surface, and travel considerable distances (Lundström & Mårtensson, 2015).

Macroplastic debris abundances differ seasonally owing to human activity patterns and differences in water levels; i.e., during summer there are many activities along the shorelines which can result in increased macroplastic pollution, whereas there are fewer activities during the winter season (Avio et al., 2017). The shape, size, and buoyancy also influence the distribution of macroplastic debris (Lee et al., 2015). Human activities and inland meteorological processes such as wind and rain directly influence the shoreline or bank macroplastic debris accumulation within urban systems (Kershaw et al., 2019).

Macroplastic pollution effects on aquatic organisms have been observed and include entanglement which can cause suffocation and/or development of severe wounds, and ingestion of plastics leading to various complications (Cable et al., 2017a, 2017b; Fischer et al., 2016). Organisms that ingest macroplastic can develop sub-lethal effects which can lead to mortality (Cable et al., 2017a, 2017b). Macroplastics also serve as carriers of alien species that can be introduced into the aquatic environment (Cable et al., 2017a, 2017b) and can transport contaminates such as dichlorodiphenyltrichloroethane polychlorinated biphenyls and polycyclic aromatic hydrocarbons (into the water body where they can be adsorbed (Katzenberger, 2015)). Macroplastic pollution can also have negative impacts on water quality, aesthetics, tourism activities, and impact on the local economy of an area (Dalu et al., 2019).

It is important to determine the distribution of macroplastic debris in aquatic ecosystems because it contributes to the knowledge base on the abundance of global macroplastics and assists in future management planning for aquatic pollution (Cable et al., 2017a, 2017b; Fischer et al., 2016). There is a knowledge gap with regard to the distribution of macroplastics and their ecological impacts on African aquatic ecosystems (Lahens et al., 2018), and hence, data about macroplastic sources, presence, and fate is still limited (Katzenberger, 2015). Hydrodynamic processes affecting macroplastic debris accumulation in urban aquatic ecosystems, particularly rivers, are scarce, and hence, more work is required to build an understanding of distribution patterns and factors that cause variation in macroplastic debris across seasons and sites.

In the current study, the Mvudi River that drains most parts of the Thohoyandou town in the Limpopo province of South Africa was chosen because it is subjected to various pollution sources, such as human settlements, water abstraction, riparian brick making, washing, bathing, subsistence and commercial agriculture, sewage discharge/spillage, and illegal solid waste disposal/dumping. The study aimed to assess the sources, driving factors, types, and abundances of macroplastic debris along the river system. We hypothesized that the macroplastic debris abundances along the Mvudi River will be very high during the summer season because of driving factors such as runoffs carrying plastic debris to the river, and due to increased human activities such as swimming and bathing which increases the chances of macroplastic debris disposal. We further expected that the macroplastic abundances would be low during the winter season since human use of rivers is reduced when the temperature is low, and hence, there would be an absence of activities that could potentially result in illegal dumping of macroplastic debris along the river shores/riparian zones.

Materials and methods

Study area

The study was conducted along the Mvudi River (30° 28′ 28″ E and 23° 0′ 13″ S), a tributary to the Luvuvhu River in the Limpopo province of South Africa (Fig. 1). The river catchment lies at an elevation of between 202 and 1506 m above sea level and covers an area of about 5942 km^2. The Mvudi River passes through the Thohoyandou town and then empties into the Nandoni dam. The river system catchment receives high rainfall during the summer (i.e. February ~ 284 mm) and low rainfall in winter (i.e. June, ~ 14 mm) and spring (i.e. September, ~ 14 mm) seasons. Average temperatures for the catchment range from 20 (June, range 14–24 °C) to 24 °C (February, range 18–28 °C), with low average temperatures of 7.5 °C occurring in July (Dalu et al., 2021).

The Mvudi River Catchment is important for agricultural activities such as banana, forestry, avocado, and macadamia plantations in the headwaters; these types of agricultural activities are being practiced in the valleys and lower slopes in the western side and urban settlements on the eastern side (Ramulifho et al., 2019), while the riparian vegetation and rivers of this catchment are home of different fauna species (Ramulifho et al., 2019). The Mvudi River catchment is subjected to various pollution sources, such as informal and formal human settlements, water abstraction, riparian brick making, washing, and bathing, subsistence and commercial agriculture, sewage discharge/spillage, and solid waste disposal/dumping from nearby communities.

Sampling was conducted at 4 sites, with site M1 located next to the University of Venda and Maungani village. The main activities taking place at this site were water abstraction and car washing. Site M2 was at the edge of Thohoyandou town, with similar site M1 activities—occurring at the site. Site M3 was located between Thohoyandou J and L, upstream of the sewage treatment works, with water abstraction, riparian zone bricking and fishing being the dominant activities, and lastly, site M4 was located downstream of the wastewater treatment works, with brick making and fishing being common. Sampling was conducted at each site (i.e. M1–M4) and season along the perennial Mvudi River, across four seasons (i.e. winter, spring, summer, autumn) (Fig. 1).

