Faulstich *et al. Microplastics and Nanoplastics* (2022) 2:24
https://doi.org/10.1186/s43591-022-00043-1

Microplastics and Nanoplastics

RESEARCH

Open Access

Microplastics in Namibian river sediments – a first evaluation

L. Faulstich[1*], J. A. Prume[2,3], R. Arendt[1], Ch. Reinhardt-Imjela[1], P. Chifflard[4] and A. Schulte[1]

Abstract

The African continent is rarely the focus of microplastics research, although the ubiquity of microplastics in the environment is undisputed and still increasing. Due to the high production and use of plastic products and the partial lack of recycling systems in many parts of the African continent, it can be assumed that microplastic particles are already present in limnic and terrestrial ecosystems. Few studies, mainly from South Africa and the Northern African region, show a contamination with microplastics, especially in marine environments. This study aims to explore the presence and composition of microplastics in fluvial sediments of the major catchments in Namibia with a regional focus on the Iishana system in Northern Namibia, as one of the most densely populated areas in the country. In March 2019 and March 2021, at the end of the rainy seasons, sediments from the Iishana system and of the largest river catchments were sampled. Extraction was performed by density separation using the Microplastic Sediment Separator (MPSS) with the separation solution sodium chloride (density of 1.20 g/cm^3). The particle size was determined by filtration and fractionation, and the polymer type by measurement with ATR-FTIR spectroscopy (minimum particle size 0.3 mm). Microplastics were found in the sediments of each river system, most of the particles in the Iishana system (average of 13.2 particles/kg dry weight). The perennial, the ephemeral rivers, and the Iishana system are similar concerning polymer type and particle size. Polyethylene and polypropylene were the dominant polymer types. Most of the particles were found in the size fractions 0.3 – 0.5 mm and 0.5 – 1.0 mm. The particles were found mainly as fragments and films, the majority transparent and brown.

Keywords: Microplastics, Fluvial sediments, Namibia, Ephemeral rivers, FTIR spectroscopy

Introduction

In Africa, plastics have been used since the late 1950s, which is long before any recycling policies have been established [1]. Since then production, import, and consumption of different polymers and plastic products increased steadily and caused a high amount of waste [2–5]. The need for more safety requirements, transport facilitations, and hygiene packaging of food and beverages triggered the increase in plastic use, especially single-use plastics [4, 6]. A growing population causes an increased waste generation, which in turn means the need for a well-functioning waste disposal system [7]. In many parts of the African continent, the management of plastics is insufficient, because of economic and political reasons, such as the lack of financing and investment mechanisms or the absence of producer-consumer responsibility [2]. Most of the waste is dumped or burned on disposal sites as there are few measures that allow proper disposal [4, 8, 9]. The growing number of people living at short distances from river systems raised the amount of land-based waste that could end up in the aquatic environment. Risk perception and communication about plastic pollution are still insufficient and social awareness within the society towards this problem is lacking [10]. Although the African continent is not the focus of microplastic research [1, 9, 11], plastic particles have been detected mainly in marine and estuarine

---

*Correspondence: leona.faulstich@fu-berlin.de

[1] Department of Earth Sciences, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany
Full list of author information is available at the end of the article

areas in South Africa, the northern, western, and eastern African regions [9, 12, 13]. Three rivers from Nigeria and Cameroon are among the top 20 polluting rivers, which transport plastic into the ocean [14]. In Arusha, Tanzania, microplastics (MP) were found in surface water and river sediments [15]. The relationship between microplastics and macroplastics in irrigated farms and an urban river was demonstrated. In general, there is a large research gap on MP in freshwater systems in central and southern Africa, except for South Africa [13, 16].

The forecasts for Sub-Saharan Africa assume a doubling of waste production from 2030 to 2050 to 510 million tons per year [17]. At the same time, the waste collection rates are in the Sub-Saharan region very low with 44%. Whereby the urban collection rates (43%) are almost five times as high as the rural collection rates (9%). More than 69% of the collected waste is openly dumped in Sub-Saharan Africa [17]. Generally, the degree of impact of urban waste on microplastic loads is enormous [7, 9]. Dealing with waste plays a crucial role when comparing remote and urban areas. Compared to remote areas, urban areas offer more waste collection and sorting infrastructure that might help to reduce the amount of plastics in the environment [8]. In remote areas the difficulty to handle waste environmentally friendly is enormous. Urban waste, littering, and consumer use generate smaller plastic particles as a breakdown from larger pieces of plastic occurs [11].

Namibia produces less than 100 tons of plastic waste per day, but its neighboring country Angola produces twice as much [1]. Increased litter on transnational rivers can lead to fluvial transport of plastic particles to Namibia. Neither Namibia nor its neighboring countries have established a plastic waste management system, some of the material is exported to South Africa or overseas [18]. On a small scale, the informal sector plays an important role in the recycling industry in Namibia. Collecting, sorting, and dropping off waste products as a small source of income has become established in many places [19].

Due to the insufficient recycling system, many particles enter the (aquatic) environment [13]. Besides the fluvial transport of plastic waste and MP, there is little known about MP in freshwater systems, compared to the knowledge about marine areas. Although about 80% of the plastic is estimated to derive from the terrestrial areas and rivers are dominant pathways for MP [1, 10, 14, 20, 21]. So far, most of the studies conducted in the freshwater environment have focused on the occurrence of plastic debris on the water surface, while sediments were hardly examined [22–25]. The number of studies focusing on MP in African lakes is scarce, it is not yet possible to draw conclusions about the total extent of microplastic pollution in limnic systems on the African continent [9]. Hydrodynamic processes, particle size and density influence the fate of MP in sediments. Particles can enter the river water via erosion and resuspension of the riverbed [26]. The particles not only remain in the free water column. Due to the different densities of polymer types, some particles settle down and accumulate in bed or bank sediments [27, 28]. The deposition of MP increases in low-flow river segments [23, 29, 30].

Plastic and especially microplastic debris have a great ecological and economic impact on freshwater systems [20, 31, 32]. Environmental variables, like water density, temperature, salt content, oxygen, flow velocity, water depth, and sediment types impede measurement and monitoring in freshwater systems [10]. Plastic poses a health risk to animals living in the aquatic environment and might act as a vector for contaminants, like persistent organic pollutants (POPs) or heavy metals [33, 34], which, however, is still controversially discussed [34].

This study will investigate the number of plastic particles in the main river systems in Namibia with a focus on the Iishana system, which is one of the most densely populated areas in the country and the dominant freshwater system in Namibia. The aim is to make the first survey of microplastic pollution in Namibian freshwater systems. For the first time, the occurrence, abundance, and composition of MP in fluvial sediments are investigated in Namibia. Polymer type and size fraction were determined to gain knowledge about the origin and distribution of the particles. Research priorities defined by Akdogan and Guven [29] and Khan et al. [9] show a lack of catchment-based research in African freshwater systems. Therefore, the central research question is how many plastic particles can be found in the sediments of the main river systems in Namibia. Subsequent question focus on the different size fractions and polymer types, and whether there are significant differences between river systems.

Material and methods

Study area

Namibia as an arid and semiarid country with a strong variability of precipitation faces big differences in water availability. The national hydrological system is characterized by four perennial boundary rivers (Kunene, Kavango, Oranje, and Zambesi) and several ephemeral river systems, in Namibia called Rivier (Fig. 1) [35]. The transboundary Cuvelai Basin in northern Namibia is the biggest national ephemeral system. The discontinuous occurrence of flow and episodic interruptions by floods characterize ephemeral rivers, water availability is episodically limited [36]. The rivers Ugab, Omaruru, Swakop, Kuiseb, and Tsauchab drain from the western escarpment to the Atlantic Ocean and are

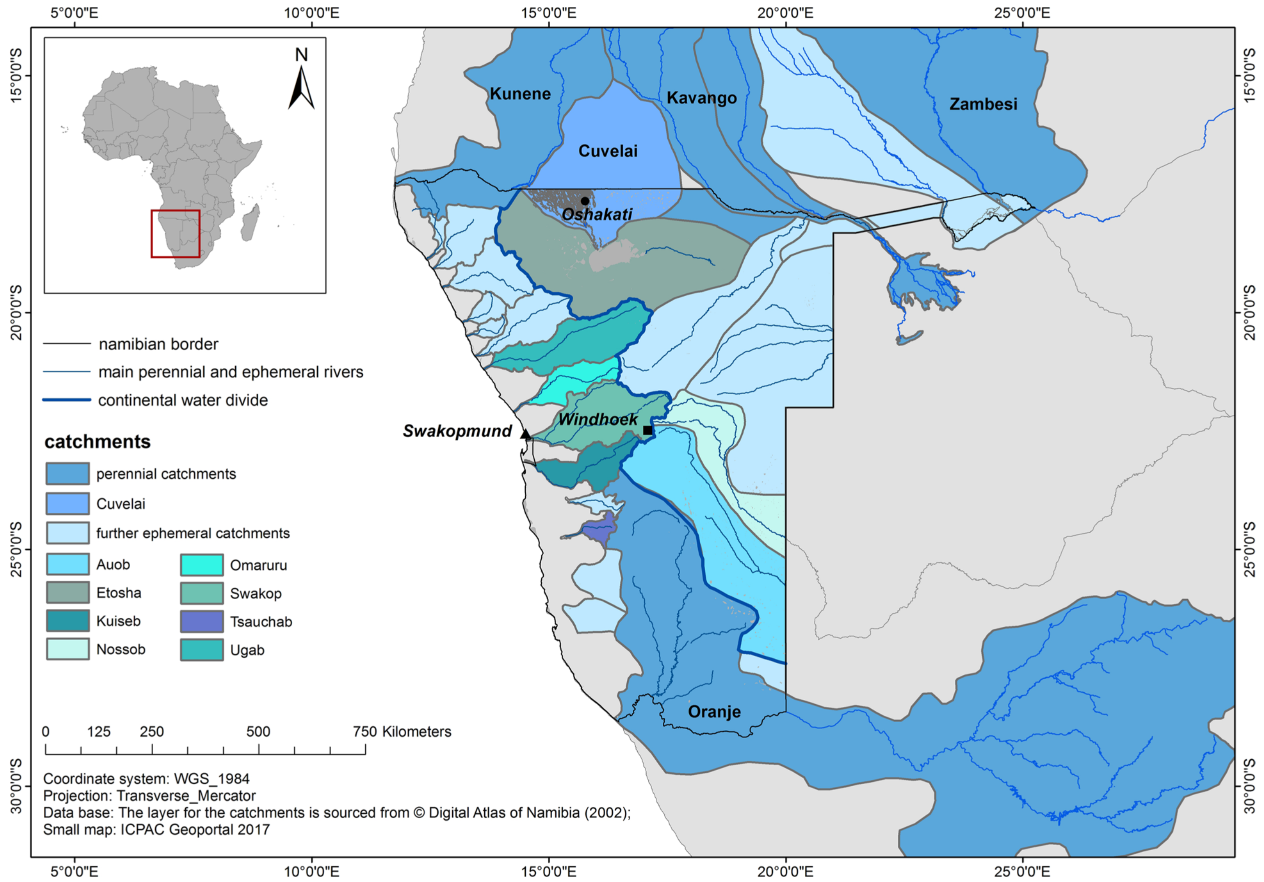


Fig. 1 The hydrological system of Namibia with the catchments of the four perennial rivers, the Cuvelai Basin, ephemeral catchments (the sampled are colored), and the continental water divide

part of the ephemeral river catchments within the Namib Desert [36]. The Owambo is a dry river in the eastern part of the Etosha National Park that rarely carries any water and ends in the Etosha pan. The Auob and its tributaries, like Olifants, and the Avis River, are dry/ruderal Riviers in the Kalahari and hardly carry any water [35].