Research design and sampling

A quantitative approach (i.e. riparian and mainstem river surveys) was undertaken to study the distribution of macroplastics (> 2.5 cm) along the Mvudi River system to represent the streams draining the rural town and also in relation to the wastewater treatment works. Riparian and mainstream river surveys were applied as these areas are clearly defined and are zones where high macroplastic abundances are likely to be found. This also facilitated repeatability over time and, in turn, thereby provided a trend assessment (Haseler et al., 2018). Such surveys are of particular importance in urban and rural aquatic environments where quantitative baselines for macroplastic pollution are lacking. Accumulation riparian surveys were utilised for this study, where plastic debris was removed from 5 × 5 m quadrats on the mainstream of the river system and on both sides of the mainstem river channel (i.e. 2 riparian zones) by two researchers (Lippiatt et al., 2013; Kershaw et al., 2019). For obtaining a reliable estimate of the presence and distribution of macroplastic pollution along the riparian zones of the Mvudi River, 4 sampling sites (4 sites × 3 replicates) were randomly selected, with two on each side of the river along the river system (i.e. littoral or riparian zone), and one in the river channel (middle mainstem channel) based on ease of site accessibility. All macroplastic debris present was collected by hand within each quadrat and transferred into labelled bags for further processing within the laboratory.

Processing of samples

Macroplastic debris was separated and categorised into different resin groups before being counted in the laboratory. Resin polymer groups were determined according to Lippiatt et al. (2013), Reifferscheid et al., (2017), and Plastics Europe (2017) methods and classifications. Macroplastics were categorised in relation to their functional origin (e.g. beverage plastic bottles, food wrappers, cleaning product containers, cups, plastic bags) and

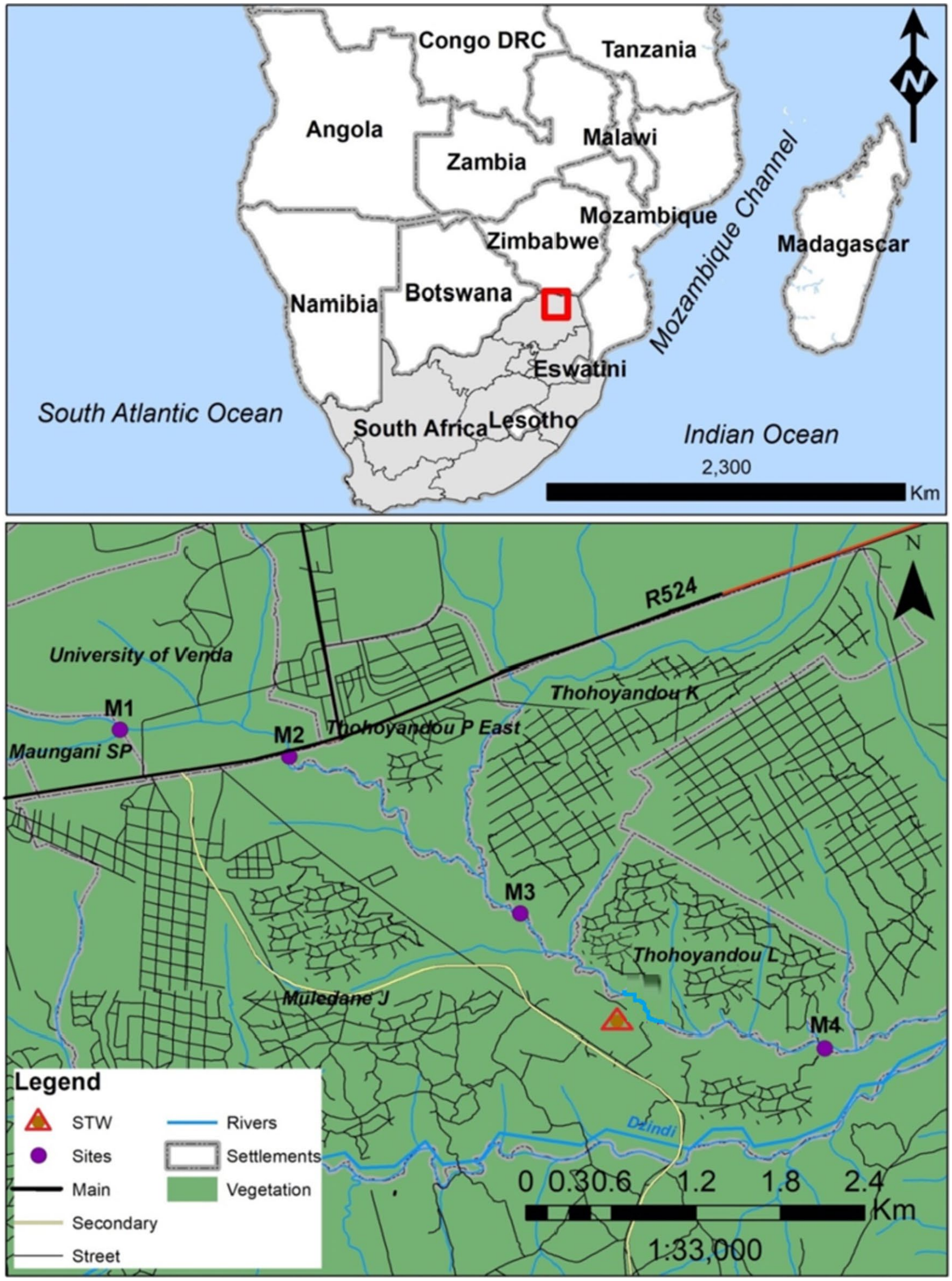

Fig. 1 Sampling sites (M1–M4) along the Mvudi River a tributary system, Limpopo province of South Africa. Adapted and modified from Dalu et al. (2021)

according to the physical form of the plastic material, either as hard, film, or foam (Lippiatt et al., 2013). The different macroplastic polymer groups, functional origin, and physical form were counted for each site and season.

Data analysis

We used a combination of non-parametric and parametric tests alongside diversity indices to quantify the distribution of plastics among sites and seasons. A PERMutational ANOVA (PERMANOVA) was used to calculate differences in macroplastic debris types across sites (i.e. M1–M4) and seasons (i.e. summer, autumn, winter, and spring), with pairwise comparisons being done for significant factors. The number of litter 'species' in each plot (a measure of α-diversity; Magurran, 2004; i.e. the number of categories of river litter—within-habitat diversity; Whittaker, 1965) was calculated. The total number of macroplastic debris 'species' in each sample (a measure of γ-diversity; Magurran, 2004) was further calculated for each site. A measure of macroplastic debris 'species' turnover inside each site (i.e. the Whittaker β-diversity corresponding to the internal heterogeneity in a 'community' or in a site) was calculated as $\beta W = \gamma/\text{mean}\ \alpha$ (Koleff et al., 2003). The Shannon–Wiener diversity index (H') and evenness for macroplastics were calculated according to Battisti et al. (2017), Battisti et al., 2018).

A two-way ANOVA was used to assess macroplastic diversity metrices and abundances, differences within sites (i.e. M1–M4) and seasons (i.e. winter, spring, summer, autumn). All assumptions for a parametric test were met based on the homogeneity of variances and normality assessments. Tukey's post hoc analysis was conducted for significant variables to see which sites were driving the differences. We further examined the differences in macroplastic debris 'communities' and identified the primary species that contributed to the differences using analyses of similarities (ANOSIM) and similarity percentages–debris 'species' contributions (SIMPER) in PRIMER 5.0. To assess differences in polymers and physical form across seasons and sites, a Kruskal–Wallis test was used since the data were found to be violating all assumptions of a parametric test.

Results

Macroplastic debris functional group and abundance

There were 26 types of macroplastic debris collected across all four seasons, and they varied in terms of functional group, resins, and abundance. Overall, the spring season was more diverse in terms of macroplastic type than all other seasons. The most dominant macroplastic debris collected across all seasons were plastic bags (mean range 3.0–55.6%) (Table 1). The most dominant macroplastic debris during winter were plastic bags (mean range 12.5–53.0%) like spring (mean range 15.0–39.2%) across all sites, while the food wrappers were the second most dominant. The least observed macroplastic items collected were cigarette filters, soap wrappers, detergent bottles, straws, pill containers, and plastic bottles (Table 1). The most dominant macroplastic debris collected during summer were beverage containers (mean range 16.7–36.7%), whereas the least observed macroplastic debris were soap wrappers, plastic rope, and small net pieces, other jugs/containers, detergent bottles, and appliance parts all with one count (Table 1). Autumn had the least diverse macroplastic debris observed, with plastic bags and food wrappers being the dominant macroplastic debris collected, similar to winter and spring (Table 1).

The analyses of similarities (ANOSIM) indicated a low global test value ($R = -0.12$) which suggested that dissimilarities were greater within sites than between sites (Table 2). The similarity percentages (SIMPER)–debris 'species' contributions indicated that there was an average dissimilarity of 58.0% between sites M1 and M2, and a high dissimilarity of 74.5% for sites M3 and M4. The main dissimilarity debris contributors across sites were food wrappers, plastic rope, and plastic bags (Table 2). Similarly, we observed that macroplastic debris' indicated dissimilarities were greater within seasons than between seasons ($R = -0.05$). Average dissimilarity was observed for summer vs autumn (48.5%), while the rest of the seasons had dissimilarity values that ranged from 61.2 to 69.6% (Table 2). The main debris dissimilarity contributors across seasons were food wrappers, plastic bags, and beverage containers (Table 2).

Table 1 Macroplastic debris type, resin, and percentage abundances found along the Mvudi River across seasons and sites. Abbreviations: *LDPE* low density polyethylene, *PET* polyethylene terephthalate, *PS* polystyrene, *PVC* polyvinyl chloride, *PP* polypropylene, *CA* cellulose acetate, *HDPE* high-density polyethylene, *PU* polyurethane, *ABS* acrylonitrile butadiene styrene