The focus region is the Iishana system as part of the Cuvelai Basin in central northern Namibia. Shallow depressions (natural pans), called Iishana (singular O*shana*), and thousands of small channels form the hydrological system [37–39]. It is an ephemeral river system, episodically coherent only during the rainy season. In the dry season, water levels in the pans decrease due to evaporation and water use, causing some Iishana to dry out completely. Many pans and depressions are connected by narrow channels and only filled with water during the rainy season. The water flows from one pan to the next, and with enough rainfall in southern Angola and northern Namibia, the channels combine, link the pans, and build a broad network of small rivers [40]. The very low slope of 1 ‰ causes hardly any flowing movements of the surface runoff. Rather, the waters stand on the surface and cause large-scale flooding. Striking differences in water and sediment quality between urban and remote areas could be identified in a previous study [41]. The Iishana system is densely populated, compared to the rest of the country. Especially in the eastern part around the cities Oshakati and Ongwediva the population density is high with up to 100 people per km^2 [37]. A high population density causes a big amount of waste, which is deposited and burned at a waste dumpsite close to Oshakati. The waste management system is partially lacking, whereby huge amounts of macroplastics were found in the focus area [17]. Even if there is no heavy industry, nor packaging industry, the waste is generated by daily consumer products.

Quality assurance and quality control

As there is no standardized method for the determination of MP in sediments so far, the individual steps were derived and adapted from existing studies. Nevertheless, there are published guidelines to standardize reproducibility [42–44] and to assure quality analysis and quality control. In this study, the guidelines from Cowger et al. [42] were followed (see supplementary data 1). The procedure of density separation was derived from Imhof et al. [28], and further process steps were evolved in the laboratory for microplastics at the Faculty of Physics, University of Marburg [45]. The sampling was carried out with wood shovels and spoons that were wet cleaned before. The samples were transported in wet-cleaned aluminum containers, which were additionally wrapped with aluminum foil, to avoid any contamination. For the extraction of the plastic particles different techniques exist on how to proceed, they mainly include density separation, sieving, filtration, microscopic detection, and spectroscopic identification [46, 47]. During the whole process in the laboratory, clean, wet wiped surfaces, containers, and tools were used. Contaminations from the air were limited by controlled room ventilation. Contaminations from clothing or other materials were prevented by wearing cotton coats, wet cleaning all surfaces, working with wood or metal tools, and cleaning all tools with compressed air before use. All samples were permanently protected and covered with aluminum foil. In total four blank samples, empty runs without samples, were taken to identify external plastic contaminations, whereby four potential plastic particles were found. These particles are fragments and have the size of 0.3 mm, three are PP and one is polytetrafluoroethylene (PTFE). The contamination probably occurred from a non-replaceable plastic part of the MPSS.

Two blank samples of the air were taken during the process of density separation. The samples of air were taken in the same metal bowls in which the sediment samples were homogenized for preparation. No plastic particles were found in these samples.

Sampling

During the first field campaign in March 2019, sediment samples were taken from dried-up pans in the Iishana system. Based on existing sampling locations of previous investigations [41] sites were selected to provide a representative picture of the focus area. In March and April 2021 river bank and river bed sediments of the major Namibian river systems were sampled to gain knowledge about the amount of MP in the aquatic system in Namibia. The measurement grid was chosen to sample rivers throughout the country. Smaller and larger streams, rivers close and far from settlements were selected (Fig. 2). At each site, about 1.4 kg of wet weight material was taken. Sediment samples from three perennial rivers (Kunene, Kavango, and Oranje), nine ephemeral rivers, and 14 Iishana were analyzed. At the time of sampling, not all of the Iishana were filled with water, some had dried out.

At the rivers and Iishana filled with water, the samples were taken in the wet part of the riverbanks. At the locations without water, the sediments were taken in the riverbed. At the Kavango, Tsauchab, and Ugab, two samples were taken: Kavango1, Tsauchab1, and Ugab1 at the riverbanks and Kavango2, Tsauchab2, and Ugab2 further in at the river bottom (distance of 5 m from the banks). The Kunene, Kavango, Oranje, Kuiseb, Fish River, and Swakop1 all carried water. The Iishana, on the other hand, all carried water except for sites 3, 12, 16, 18, and 34 (Fig. 3).

Density separation with the microplastic sediment separator

At first, the samples were homogenized with a metal spoon, weighed, and three sub-samples were separated to determine the water content. These three sub-samples were dried at 60 °C for several days and weighed every day at the same time. Once the weight was constant, the water content was calculated. The main samples were dried at 30 °C, ensuring that they were covered and no contamination of the samples could occur.

The Microplastic Sediment Separator (MPSS; Hydro-Bios Apparatebau GmbH, Kiel, Germany) was used for density separation [28, 48]. Recovery rates of 100% for large particles (> 1 mm) and 95% for small particles (1000 μm – 40 μm) are described by Imhof et al. [28].

The separation liquid was made of filtered tap water (> 50 μm) and sodium chloride. A density of 1.19 g/cm^3 was produced by adding about 6 kg of sodium chloride to 15 l of water (solution concentration 6.8 M). The separation liquid was filtered again (> 300 μm) and introduced into the standpipe until a fill height of 85%. Then the sample was added into the MPSS while the motor was rotating. The liquid and the sample were mixed for 60 min. Big organic material was skimmed and stored for further analysis. In the following 14 h the descent process was performed. After this period the sample chamber with ball valve was removed, rinsed and the sample with the ascended material was filled into steep-bottomed glass bottles. About 750 ml were extracted per sample. For the analyses in 2021, the standing time was extended to 20 h to prolong the separation process.

Fractionation, filtration, staining and microscopy

The size fractionation was done by wet sieving the samples with a metal sieve cascade with a diameter of 150 mm (Test Sieve, DIN ISO 3310-1, stainless steel; VWR, Germany). Mesh sizes of 5 mm, 1 mm, 0.5 mm, 0.3 mm, and 0.1 mm were used. In 2021, sieves with a diameter of 75 mm (Test Sieve, DIN ISO 3310-1, stainless steel; ATECHNIK, Germany) were used to simplify