Plastic fragment	Type	Resin group	Winter				Spring				Summer			Autumn		
			M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M1	M2	M3
Appliances parts	Hard	ABS				8.5 ± 7.5	4.5 ± 4.0	2.0 ± 3.4	2.8 ± 4.8							
Beverage containers	Hard	PET	2.2 ± 3.8	4.9 ± 5.0	4.2 ± 7.2	4.8 ± 8.2	9.3 ± 2.1	10.6 ± 9.4	13.9 ± 12.7	6.7 ± 11.5	36.7 ± 2.62	22.2	16.7	18.9 ± 13.5	33.3 ± 47.1	
Bottle caps	Hard	HDPE	2.3 ± 4.1	3.2 ± 5.5		3.7 ± 6.4	3.8 ± 6.6	2.0 ± 3.4	2.8 ± 4.8	8.3 ± 14.4	3.0 ± 5.2	22.2		5.6 ± 9.6		
Cigarettes filters	Hard	CA			2.1 ± 3.6			7.8 ± 13.6	2.8 ± 4.8							
Detergent bottle	Hard	HDPE		1.6 ± 2.7			1.0 ± 1.6							11.1 ± 19.2		
Disposable cup	Foam	PS	7.1 ± 12.4	3.3 ± 5.8			3.8 ± 6.6	14.3 ± 24.7			9.8 ± 9.2					
Disposable medical masks	Film	PP			6.3 ± 10.8											
Foam food containers	Foam	PS	4.4 ± 7.7	9.8 ± 10.0			6.8 ± 6.1	6.7 ± 7.2								
Food wrappers	Film	PP	39.6 ± 15.2	9.8 ± 10.0	12.5 ± 12.5	11.1 ± 19.2	26.8 ± 16.7	4.8 ± 8.2	13.9 ± 12.7	20.0 ± 34.6	16.5 ± 14.2		16.7	26.1 ± 26.7		
Furniture wrappers	Film	LDPE		3.2 ± 5.57	12.5 ± 21.7	22.2 ± 38.5	1.9 ± 3.3	2.0 ± 3.4								
Hard food containers	Hard	PET	6.7 ± 11.5		2.1 ± 3.6		9.7 ± 12.0	3.9 ± 6.8								
Maize meal sack	Film	PP					2.6 ± 44		8.3 ± 7.2		6.7 ± 11.5		16.7			
Medicine bottle	Hard	PET							2.8 ± 4.8							
Other jugs/containers	Hard	PET	7.4 ± 12.8													
Pill container	Hard	HDPE					2.0 ± 3.4									
Plastic bags	Film	LDPE	22.0 ± 22.2	53.0 ± 42.0	12.5 ± 12.5	33.9 ± 30.0	23.1 ± 5.5	39.2 ± 20.0	18.1 ± 18.8	15.0 ± 13.2	3.0 ± 5.2	22.2	16.7	35.6 ± 3.8	66.7 ± 47.1	55.6 ± 50.9
Plastic bottle	Hard	PET		1.6 ± 2.7			2.9 ± 4.9				9.1 ± 15.7			2.8 ± 4.8		
Plastic matt	Hard	PVC					1.0 ± 1.6									
Plastic rope pieces	Hard	PP		1.6 ± 2.7	38.2 ± 5.2				30.6 ± 39.4	8.3 ± 14.4		33.3	33.3			33.3 ± 57.7

Table 1 (continued)

Plastic fragment	Type	Resin group	Winter				Spring				Summer			Autumn		
			M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M1	M2	M3
Plastic utensils	Hard	PP		3.2±5.5							6.7±11.5					
Plumbing pipe	Hard	PVC			5.6±9.6				4.2±14.4	8.3±14.4	6.7±11.5					
Rubber	Hard	PVC	8.1±7.1	3.2±5.57		11.1±19.2										
Soap wrappers	Film	LDPE		1.6±2.7	4.2±7.2	4.8±8.2				33.3±57.7	1.9±32					11.1±19.2
Sponge	Foam	PU						6.7±7.2								
Straw	Film	PP					1.0±1.6									

Macroplastic distribution

A total of 358 macroplastic items (mean site range 0.55 ± 0.30 (SD) to 1.34 ± 0.92 particles per m^2) were collected for this study, with 127 (site mean 1.27 ± 0.35 particles per m^2) macroplastic items collected during winter, 134 (site mean 1.34 ± 0.92 particles per m^2) in spring, and 37 (site mean 0.55 ± 0.30 particles per m^2) in summer, whereas 60 (site mean 0.60 ± 0.51 particles per m^2) macroplastic items were collected during autumn. Most macroplastic debris were collected in site M1 (Fig. 2) whereas the fewest macroplastic debris were counted at M4 (Fig. 2). Based on PERMANOVA, we observed no significant differences in macroplastic debris across sites (Pseudo-F = 1.114, $p(MC) = 0.349$) and seasons (Pseudo-F = 1.496, $p(MC) = 0.112$).

The γ-diversity generally decreased across study sites from M1 to M4 for winter, spring, and autumn. Spring had high γ-diversity (mean range 2.67–8.00), with autumn having lower γ-diversity (mean range 1.00–5.00) (Fig. 3a). The Whittaker β-diversity for all four seasons ranged between 1.75 and 7.25 among seasons, with a variable trend across the study sites (Fig. 3b). Shannon–Wiener diversity index had no clear trends across seasons with autumn having low diversity index values (mean range 0.42–1.48). Winter (mean 1.00 ± 0.32) and spring (mean 0.78 ± 0.71) seasons at site M4 generally had low Shannon–Wiener diversity index values (Fig. 3c). Evenness was high for all seasons except in site M2 during the summer (Fig. 3d).

Significant differences for γ-diversity ($F = 4.338$, $p = 0.011$), abundances ($F = 5.604$, $p = 0.003$), and Shannon–Weiner ($F = 5.282$, $p = 0.005$) were observed among the study sites, with significant seasonal differences being observed for γ-diversity ($F = 5.767$, $p = 0.003$), abundances ($F = 4.084$, $p = 0.015$), Shannon–Weiner diversity ($F = 5.733$, $p = 0.003$), Whittaker β-diversity ($F = 3.940$, $p = 0.036$), and evenness ($F = 5.201$, $p = 0.005$). Tukey's pairwise comparisons indicated significant site differences for γ-diversity site M1 vs M4 ($p = 0.006$), abundance sites M1 vs M4 ($p = 0.002$), Shannon-Weiner diversity sites M1 vs M2 ($p = 0.013$), and M1 vs M4 ($p = 0.003$). Pairwise comparisons for seasonal differences were observed for γ-diversity spring vs summer ($p = 0.015$) and spring vs winter ($p = 0.012$), Shannon–Weiner diversity winter vs autumn ($p = 0.030$), spring vs summer ($p = 0.035$) and spring vs autumn ($p = 0.011$), evenness winter vs summer ($p = 0.008$) and

Table 2 Two-way crossed ANOSIM and SIMPER for testing the groups on macroplastic debris 'communities' along the Mvudi River

Groups	Global Test R	Dissimilarity distance (%)	Main dissimilarity contribute debris (%)
Sites	−0.12		
M1 × M2		58.8	Food wrappers (18.86%), beverage containers (12.49%), plastic bags (8.20%), disposable cup (7.16%)
M1 × M3		69.8	Plastic rope (13.95%), food wrappers (12.46%), plastic bags (11.16%), beverage containers (10.12%)
M1 × M4		58.0	Food wrappers (16.68%), plastic bags (14.27%), beverage containers (11.95%)
M2 × M3		70.5	Plastic ropes (17.15%), plastic bags (14.88%), food wrappers (12.84%), beverage containers (10.89%)
M2 × M4		71.7	Plastic bags (23.50%), food wrappers (13.78%), beverage containers (9.78%), food containers (7.26%)
M3 × M4		74.5	Plastic ropes (23.68%), plastic bags (17.69%), beverage containers (12.13%), food wrappers (9.06%)
Seasons	−0.05		
Winter × spring		61.2	Plastic bags (11.34%), food wrappers (10.20%), beverage containers (9.31%), furniture covers (7.98%)
Winter × summer		67.5	Food wrappers (14.16%), beverage containers (12.95%), bottle caps (6.48%)
Spring × summer		63.3	Food wrappers (13.39%), beverage containers (11.24%), maize meal packages (7.08%)
Winter × autumn		69.6	Food wrappers (15.43%), plastic bags (15.36%), beverage containers (10.18%), furniture covers (8.57%), plastic ropes (8.48%)
Spring × autumn		68.1	Food wrappers (15.08%), plastic bags (14.61%), beverage containers (10.32%), plastic ropes (8.74%), soap wrappers (8.65%)
Summer × autumn		48.5	Beverage containers (18.03%), plastic bags (13.75%), food wrappers (12.06%), bottle caps (8.94%)

spring vs summer ($p = 0.010$), and Whittaker β-diversity summer vs autumn ($p = 0.010$).

Polymer group variation and macroplastic physical form

Macroplastic debris consisted of 9 different polymers which varied in terms of abundance among sites and seasons (Table 1 and 3; Fig. 4a). The most dominant polymers were polypropylene (PP) (30.4%) and low-density polyethylene (LDPE) (33.7%), while the least observed polymer was polyurethane (PU) (0.4%), cellulose acetate (CA) (1.2%), and acrylonitrile butadiene styrene (ABS) (1.5%) across all seasons (Table 1; Fig. 4a). The polymer abundances differed across sites (Table 1). Site M1 was dominated by PP and LPDE during winter (42.2%) and spring (27.7%), respectively, while summer and autumn were dominated by PP (31.8%) and polyethylene terephthalate (PET) (34.4%), respectively. The PU and CA were not observed in site M1 (Table 1; Fig. 4a). The LPDE (41.2% winter; 35.5% spring), PET (61.1% summer), and PP (50.0% autumn) were dominant for site M2

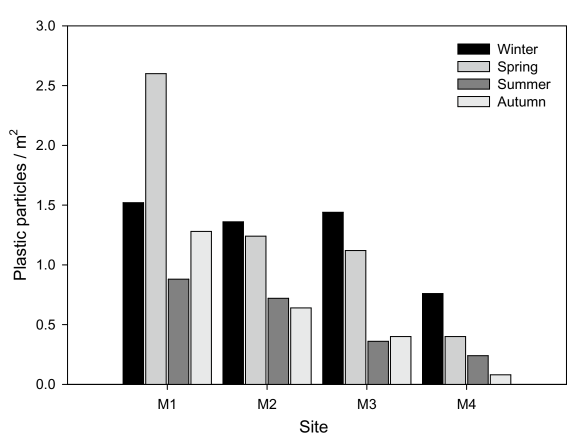

Fig. 2 Macroplastic debris total abundances per m^2 collected across four seasons (i.e., winter spring, and summer, autumn) in the Mvudi River system, South Africa