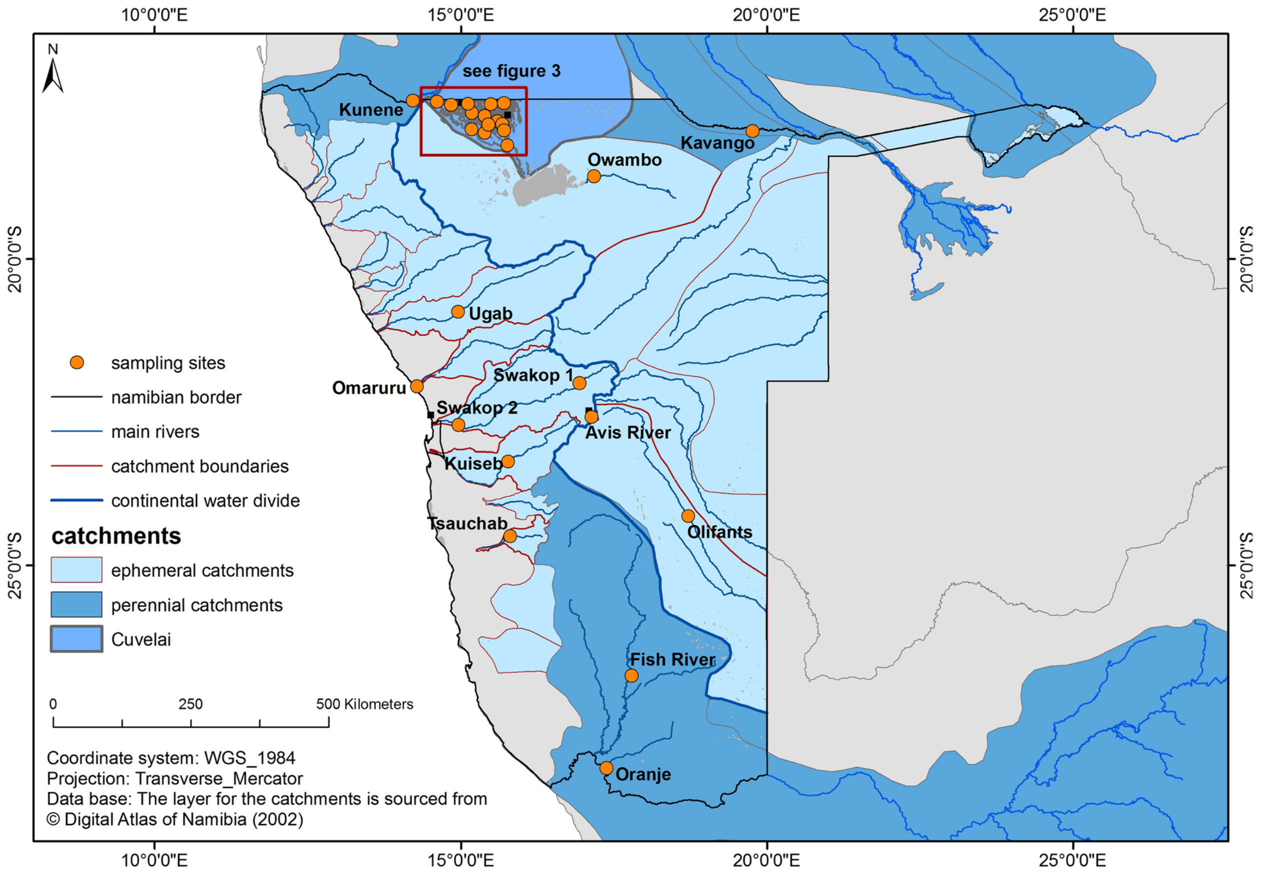


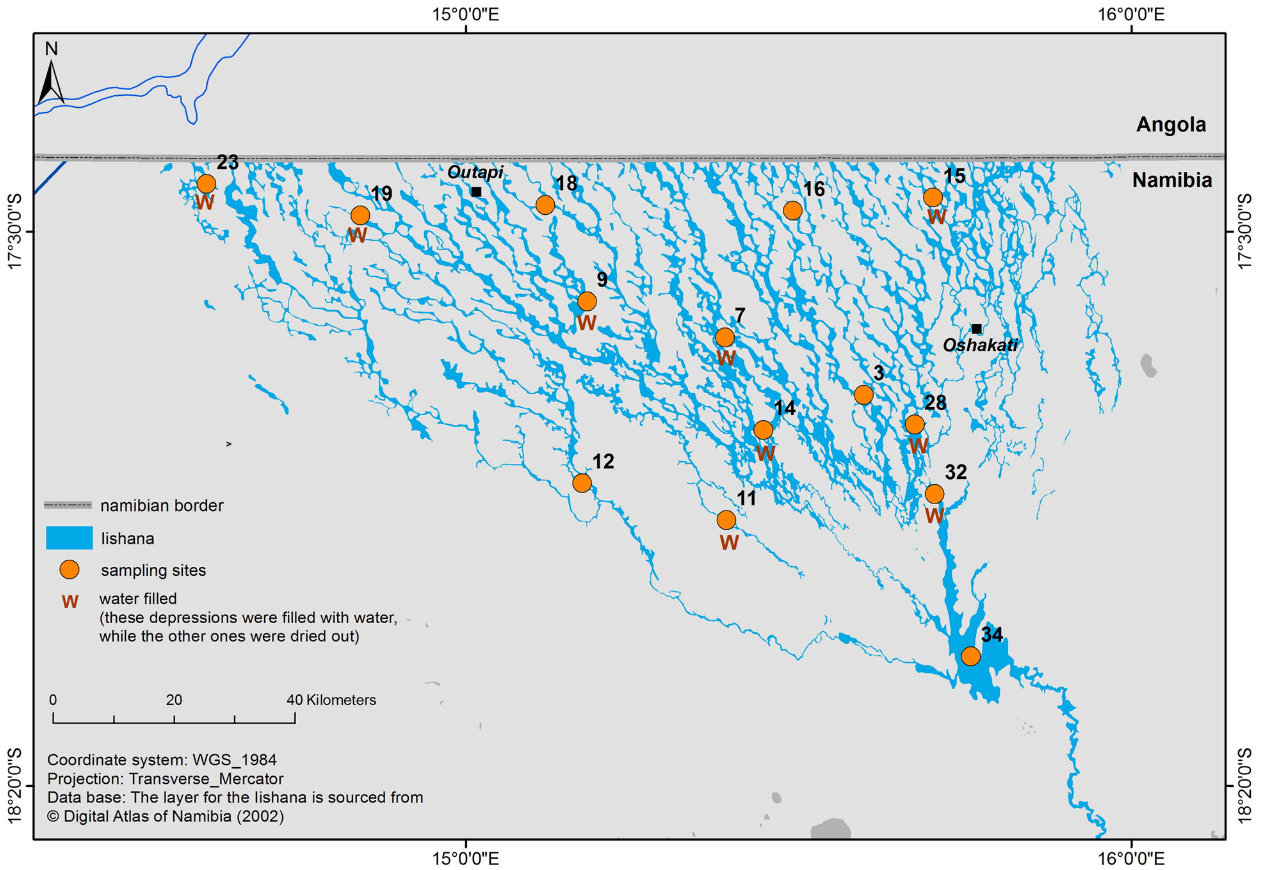
Fig. 2 Locations of the sampling sites in Namibia, with the focus region in central northern Namibia

the handling and reduce particle loss. Each sieve was flipped by 180° and rinsed individually with particle-free water (> 50 μm) into a glass filtration unit to ensure that no material remains on the sieves. For the glass vacuum filtration unit 0.45 μm cellulose and pleated filters (LLG-Plain disc filter paper, qualitative, medium/fast, Ø 47 mm; LLG Labware, France) were used. Each fraction was drawn onto several filters. Between 3 and 10 filters were generated per sample and fraction. All wet filters were stored in glass petri dishes, covered, and dried at about 60 °C. The smallest fraction of 0.1 – 0.3 mm (still in water) was collected in steep-bottomed glass bottles, for further analyses. In 2021 the sieve residues on the filter were directly rinsed into a glass petri dish and dried, to perform microscopic detection on a transparent background. The filter was discarded. The petri dishes were covered and dried at about 60 °C [45].

In 2019, a Nile Red solution that dyes plastic particles to make them fluoresce under a microscope was used to distinguish plastic from other particles. One milliliter of Nile red solution (1 mg/ml in acetone) was added to the filters and left to stain for 1 – 2 h. Each filter was examined under a microscope (Wild by Heerbrugg; magnification range 6x-50x) and light from a blue LED. The fluorescent plastic particles (highly luminous) were removed from the filter with metal tweezers and collected in well plates before spectroscopic measurements. In 2021, the samples were analyzed under a stereo microscope (SMZ-171; Motic Deutschland GmbH, Wetzlar, Germany; magnification range 11.25x-75x) without staining. Particles without cell structure, which did not break apart under pressure and did not have a glass-like texture were selected manually [49]. The color and shape of the particles were visually detected under the microscope, the polymer type was determined by FTIR spectroscopy.

FTIR spectroscopy

The Fourier-Transform-Infrared (FTIR) spectroscopy is one of the most common analytical methods for the chemical identification of MP in the aquatic environment [50]. The ATR (attenuated total reflection) spectroscopy is a non-destructible method to measure single particles after presorting. There are characteristic spectral fingerprints for different chemical structures and



Coordinate system: WGS_1984
Projection: Transverse_Mercator
Data base: The layer for the lishana is sourced from
© Digital Atlas of Namibia (2002)

Fig. 3 The focus region of the lishana system with sampling sites, indicating whether the lishana were carrying water at the time of sampling

thus unknown materials or substances can be identified by comparing their spectrum with the spectra of known materials [47, 51]. With this method, it is possible to identify the exact polymer type of the MP and also to obtain information about their physiochemical weathering [47]. All particles of the campaign in 2019 were measured with the FTIR spectroscope Tensor 37 (Bruker Optik GmbH, Ettlingen, Germany) in ATR mode (wavenumber range 400 – 4000 cm^{-1}; 20 scans per measurement). At first, the measured spectra were manually compared with known spectra of the most common polymer types: acrylonitrile butadiene styrene (ABS), polyamide (PA), polyamide/nylon 6, polyamide/nylon 6.6, polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET), poly(methyl methacrylate) (PMMA), polypropylene (PP), polystyrene (PS) and polyvinylchloride (PVC). The reference materials were provided by the University of Bayreuth. For the second data set in 2021 the FTIR-microscope Lumos II (Bruker Optik GmbH, Ettlingen, Germany) was used. With the Lumos II spectrometer by mapping it is possible to measure the particles faster, since with the Tensor 37 spectrometer only one particle can be measured per measurement. The measurements were performed in ATR mode (wavelength range 680 – 4000 cm^{-1}; 30 scans at the beginning, after 15 samples 50 scans), with an open aperture and a low pressure to ensure no particle slips away. The minimum Hit Quality Index (HQI) was 50 and the selected maximum number of hits was 5. An HQI of 700 is not necessarily a characteristic for the correct definition as plastic particles but is often named as a threshold [52, 53]. An atmospheric correction (CO_2, H_2O, aqueous solutions) was performed in the operating software Opus after every measurement. In Opus (version 8.5.29), the measured particles were compared to the following commercial data bases: BPAD Bruker Polymer ATR Library, ATF-FTIR LIBRARY KIMW, and BIBL ATR-FTIR FORENSICS Library. The standard or vector normalization search algorithm was applied. The results and the statistical consistency were dependent on comparison with the data bank of spectra. Unambiguously polymer spectra of the samples from Namibia were collected in a new database. This database was used again for matching further, less unambiguously, samples from Namibia. All the spectra from 2019 were compared with the data bases from Bruker and the self-made one to verify the previous manual evaluation.

Data analysis

The data analysis was performed in an RStudio environment (Version: 2021.09.2 Build 382) using the scripting language R (Version: 3.6.1) [54]. The following packages were used in RStudio: "psych", "car", and "dplyr". At first, the Shapiro-Wilk test was done to test the three groups (perennial, ephemeral rivers, and the Iishana system) for normal distribution. A Levene test was performed to check the differences in variances. Due to no normal distribution and unequal variances, a Kruskal-Wallis test was used to gain knowledge of the differences between the three different main river systems. Furthermore, the individual sites were correlated with the classification of urban and rural regions and the water level (dry or water filled) by using multiple regression. The statistical analysis results were defined as significant with a *p*-value <0.05. The definition of rural and urban was taken from the Namibia Statistics Agency in Namibia (Digital Namibia, the National Geographic Portal for the National Spatial Data Infrastructure (NSDI), which is coordinated by Namibia Statistics Agency – 2017) [55].

Results

A total number of 703 particles were visually detected as potential plastics under the microscope. During the process, 69 particles got lost due to their form, mostly fibers. Six hundred thirty-four particles were measured with the FTIR spectroscope, whereby 410 particles were clearly identified as polymers (64.7%). The 410 plastic particles were found at 28 of 30 sampling sites with a range of 1 – 66 particles kg^{-1} dry weight (a detailed table differentiated by sampling site can be found in the supplementary data 2). The identified amounts are differentiated between the perennial rivers, the ephemeral rivers, and the Iishana system. In the perennial rivers (Kunene, Kavango, Oranje), MP was found at all sites in very small quantities, with an average of 2.5 ± 1.2 particles kg^{-1} dry weight and a range of 2-7 particles kg^{-1}. In the ephemeral river systems, the average plastic concentration is 12.6 ± 17.2 particles kg^{-1}. The Owambo was found to have the highest content of MP, with 66 particles kg^{-1} dry weight, followed by the Olifants with 39, Kuiseb with 20, the Avis and Tsauchab1 with 14 particles (Fig. 4). At Kavango, Tsauchab, and Ugab two samples were taken each. With a ratio of 7:2 (Kavango), 14:2 (Tsauchab), and 1:0 (Ugab) particles kg^{-1}, more particles were found on the riverbank than on the river bottom at each river.