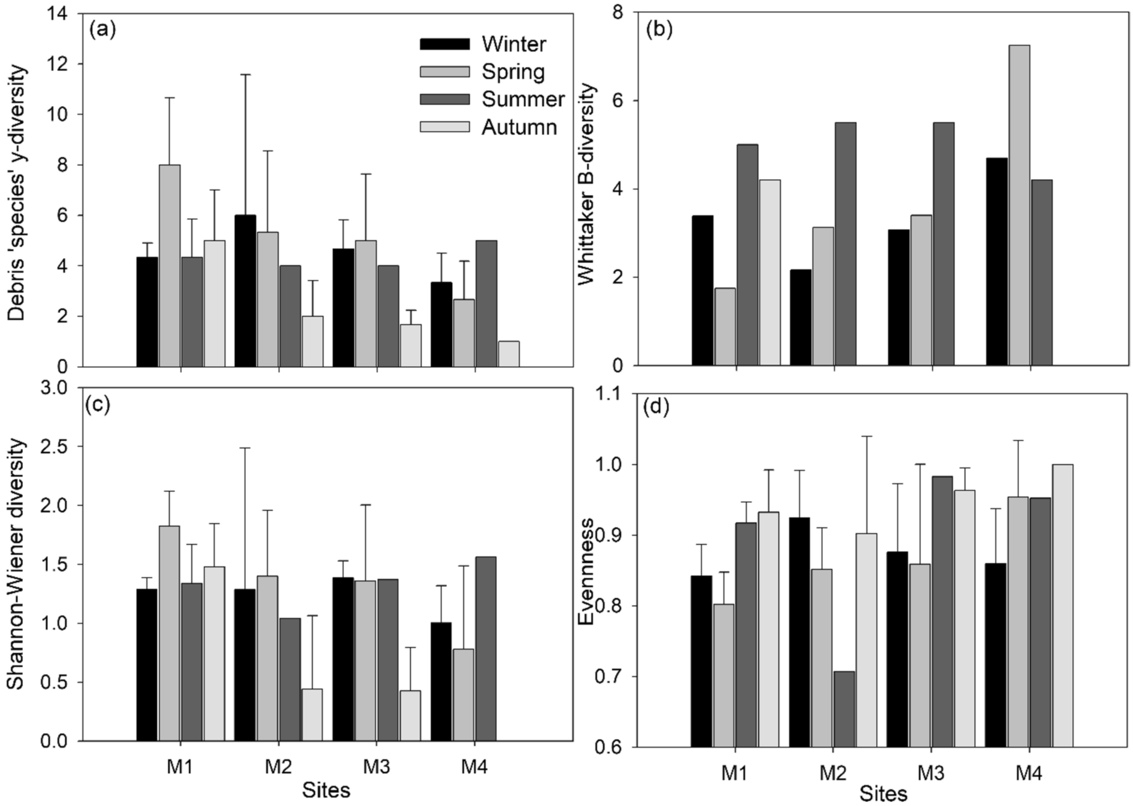

Fig. 3 Macroplastic functional groups (**a**) debris 'species' (γ-diversity), (**b**) Whittaker β-diversity (**c**) Shannon–Wiener index, (**d**) evenness for four seasons (i.e. winter, spring, summer, autumn)

(Table 1; Fig. 4a). Sites M3 and M4 were dominated by LPDE and PP during winter, summer, and autumn. High-density polyethylene (HDPE) was not observed across sites M3 and M4, while ABS and CA were not observed on site M4 except for winter (Table 1; Fig. 4a). Significant differences ($p<0.05$) among macroplastic debris polymers were observed across sites for PET and PS, with no significant differences being observed for other polymers (Table 3). Significant seasonal differences were observed for LPDE and PVC polymers (Table 3).

Macroplastic physical forms, namely hard, foam, and film, were observed across all seasons and sites in varying proportions (Table 1). The most dominant macroplastic physical form in terms of abundance was film, followed by hard form, and lastly, foam form across all seasons and sites (Fig. 4b). Significant site differences ($p<0.05$) were observed for form, with similarities ($p<0.05$) being observed for hard form. Film tended to be high across all sites except in sites M1 (autumn), and M2 and M3 (summer). Foam physical form was the least observed across all sites, with no recordings for sites M3 and M4 across all seasons, and site M2 (autumn) (Table 1; Fig. 4b). No significant ($p>0.05$) seasonal differences were observed for all physical forms (Table 3).

Discussion

The study aimed to investigate the source, driving factors, type, and abundance of macroplastic debris within the Mvudi River Catchment, South Africa. We observed that there was a non-significant difference in macroplastic debris abundance across sites and seasons. We therefore reject our core hypothesis. The detected high PP polymer macroplastic debris abundance suggests that human activities such as waste disposal and the visitation of people to the river were high across all four seasons. Those activities

Table 3 Two-way ANOVA of the macroplastic debris polymer and physical foam from Mvudi River. Bold values indicate significant differences at $p < 0.05$ and abbreviations *PP* polypropylene, *PET* polyethylene terephthalate, *PS* polystyrene, *HDPE* high-density polyethylene, *LDPE* low-density polyethylene, *PVC* polyvinyl chloride, *CA* cellulose acetate, *ABS* acrylonitrile butadiene styrene, *PU* polyurethane

Resin group	Season			Site		
	H	df	*p*	H	df	*p*
Polymer						
ABS	4.805	3	0.187	0.997	3	0.802
CA	4.393	3	0.222	3.857	3	0.277
HDPE	2.716	3	0.438	4.107	3	0.250
LDPE	**7.874**	**3**	**0.049**	3.136	3	0.371
PET	1.139	3	0.768	**10.810**	**3**	**0.013**
PP	2.863	3	0.413	4.782	3	0.188
PS	1.630	3	0.653	**11.087**	**3**	**0.011**
PU	3.000	3	0.392	3.000	3	0.392
PVC	**10.989**	**3**	**0.012**	1.533	3	0.675
Physical form						
Film	7.755	3	0.051	5.331	3	0.149
Foam	1.703	3	0.636	**10.926**	**3**	**0.012**
Hard	4.054	3	0.256	6.875	3	0.076

increase the chances of macroplastic litter along the Mvudi River shoreline, while the meteorological factors such as wind and rain (Dalu et al., 2019) will also have contributed to the distribution and abundance of macroplastic along the Mvudi River.