In the Iishana system (Fig. 5) 224 particles were found with an average of $13.2 \pm 16.4\,kg^{-1}$ dry weight. Most particles were found at sites 18 and 16 in the northern part, close to the border with Angola (53 and 43 particles kg^{-1} dry weight). Sites 12, 32, 28, 7, and 9 contain between 10 and 26 particles (Fig. 5). At 50.0% of the sites less than 10 particles were found (3, 11, 14, 15, 19, and 34). No MP was found at site 23.

The most common and in this case dominant polymer types are PE (59.3%), PP (20.7%), and PS (11.5%) (Fig. 6). The polymers at the perennial rivers consist of 75% PP and 16.7% PE. In the ephemeral rivers and the Iishana system, the majority of identified polymers is PE (43.7% at the ephemeral rivers and 73.7% at the Iishana), followed by PP (18.4% and 19.6%). The ephemeral rivers contain with 23.6% PS more than the others.

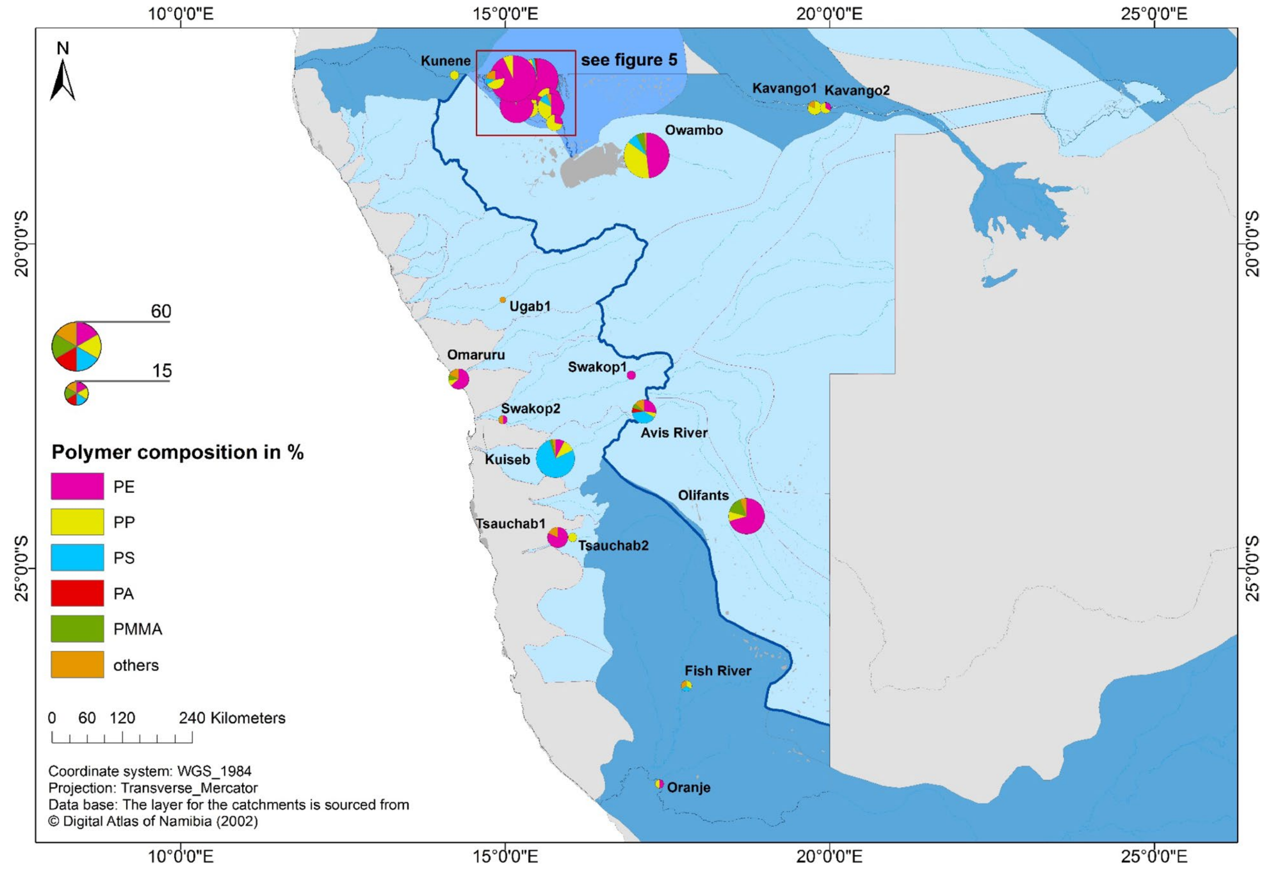
The size of the detected and identified particles varies between the fractions 1.0 – 5.0 mm (23.7%), 0.5 – 1.0 mm (42.4%) and 0.3 – 0.5 mm (33.7%) (Table 1). In the perennial rivers particles of the two smallest fractions are equally represented, and the bigger fraction is underrepresented. The ephemeral rivers contain more particles of the size 0.3 – 0.5 mm (39.1%) and the Iishana system more of the fraction 0.5 – 1.0 mm (46.9%).

The classification of Rochman et al. [44] was used to categorize the morphology of the particles. Fragments, films, fibers, fiber bundles, and pellets were found. Spheres and foams could not be identified. The particle morphology is composed of 69.7% fragments, 23.3% films, and 6.2% fibers (Fig. 7). Only one fiber bundle and 3 pellets were found. No significant differences were detected between the three systems.

The color of the particles was classified according to Frias et al. [56] and Wang et al. [57]: transparent, white, yellow, black, blue, brown, grey, green, pink, red, and orange. The color could help to identify the source of the plastic particle and due to that all colors were noted and not merged as "others" (Table 2). Most of the particles were transparent (30.5%), brown (23.9%), and black (13.2%).

With a *p*-value of 0.33, the Kruskal-Wallis test showed that there were no significant differences between the three river systems with regard to particle concentrations (Fig. 8). Although unlike perennial waters, Iishana and ephemeral rivers contain similar amounts of MP. The minimum is 0 and the maxima are outliers at 53 and 66, which results in a high range. The first and third quartiles and medians are similar. The perennial rivers have a smaller range between 2 and 7 and no outliers.

Microplastic abundance was tested by using multiple regression and the variables rural and urban waterbodies and the water level (dry or water filled). With a *p*-value of 0.08, there was no significant explanation of the plastic amount by the urban and rural regions or the water level.



river	Kunene	Kavango1	Kavango2	Oranje
MP kg^{-1}	1.8	6.9	2.4	1.6

river	Avis River	Fish River	Kuiseb	Olifantes	Omaruru	Owambo	Swakop1	Swakop2	Tsauchab1	Tsauchab2	Ugab1	Ugab2
MP kg^{-1}	14.4	2.6	20.3	38.8	8.7	65.9	2.4	1.5	13.5	1.6	0.8	0.0

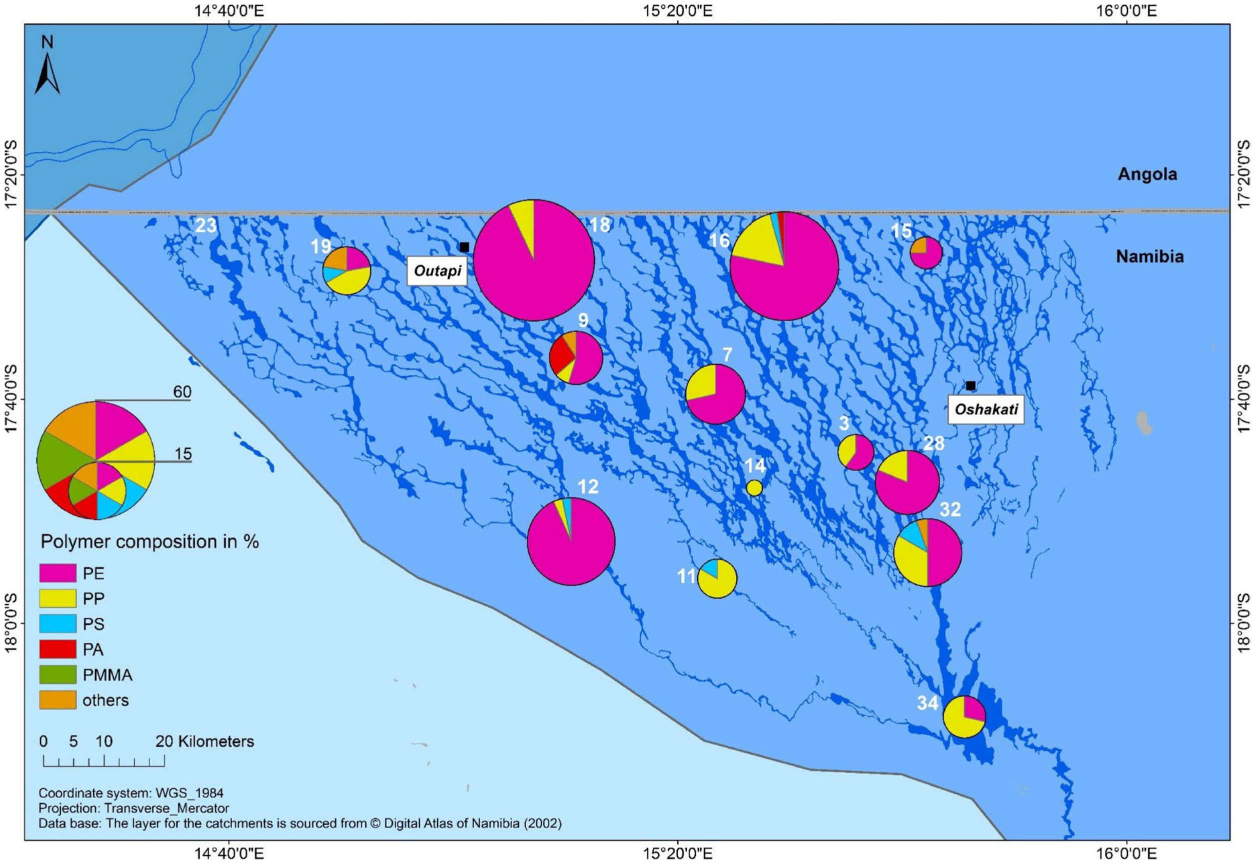
Fig. 4 Amount and polymer type of found microplastics at the sampling sites of the perennial and ephemeral Namibian river systems

Discussion

Methodological approach

The missing standardized method to extract and identify MP in sediments is a lack in all recent studies [52] and results in a few limitations. The density separation (with the MPSS) is commonly applied for the separation of polymer types with a density between 0.8 and 1.70 g/cm^3. The most frequently used separation solution is a saturated sodium chloride (NaCl) solution (density of 1.20 g/cm^3). It is non-toxic and likely to extract the low-density MP [47]. Several polymer types have a density less than 1.2 g/cm^3, like PE with a density of 0.92 – 0.97 g/cm^3, PP with a density of 0.85 – 0.94 g/cm^3 and PS with a density of 1.04 – 1.10 g/cm^3 [58]. These polymers can be separated with the density separation with sodium chloride [58, 59]. Other polymers, with densities of 1.3 – 1.7 g/cm^3 and 1.4 – 1.6 g/cm^3 (e.g. polyvinylchloride (PVC) and polyethylene terephthalate (PET)) are rather underestimated [60]. As the used separation solution NaCl for the density separation has a density of 1.2 mg/l, some polymers, like PET and PVC are denser and cannot be detected. The attachment of organic and inorganic material results in density gain that in turn brings the debris to sink and settle. Thus, by only measuring the amount of microplastic on the water surface or even in the water column could cause an underestimation of the actual quantity of debris [28]. The results presented here probably slightly underestimate the exact MP content, since some particle loss is to be expected during density separation with the MPSS.