The distance of households from shorelines is another factor that can be considered for the non-correlation between household density and macroplastic concentrations; at great distances (100 m), it is unlikely that household density will have an impact on the accumulation of macroplastic debris near the river (Lee et al., 2015). People visiting the river directly contribute to litter, and it may be challenging to distinguish this from the litter that is washed to the shoreline (Kershaw et al., 2019). Moreover, additional environmental variables such as wind direction, river flow, and precipitation can also influence the distribution of macroplastics at small to large scales.

There was a variety of macroplastic functional group 'species' collected across all seasons and sites, mainly plastic litter associated with household and recreational activities, with plastic bags and food wrappers functional groups identified as the predominant plastic sources over the course of four seasons; this was indicated by the high trend of evenness across all the seasons in the current study which shows less frequent dominance of one type of macroplastic debris. The considerable differences indicated by the Shannon–Wiener index were related to seasonal changes in the number of plastic debris. The observed changes in total plastic item numbers for α, β, and *y*-diversity throughout the four seasons can be attributed to variations in deposition patterns caused by context-specific micro-geographical and environmental factors (Battisti et al., 2018). The higher diversity seen during the spring season suggested that there was a higher transition of plastic litter between seasons (Battisti et al., 2018).

Similar to this study, research on other river systems has found that plastic bags were the most dominant macroplastic collected (Pe et al., 2020). According to Jambeck et al. (2015), wind can transport plastic waste from poorly managed landfill sites and residential areas to waterbodies, where it eventually accumulates. However, we believe that, in the primary urban river of our study, the majority of macroplastics accumulated directly from in situ human activity, with climatic or hydrodynamic influences being less significant. Pe et al. (2020) suggested that most plastic bag comes from community economic activities such as markets, household waste, and recreation activities along the shoreline.

The identification of plastic polymer types is essential since it allows for inferences on the origin of plastic pollutants and further determines whether they originate from the breakdown of macroplastic components from nearby industrial or recreational activities (Veerasingam et al., 2016). The plastic polymer type results of this study showed that the most dominant polymers were PP and LPDE. Dalu