The visual-eye identification is well established, but just in combination with another identification step, like the FTIR spectroscopy, it generates trustful results



Oshana	03	07	09	11	12	14	15	16	18	19	23	28	32	34
MP kg^{-1}	3.8	9.8	9.6	4.9	26.2	0.9	3.4	43.0	53.0	7.0	0.0	13.0	15.3	5.5

Fig. 5 Amount and polymer type of found microplastics at the sampling sites of the focus region, the Iishana system

[53]. The error quote during the identification process is caused by a conservative identification of the selected particles. In some cases, the plastic particles were contaminated with sediment, clay, or silt, which changed the measured spectra. Other particles were degraded and therefore had changed spectra. Their measured spectra had limited quality, were not unique [61], and were therefore conservatively not evaluated as polymers. Using the ATR-FTIR spectroscopy, particles < 300 µm are hard to measure, because of the small surface that is partially too small for the ATR crystal. The manual handling is challenging, which causes some particle damage or loss (1.2% in 2019 and 18.0% in 2021). In particular, fibers are challenging to handle. Some of them are bigger than 300 µm but too slim for the ATR crystal. In 2021 many fibers were found, but not all could be transferred to the measurement plate. The different spectrometers do not affect the comparability of the results, since both times were measured in ATR mode. The slightly adapted method between 2019 and 2021 should be considered while comparing the results. The longer standing time during the density separation in 2021 caused a higher suspension of microplastic particles and result in higher recovery rates. The staining with Nile red (applied in 2019) is strongly dependent on the solvent. The used acetone showed good recovery rates, but was not as satisfying as chloroform [62, 63]. Therefore, some particles may not be recovered and there may be an underestimation of plastic particles. For this reason, in 2021, staining was omitted, resulting in a visual-eye identification and a better selection of plastic particles. The adjustment to the methodology may have caused an underestimation of 2019 results in hindsight.

MP concentrations in Namibia

All investigated Namibian river systems contain MP. At the perennial rivers Kunene, Kavango, and Oranje an average of 2.5 ± 1.2 particles kg^{-1} were found. This abundance of MP is low, compared to rivers with similar

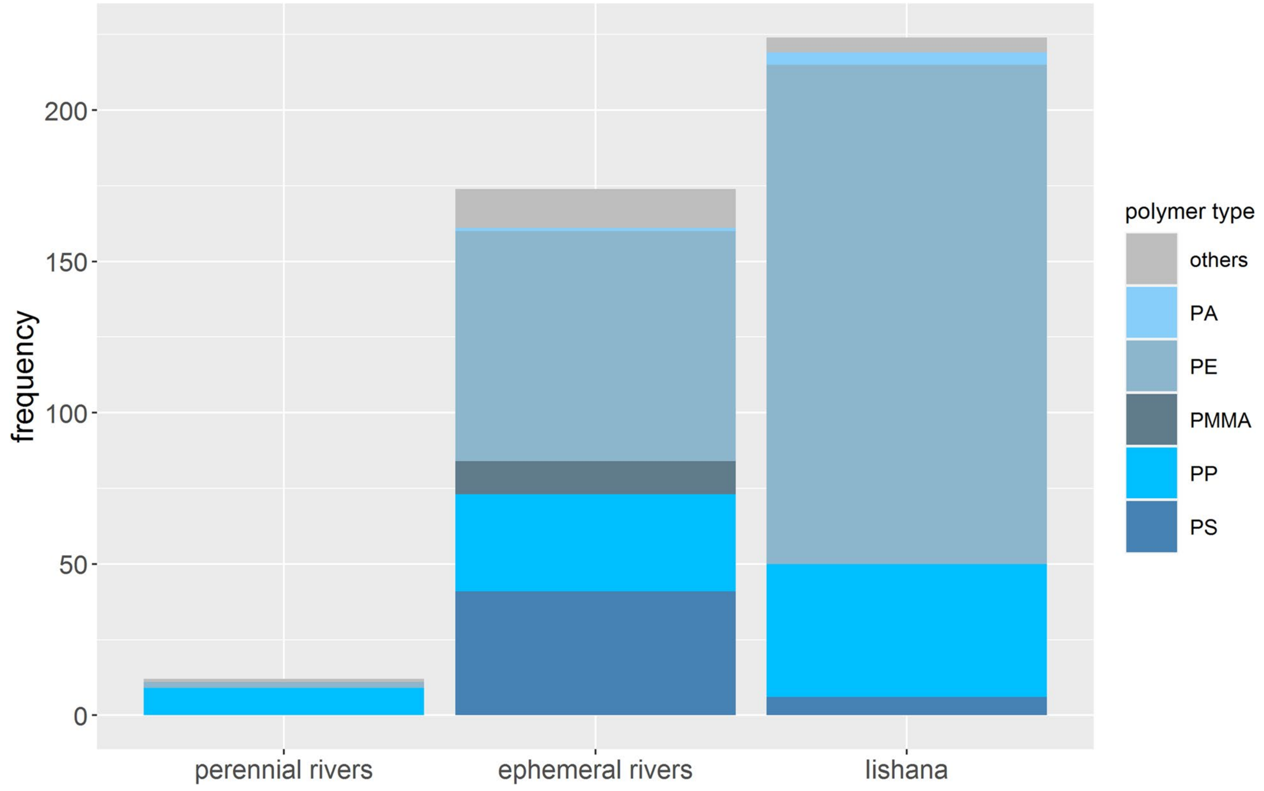


Fig. 6 Polymer type differentiated according to river systems

dimensions, concerning discharge [16]. In the Amazon River (Brazil) up to 5725 particles kg^{-1} dry weight were found [64]. In Portugal at the Antuã Rivera between 100 and 629 particles kg^{-1} sediment were identified [65]. Weber et al. [48] used a similar method (MPSS with NaCl, fractionation, staining with Nile red, visual-eye identification, ATR-FTIR spectroscopy) and identified MP in floodplains of the Lahn River (Germany) as temporary sinks. In their study at the Lahn, they found an average of 2.75 MP kg^{-1}. The river Themi in Arusha, Tanzania, contained up to 180 particles kg^{-1} [15] (see Table 3 for corresponding data of compared studies).

Table 1 Particle size of found microplastics, differentiated between perennial rivers, ephemeral rivers and the Iishana system

	5 mm [%]	1 mm [%]	0.5 mm [%]	0.3 mm [%]
Perennial rivers	0.0	16.7	41.7	41.7
Ephemeral rivers	0.0	24.1	36.8	39.1
Iishana	0.4	23.7	46.9	29.0
In total	0.2	23.7	42.4	33.7

At the ephemeral rivers in Namibia (Avis River, Fish River, Kuiseb, Olifants, Omaruru, Owambo, Swakop, Tsauchab, and Ugab) on average 12.6 ± 17.2 particles kg^{-1} sediment were identified. The Iishana system, as an ephemeral system, contains 13.2 ± 16.4 particles kg^{-1} on average. Ephemeral systems face seasonal or episodic flows and floods. These seasonal flow processes mobilize deposited sediments and attached MP. Large pulses of transport and a variable mobilization of MP could occur throughout the year [66]. Concerning the MP concentrations, the riverbed morphology and hydraulic characteristics of the sampling sites are important. Low flow velocities and in general low energy in the Iishana system cause deposition of suspended matter and MP. A high content of suspended material favors the attachment of MP. Previous studies showed a high content of suspended matter in the Iishana system that could affect the MP content [41]. Seasonal conditions, like rain events, water volume, and flow velocity have a strong effect on the deposition and retention of MP in sediments [65]. In this study, all ephemeral rivers were dry at the time of sampling at the end of March. In 2019 occurred a drought event in the country, in 2021 the rainy season was very well and caused some flooding. It can be assumed that plastic particles were transported and relocated by the

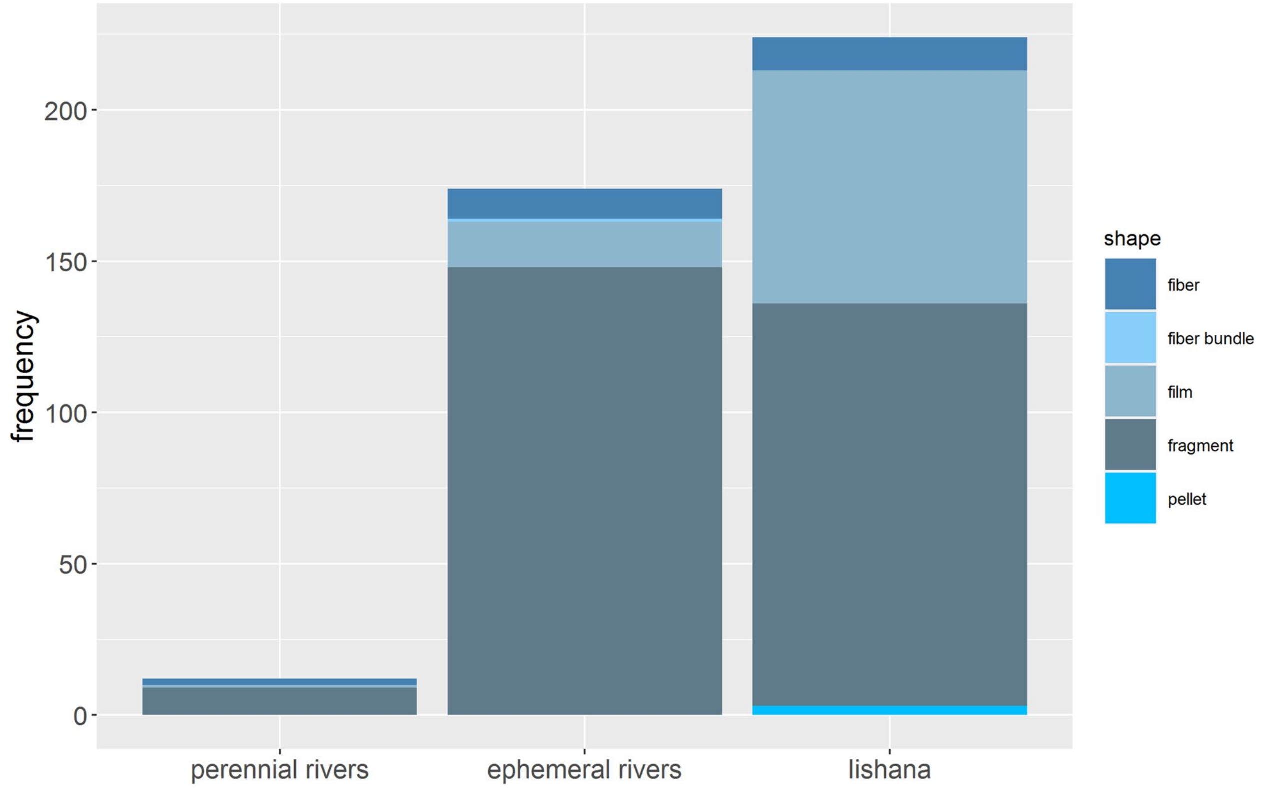


Fig. 7 Shape of the found MP, differentiated according to the three river systems

rain events in 2021. In the Iishana system, nine Iishana were filled with water and five Iishana were dried-up during sampling. In both years, there was no flow movement at the sampled Iishana and the ephemeral rivers, even though sampling occurred at the end of the rainy season. These missing flow movements caused a higher deposition of particles in the depressions. There was no statistical correlation between water level (dry and water filled) and MP concentration in the Iishana system. The perennial rivers showed flow movements that could transport the particles downstream and cause low recovery rates of MP in the samples. In Tanzania, it was possible to detect more MP downstream of rivers [15]. Rodrigues et al. [65] identified seasonal changes of MP in sediments of a river in Portugal between March and October with a higher abundance in March. A mobilization of the particles at the time of higher precipitation is given as a reason. However, it was not possible to identify the exact reason for the higher abundance in March [65]. There are nearly no studies on MP in ephemeral systems. Eppehimer et al. [67] investigated the ephemeral Santa Cruz River in the USA. They identified differences between the base flow of the river, caused by water treatment plants, and the post-flood conditions, after rainfall events. After the runoff less MP was found in sediments, but more in the water column. In particular, less fibers were found after the flood, they seem to be easily mobilized and get less attached by biofilms than fragments [67, 68]. Runoff mobilizes plastic particles in sediments and floods are a transport medium while no or low flow conditions cause deposition of MP [69, 70]. With increased surface roughness sedimentation and deposition of MP increase [48]. Smaller particles in general are more likely to be resuspended during rainfall than bigger particles [71].

At the Kavango, Tsauchab, and Ugab more MP were found at the riverbanks, than at the river bottom. For the Kavango this can be explained by a higher flow velocity in the stream that cause erosion and prevent deposition of MP in the riverbed [64]. At the Tsauchab and the Ugab recently occurred flow movements in 2021 could cause the same effect. Several studies identified similar differences [16]. Different flow velocities are found in the width of the river and cause areas of erosion and accumulation. Soils, sediments from river deltas, riverbanks and lake bottom sediments are sinks for MP [16, 72]. Lower density MP, like PE or PP, have a high mobility and are transported over larger distances. High density particles, like PA or PET, retain earlier in the sediments and therefore riverbeds, in particular river bottoms, could become

Table 2 Colors of the found MP, differentiated according to the three river systems

	Transparent [%]	White [%]	Yellow [%]	Black [%]	Blue [%]	Brown [%]	Grey [%]	Green [%]	Pink [%]	Red [%]	Orange [%]
Perennial rivers	0.0	0.0	25.0	0.0	8.3	66.7	0.0	0.0	0.0	0.0	0.0
Ephemeral rivers	27.6	12.6	2.3	28.7	12.1	12.1	0.0	0.6	0.6	2.9	0.6
Iishana	34.4	10.7	1.3	1.8	3.6	30.8	14.3	0.4	2.2	0.0	0.4
In total	30.5	11.2	2.4	13.2	7.3	23.9	7.8	0.5	1.5	1.2	0.5

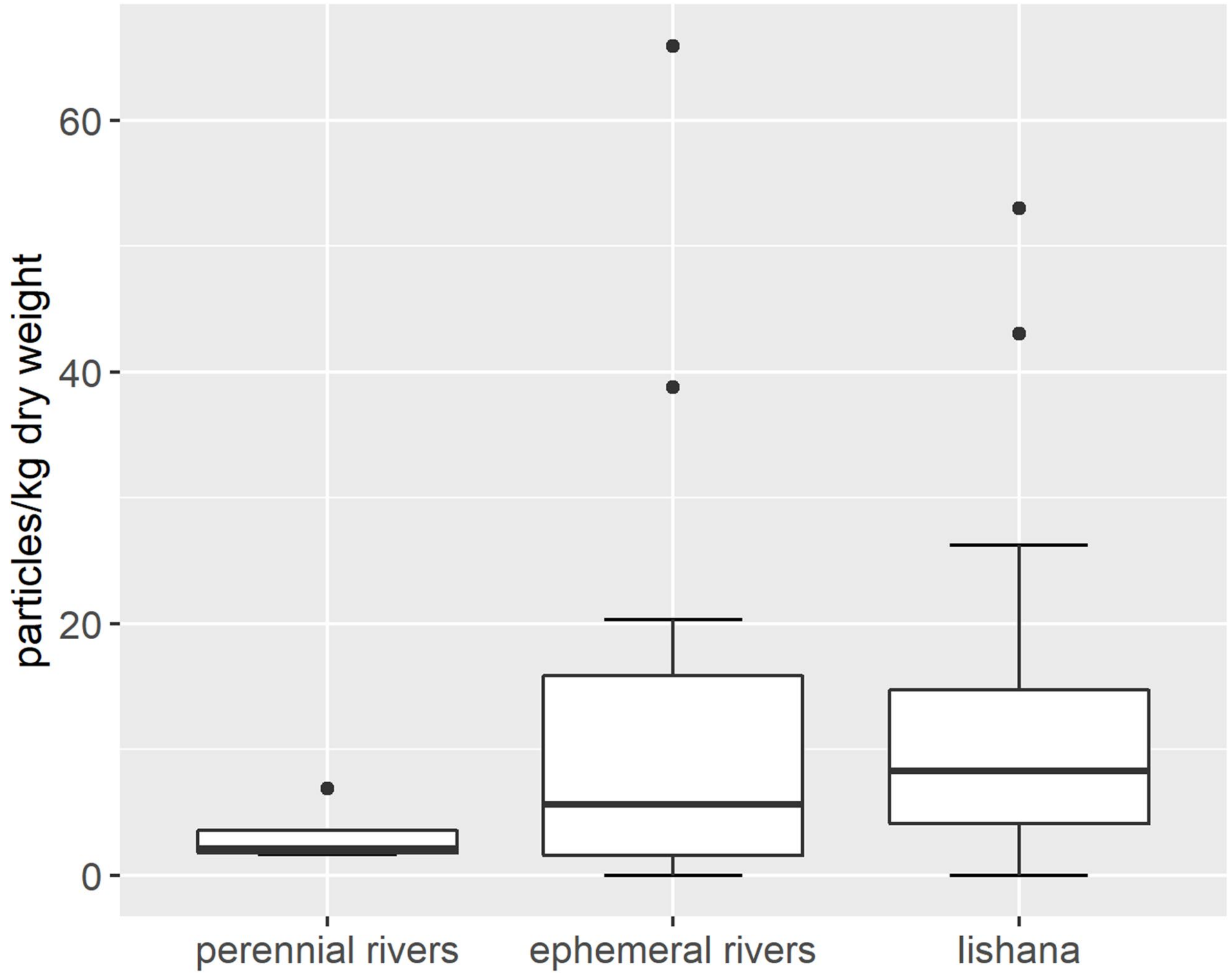


Fig. 8 Comparison of the amount of microplastics at the three river systems (perennial rivers, ephemeral rivers and the lishana system)

Table 3 Comparison of MP concentrations in different regions

Country	Water body	Concen-tration range [MP kg^{-1}]	Dominant polymer type	Dominant size [mm]	Dominant shape	Dominant color	Year	Study
Brazil	Amazon river	417-8178	–	1–3	fibers	white	2020	Gerolin et al.
Portugal	Antuã Rivera	100-629	PE and PP	–	foams and fibers	colored and white	2018	Rodrigues et al.
Germany	Lahn river	0.36-30.46	resin and LDPE	0.3–2	films and fragments	–	2021	Weber et al.
Tanzania	Themi river	70-160	HDPE and PP	–	fibers	–	2022	Kundu et al.
Namibia	perennial rivers *Kunene* *Kavango* *Oranje*	2-7	PP and PE	0.3–1	fragment	brown	2019/2021	this study
	ephemeral rivers	0-66	PE and PS	0.3–1	fragments	black and transparent	2021	this study
	lishana system	0-53	PE and PP	0.3–1	fragments and films	transparent and brown	2019/2021	this study

sinks for MP [73]. This study showed that low density particles can also sink and accumulate in sediments.