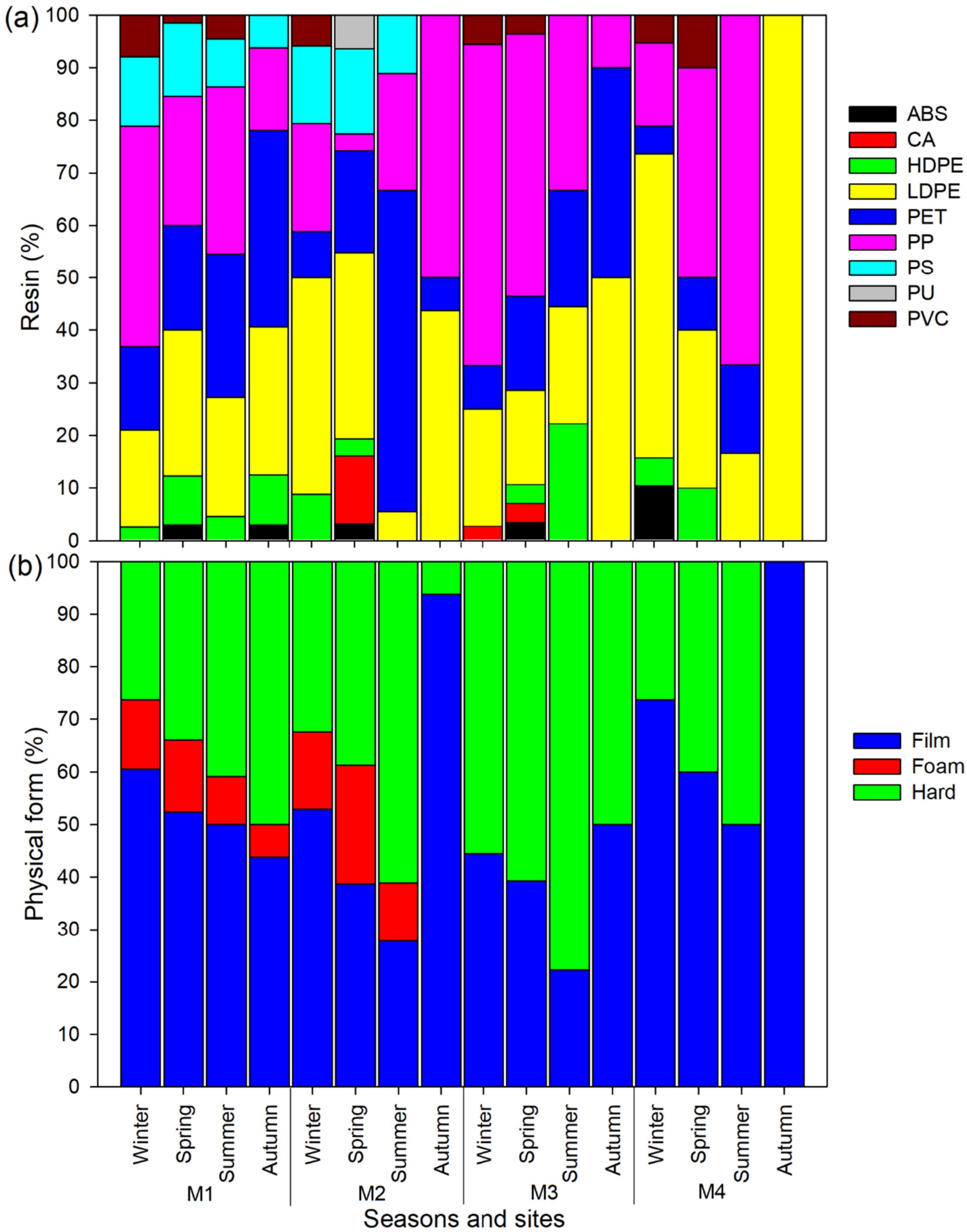

Fig. 4 The macroplastic functional group (**a**) counts (%) of polymers and (**b**) macroplastic physical form counts (%) over a period of four seasons (i.e. winter, spring, summer, and autumn). Abbreviations: PP polypropylene, PET polyethylene terephthalate, PS polystyrene, HDPE high-density polyethylene, LDPE low-density polyethylene, PVC polyvinyl chloride, CA cellulose acetate, ABS acrylonitrile butadiene styrene, PU polyurethane

et al. (2019), Maharana et al. (2020), and Blettler et al. (2017) also showed that the dominant polymer was PP. According to Claessens et al. (2011), PP is mostly used in the manufacturing of packaging applications such as bottles, beverage caps, bags, and other home appliances. Most of the PP polymer-type plastic was collected floating in the river during data collection (personal observation). In the current study, LPDE polymer was collected on film plastic-type materials such as plastic bags, soap, and furniture wrappers. Nakashima et al. (2012) also observed the high abundance of LPDE in their study. These polymer type macroplastics may later be washed to the nearest shoreline, suggesting that the distribution of polymers is also influenced by the availability of transport for a polymer and the climatic condition from the source area to another area (Erni-Cassola et al., 2019). The reason why LPDE plastics dominated was mostly due to their lightweight and buoyance, which makes them less likely to sink and more likely to be transported by water currents, thereby increasing visibility and prevalence in rivers (van Emmerik & Schwarz, 2020). These plastics tend to dominate in many rivers of the world (e.g. Kurniawan and Imron (2019a, 2019b) in the Wonorejo River, Surabaya, Indonesia; Rowley et al. (2020) along the Thames River system, UK; and Parvin et al. (2022) in urban lakes and peripheral Rivers of Dhaka, Bangladesh). Furthermore, LDPE are resistant to tearing and breaking (i.e. exhibit durability), making them less susceptible to fragmentation in the fast-flowing environment of rivers compared to other plastics (Dilara & Briassoulis, 1998; Fotopoulou & Karapanagioti, 2019). While sunlight degradation breaks down some plastics, LDPE may only experience surface changes, leaving the core structure intact and persistent in the aquatic environment (Doğan, 2021). Lastly, their wide range of applications in a vast array of everyday items, including plastic bags, packaging, squeeze bottles, and agricultural films, can translate to a high probability of accidental or intentional release into aquatic ecosystems (Dilara & Briassoulis, 1998). Thus, understanding the reasons behind LDPE's dominance is crucial for addressing plastic pollution in rivers as it highlights the need for better waste management systems, improved recycling infrastructure for complex plastics, and a shift towards more sustainable packaging materials and consumer choices.

Film was the most dominant macroplastic physical form observed in this study, similar to the study conducted by Rohaningsih et al. (2022); this is attributed to the influence of the human activities that occur in the vicinity. These are lightweight plastic forms that are unlikely to be transported long distances in water (Martí et al., 2017). Most of the film macroplastics collected in this study were made from the PP polymer. Film plastics are widely used because they are light in weight, slow to degrade, and reusable, while packaging bags are one of the most used plastic films as observed in this study. Film plastics such as black perforated film and white transparent and non-transparent plastic film are widely used in agricultural activities (Yan et al., 2016). Film plastics have a negative impact on aquatic environments since they can be ingested by organisms and cause physical and chemical effects (Dris, 2017). We found that the Mvudi River Catchment was dominated by film plastic pollution, which needs to be taken into consideration before those macroplastics are broken down by degradation and continue to pose a threat to aquatic organisms and the people who use water from the catchment.

Conclusions

The distribution of macroplastic debris based on the functional group, physical form, and polymer group were widespread and similar across sites and seasons, indicating that pollution intensity is consistent spatially in the study system and broadscale management is needed. Macroplastics found in the Mvudi River are associated with human activities such as settlement, recreation, and dumping as well as economic activities such as markets. We also suspect that the meteorological and hydrological factors played a major role in macroplastic accumulation due to the macroplastic debris that we collected floating in the Mvudi River, but these require further assessment. The diversity of macroplastic functional groups was significantly different among seasons and sites, with high diversity in winter and pollution levels elevated on the shoreline compared to mainstreams. Understanding seasonal variations in plastic loads and their drivers provides information on the sources and destiny of plastic, which can improve management methods for reducing this risk to the aquatic ecosystem.

Data Availability

The datasets generated and/or analysed during the current study are not publicly available as they are part of larger study that is currently on-going but are available from the corresponding author on reasonable request.

Author contribution RM: writing, reviewing and editing, investigation, data analysis, RNC: writing of the manuscript, conceptualization, supervision, visualisation, data analysis, funding, writing, reviewing and editing, FD: funding, investigation, visualisation, funding, writing, reviewing and editing, LFM: data analysis, visualisation, investigation, writing, reviewing and editing, NW: funding, methodology, visualisation, funding, data analysis, writing, reviewing and editing, TD: writing of the manuscript, conceptualization, methodology, supervision, visualisation, data analysis, funding, writing, reviewing and editing.

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