Type, morphology and potential sources of Namibian MP

The differences between the three river systems are causal but not statistically significant. This could be due to the small number of samples. MP are mostly more abundant in densely populated areas [16, 73]. Most of the plastic particles were found in the most densely populated region in Namibia, the Iishana system as part of the Cuvelai Basin. Almost as many particles were found in the further ephemeral systems in the country. Surrounding population, building density and land use are potential factors influencing the amount of MP in the water bodies [74]. In this study, no significant correlation was found between rural and urban regions and the MP amount. Several studies showed no correlation between population density and the occurrence of MP [25, 74]. Kataoka et al. [75] could prove a significant correlation between MP concentration in Japanese rivers and population density. However, the ranges and the spatial differences in this study, are huge. From a small-scale perspective, all sites are located close to bridges or culverts, which indicates a big anthropogenic influence, like plastic waste dumping. It was shown that small-scale differences have a bigger influence on the plastic amount than large-scale differences (e.g. urban or rural regions). Besides the spatial relations, there was no significant correlation between the amount of MP and the condition of the rivers (dry or water filled).

The particle morphology of the Namibian particles is dominated by fragments (69.7%) and films (23.3%). In several studies mostly fibers were found [12]. In this study, only 6.2% fibers were found, but due to the used method, the identification of fibers was quite difficult. The shape of the particles is characteristic for secondary microplastics introduced into the environment through anthropogenic use or fragmentation [44]. Of primary plastic, such as pellets, three pieces were found in the Iishana system. Colorful fibers can come from synthetic clothing, films from agricultural runoff, and fragments from plastic bottles [44]. Since the identified MP is mostly secondary plastic, it can be assumed to be degraded MP from locally disposed plastic products. Most of the particles were transparent, brown, black, or white. Martí et al. [76] identified white and transparent/translucent as the most common colors in ocean plastics. A discoloration could occur by photo-oxidation and cause a dominance of white and yellow particles [76, 77]. A long exposure time to sunlight can cause fragmentation and discoloration [76]. The discoloration of original colored particles to transparent, white, and yellow could possibly occur in Namibia, due to high temperatures and intensive sunlight exposure.

PE and PP were the most common polymers found in Namibia, which can result from packaging, carrier bags, food wrappers, and beverage bottles [11]. The results correspond to the mostly used polymer types in southern Africa [5, 9, 78]. Between 1987 and 2020 most of the studies conducted in Africa identified PE, PP, and PS as the three most common polymer types of MP [13]. Furthermore, PE and PP are globally the most common polymers, because of their light density they are easily fluvial transported [25]. He et al. [79] indicate a great impact of land use on the plastic type.

Rochman et al. [80] and He et al. [81] detected metals on plastic particles. In the Iishana system metals in the water column, suspended solids and sediments already have been detected [41]. It is possible that metals attach to plastic particles and are transported through the rivers, however, this assumption has to be evaluated by further investigations. The application of sewage sludge contributes to MP in soils [82, 83]. Surface runoff from urban areas or agricultural lands, wind dispersal, and soil erosion transport MP into the aquatic environment [84]. This movement of plastics from land to freshwater systems is dependent on various factors, such as weather conditions and land cover types [85]. Physical processes, like wind, surface runoff, fluvial transport, and flooding cause a spatial distribution of MP in environmental compartments [28, 86].

Conclusion and outlook

This study was conducted to significantly contribute to the state of research on MP in Namibia, in particular in the Iishana system. The main river catchments in Namibia contain MP. Even in rural areas, far away from settlements, MP were found in river sediments. More particles were found in the Iishana system than in perennial rivers or ephemeral systems. Most of the particles were found in the smaller fractions between 0.3 and 0.5 mm and the most common polymer types are PE and PP. Secondary plastic, in form of transparent and brown fragments and films, was mainly found. As primary plastic, only three pellets (transparent, grey, and black) could be identified. The consequences of uncontrolled waste disposal and littering are investigated worldwide [87]. Namibia is one of the countries with more than 0.8 kg of mismanaged plastic waste per capita per day [1]. The forecast for mismanaged plastic waste for Namibia will increase up to 10,000 tonnes per year in 2025. Only by identifying, quantifying, and qualifying the amount of plastic waste on the African continent, adapted measurements and strategies can be developed [1]. Within the last few years plastic production, detection, collection, sorting, recycling, and prevention are being addressed with information technologies and artificial intelligence. The goal is a closed-loop economy for plastic products [8]. On the African continent, it is just the beginning of studies about MP in freshwater and terrestrial systems [88]. This study showed for the first time the occurrence and characteristics of MP in freshwater sediments in Namibia. As an initial study, the focus was on the sinks, in particular the depressions (Iishana) and rivers. The influence of floods on the mobilization and deposition of MP in river sediments could be further analyzed by sediment dating [48]. To gain more knowledge about the source, transport, and fate of MP in Namibian river systems, aeolian sediments should be investigated. In particular, during a dry episode in ephemeral systems, aeolian erosion and deposition play a crucial role in the composition of the sediments.

Abbreviations

ABS: Acrylonitrile butadiene styrene; ATR spectroscopy: Attenuated total reflectance spectroscopy; FTIR spectroscopy: Fourier-transform infrared spectroscopy; HQI: Hit quality index; MP: Microplastics; MPSS: Microplastic Sediment Separator; PA: Polyamide; PC: Polycarbonate; PE: Polyethylene; PMMA: Poly (methyl methacrylate); PS: Polystyrene; PP: Polypropylene; PTE: Polyethylene terephthalate; PTFE: Polytetrafluoroethylene; PVC: Polyvinylchloride.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43591-022-00043-1.

Additional file 1: Supplementary data 1. Reporting Guidelines Checklist (According to Cowger et al. 2020). **Supplementary data 2.** General information: table differentiated by sampling site & MP data: table differentiated by sampling site.

Acknowledgments

The authors thank the residents of the Iishana system for their willingness to give access to the water bodies, for their kindness and for all the interesting information, they generously shared with us.

Authors' contributions

Conceptualization: LF, PC, AS; Methodology: LF, JP; Formal analysis and investigation: LF, JP, RA, CRI, PC; Writing - original draft preparation: LF, JP; Writing - review and editing: LF, JP, RA, CRI, PC, AS; Funding acquisition: LF, PC, AS; Resources: PC, AS; Supervision: AS, CRI. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. The fieldtrip for Leona Faulstich in 2019 was supported by the Geo.X Research Network for Geosciences in Berlin and Potsdam. In 2021, the fieldtrip for Leona Faulstich was supported by the German Hydrological Society (Deutsche Hydrologische Gesellschaft - DHG).
No funds, grants, or other support was received.

Availability of data and materials

The data set collected within the scope of this study will be published and accessible at GFZ Data Services. Additional data are properly cited and referred to in the reference list.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors agree to the publication.

Competing interests

The authors have no relevant financial or non-financial interests to disclose. No other affiliations for any author exist, that may be perceived as a conflict of interest concerning the results of this paper.

Author details

[1]Department of Earth Sciences, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany. [2]Department of Physics, Philipps-Universität Marburg, Hans-Meerwein-Straße 6, 35043 Marburg, Germany. [3]Bayreuth Graduate School of Mathematical and Natural Sciences (BayNAT), University of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany. [4]Department of Geography, Philipps-Universität Marburg, Deutschhausstraße 10, 35032 Marburg, Germany.

Received: 17 June 2022 Accepted: 16 September 2022

References

1. Jambeck J, Hardesty BD, Brooks AL, Friend T, Teleki K, Fabres J, et al. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Mar Policy. 2018;96:256. https://doi.org/10.1016/j.marpol.2017.10.041.
2. Angnunavuri PN, Attiogbe F, Mensah B. Consideration of emerging environmental contaminants in africa: review of occurrence, formation, fate, and toxicity of plastic particles. Sci Afr. 2020;9. https://doi.org/10.1016/j.sciaf.2020.e00546.
3. Babayemi JO, Nnorom IC, Osibanjo O, Weber R. Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. Environ Sci Eur. 2019;31:1. https://doi.org/10.1186/s12302-019-0254-5.
4. Fobil JN, Hogarh JN. The dilemmas of plastic wastes in a developing economy: proposals for a sustainable management approach for Ghana. West Afr J Appl Ecol. 2009;10:1. https://doi.org/10.4314/wajae.v10i1.45716.
5. Galie F. Market outlook: Africa's polymer potential. Edited by ICIS - Independent Commodity Intelligence Services (chemical business report). 2016. https://www.icis.com/explore/resources/news/2016/07/21/10018585/market-outlook-africa-s-polymer-potential/. Accessed 17 June 2020.
6. Iroegbu AOC, Sadiku RE, Ray SS, Hamam Y. Plastics in municipal drinking water and wastewater treatment plant effluents: challenges and opportunities for South Africa-a review. Environ Sci Pollut Res Int. 2020;27:12–12953. https://doi.org/10.1007/s11356-020-08194-5.
7. Hasheela R. Municipal Waste Management in Namibia: The Windhoek Case Study. Dissertation Thesis. Innsbruck, Austria: Universidad Azteca; 2009.
8. Adebiyi-Abiola B, Assefa S, Sheikh K, García JM. Cleaning up plastic pollution in Africa. Science (New York, NY). 2019;365:6459–1249. https://doi.org/10.1126/science.aax6190.
9. Khan FR, Mayoma BS, Biginagwa FJ, Syberg K. Microplastics in Inland African Waters: Presence, Sources, and Fate. In: Wagner M, Lambert S, editors. Freshwater Microplastics. Heidelberg, Germany: Springer; 2018. p. 101–24.
10. Bouwman H, Minnaar K, Bezuidenhout C, Verster C. Microplastics in freshwater water environments - a scoping study. WRC report no. 2610/1/18. Edited by North West University. 2018. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/2610-1-18.pdf. Accessed 27 Sept 2018.
11. Biginagwa FJ, Mayoma BS, Shashoua Y, Syberg K, Khan FR. First evidence of microplastics in the African Great Lakes: recovery from Lake Victoria Nile perch and Nile tilapia. J Great Lakes Res. 2016;42:1–146. https://doi.org/10.1016/j.jglr.2015.10.012.
12. Abidli S, Toum H, Lahbib Y, Trigui El Menif N. The first evaluation of microplastics in sediments from the complex lagoon-channel of Bizerte (Northern Tunisia). Water Air Soil Pollut. 2017;228:7. https://doi.org/10.1007/s11270-017-3439-9.
13. Alimi OS, Fadare OO, Okoffo ED. Microplastics in African ecosystems: current knowledge, abundance, associated contaminants, techniques, and research needs. Sci Total Environ. 2021;755:1–142422. https://doi.org/10.1016/j.scitotenv.2020.142422.

14. Lebreton LCM, van der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. River plastic emissions to the world's oceans. Nat Commun. 2017;8:15611. https://doi.org/10.1038/ncomms15611.
15. Kundu MN, Komakech HC, Lugomela G. Analysis of macro- and microplastics in riverine, riverbanks, and irrigated farms in Arusha, Tanzania. Arch Environ Contam Toxicol. 2022;82(1):142–57. https://doi.org/10.1007/s00244-021-00897-1.
16. Yang L, Zhang Y, Kang S, Wang Z, Wu C. Microplastics in freshwater sediment: a review on methods, occurrence, and sources. Sci Total Environ. 2021;754:141948. https://doi.org/10.1016/j.scitotenv.2020.141948.
17. Kaza S, Yao L, Bhada-Tata P, van Woerden F. What a waste 2.0: a global snapshot of solid waste managment to 2050. Edited by World Bank Group. Washington DC: Urban Development Series; 2018.
18. Schraml L. Partnership ready Namibia: Abfallwirtschaft. Edited by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Eschborn, Germany: Global Business Network (GBN) Program; 2020.
19. Nambuli F, Togarepi C, Shikongo A. Waste scavenging a problem or an opportunity for integrated waste management in Namibia: a case of Keetmanshoop municipality, Namibia. Environ Pollut. 2021;10:2–47. https://doi.org/10.5539/ep.v10n2p47.
20. Anderson JC, Park BJ, Palace VP. Microplastics in aquatic environments: implications for Canadian ecosystems. Environ Pollut. 2016;218:269. https://doi.org/10.1016/j.envpol.2016.06.074.
21. Schmidt C, Krauth T, Wagner S. Export of plastic debris by rivers into the sea. Environ Sci Technol. 2017;51:21–12246. https://doi.org/10.1021/acs.est.7b02368.
22. Lenaker PL, Baldwin AK, Corsi SR, Mason SA, Reneau PC, Scott JW. Vertical distribution of microplastics in the water column and surficial sediment from the Milwaukee River basin to Lake Michigan. Environ Sci Technol. 2019;53:21–12227. https://doi.org/10.1021/acs.est.9b03850.
23. Nizzetto L, Bussi G, Futter MN, Butterfield D, Whitehead PG. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environ Sci Process Impacts. 2016a;18:8–1050. https://doi.org/10.1039/c6em00206d.
24. Matsuguma Y, Takada H, Kumata H, Kanke H, Sakurai S, Suzuki T, et al. Microplastics in sediment cores from Asia and Africa as indicators of temporal trends in plastic pollution. Arch Environ Contam Toxicol. 2017;73:2–230. https://doi.org/10.1007/s00244-017-0414-9.
25. Klein S, Worch E, Knepper TP. Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. Environ Sci Technol. 2015;49:10–6070. https://doi.org/10.1021/acs.est.5b00492.
26. Kooi M, Besseling E, Kroeze C, van Wezel AP, Koelmans AA. Modeling the fate and transport of plastic debris in freshwaters: review and guidance. In: Wagner M, Lambert S, editors. Freshwater microplastics, The handbook of environmental chemistry, vol. 58. Cham: Springer International Publishing; 2018. p. 125–52.
27. Waldschläger K, Schüttrumpf H. Erosion behavior of different microplastic particles in comparison to natural sediments. Environ Sci Technol. 2019;53:22–13219. https://doi.org/10.1021/acs.est.9b05394.
28. Imhof HK, Schmid J, Niessner R, Ivleva NP, Laforsch C. A novel, highly efficient method for the separation and quantification of plastic particles in sediments of aquatic environments. Limnol Oceanogr Methods. 2012;10:7–524. https://doi.org/10.4319/lom.2012.10.524.
29. Akdogan Z, Guven B. Microplastics in the environment: A critical review of current understanding and identification of future research needs. Environ Pollut. 2019;11:254–113011. https://doi.org/10.1016/j.envpol.2019.113011.
30. Besseling E, Quik JTK, Sun M, Koelmans AA. Fate of nano- and microplastic in freshwater systems: a modeling study. Environ Pollut. 2017;220(Pt A):540. https://doi.org/10.1016/j.envpol.2016.10.001.
31. Syberg K, Khan FR, Selck H, Palmqvist A, Banta GT, Daley J, et al. Microplastics: addressing ecological risk through lessons learned. Environ Toxicol Chem. 2015;34:5–945. https://doi.org/10.1002/etc.2914.
32. Akindele EO, Ehlers SM, Koop JHE. First empirical study of freshwater microplastics in West Africa using gastropods from Nigeria as bioindicators. Limnologica. 2019;78:125708. https://doi.org/10.1016/j.limno.2019.125708.
33. Driedger AGJ, Dürr HH, Mitchell K, van Cappellen P. Plastic debris in the Laurentian Great Lakes: a review. J Great Lakes Res. 2015;41:1–9. https://doi.org/10.1016/j.jglr.2014.12.020.
34. Koelmans AA, Besseling E, Wegner A, Foekema EM. Plastic as a carrier of POPs to aquatic organisms: a model analysis. Environ Sci Technol. 2013;47(14):7812–20. https://doi.org/10.1021/es401169n.
35. Strohbach BJ. Mapping the major catchments of Namibia. Washington, USA: Agricola; 2008. p. 18–63.
36. Jacobson PJ, Jacobson KM. Hydrologic controls of physical and ecological processes in Namib Desert ephemeral rivers: implications for conservation and management. J Arid Environ. 2013;93:80. https://doi.org/10.1016/j.jaridenv.2012.01.010.
37. Mendelsohn J, Jarvis A, Robertson T. A profile and atlas of the Cuvelai-Etosha Basin. Windhoek: John Meinert Printing; 2013.
38. Persendt FC, Gomez C, Zawar-Reza P. Identifying hydro-meteorological events from precipitation extremes indices and other sources over northern Namibia, Cuvelai Basin. Jàmbá J Disaster Risk Stud. 2015;7:1–177. https://doi.org/10.4102/jamba.v7i1.177.
39. Cunningham T, Hubbard D, Kinahan J, Kreike, E, Seely M, Stuart-Williams V, Marsh A. Oshanas. In: Marsh A, Seely MK, editors. Oshanas. Sustaining people, environment and development in Central Owambo, Namibia. Windhoek, Namibia: Typoprint; 1992.
40. Arendt R, Reinhardt-Imjela C, Schulte A, Faulstich L, Ullmann T, Beck L, et al. Natural pans as an important surface water resource in the Cuvelai Basin—metrics for storage volume calculations and identification of potential augmentation sites. Water. 2021;13:2–177. https://doi.org/10.3390/w13020177.
41. Faulstich L, Schulte A, Arendt R, Kavishe F, Lengricht J. Die Qualität der intensiv genutzten Oberflächengewässer im Cuvelai-Becken (Nord-Namibia) zum Ende der Trockenzeit 2017. In: Chifflard P, Karthe D, Möller S, editors. Beiträge zum 49. Jahrestreffen des Arbeitskreises Hydrologie vom 23.-25.November 2017, vol. 26. Augsburg: Geographica Augustana; 2018. p. 9–21.
42. Cowger W, Booth AM, Hamilton BM, Thaysen C, Primpke S, Munno K, et al. Reporting guidelines to increase the reproducibility and comparability of research on microplastics. Appl Spectrosc. 2020;74(9):1066–77. https://doi.org/10.1177/0003702820930292.
43. Hermsen E, Mintenig SM, Besseling E, Koelmans AA. Quality criteria for the analysis of microplastic in biota samples: a critical review. Environ Sci Technol. 2018;52(18):10230–40. https://doi.org/10.1021/acs.est.8b01611.
44. Rochman CM, Brookson C, Bikker J, Djuric N, Earn A, Bucci K, et al. Rethinking microplastics as a diverse contaminant suite. Environ Toxicol Chem. 2019;38(4):703–11. https://doi.org/10.1002/etc.4371?download=true.
45. Prume JA, Gorka F, Löder MGJ. From sieve to microscope: an efficient technique for sample transfer in the process of microplastics' quantification. MethodsX. 2021;8:101341. https://doi.org/10.1016/j.mex.2021.101341.
46. Blettler MCM, Ulla MA, Rabuffetti AP, Garello N. Plastic pollution in freshwater ecosystems: macro-, meso-, and microplastic debris in a floodplain lake. Environ Monit Assess. 2017;189:581. https://doi.org/10.1007/s10661-017-6305-8.
47. Wang W, Wang J. Investigation of microplastics in aquatic environments: an overview of the methods used, from field sampling to laboratory analysis. TrAC Trends Anal Chem. 2018;108:195. https://doi.org/10.1016/j.trac.2018.08.026.
48. Weber CJ, Opp C, Prume JA, Koch M, Andersen TJ, Chifflard P. Deposition and in-situ translocation of microplastics in floodplain soils. Sci Total Environ. 2021;819:152039. https://doi.org/10.1016/j.scitotenv.2021.152039.
49. Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 2012;46:6–3060. https://doi.org/10.1021/es2031505.
50. Käppler A, Fischer M, Scholz-Böttcher BM, Oberbeckmann S, Labrenz M, Fischer D, et al. Comparison of μ-ATR-FTIR spectroscopy and py-GCMS as identification tools for microplastic particles and fibers isolated from river sediments. Anal Bioanal Chem. 2018;410:21–5313. https://doi.org/10.1007/s00216-018-1185-5.
51. Tagg AS, Sapp M, Harrison JP, Ojeda JJ. Identification and quantification of microplastics in wastewater using focal plane array-based reflectance micro-FT-IR imaging. Anal Chem. 2015;87:12–6032. https://doi.org/10.1021/acs.analchem.5b00495.
52. Weber CJ, Weihrauch C, Opp C, Chifflard P. Investigating microplastic dynamics in soils: orientation for sampling strategies and sample preprocession. Land Degrad Dev. 2021;32(1):270–84.

53. Renner G, Nellessen A, Schwiers A, Wenzel M, Schmidt TC, Schram J. Data preprocessing & evaluation used in the microplastics identification process: a critical review & practical guide. TrAC Trends Anal Chem. 2019;111:229. https://doi.org/10.1016/j.trac.2018.12.004.
54. R Core Team. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2019. https://www.R-project.org/
55. Namibia Statistics Agency. Namibia-NSA | Digital Namibia: the National Geographic Portal for the National Spatial Data Infrastructure (NSDI). 2017; https://digitalnamibia.nsa.org.na/.
56. Frias J, Pagter E, Nash R, O'Connor I, Carretero O, Filgueiras A, et al. Standardised protocol for monitoring microplastics in sediments. Deliverable D4.2. BASEMAN. Microplastic analyses in European waters: JPI Oceans; 2018. https://doi.org/10.13140/RG.2.2.36256.89601/1.
57. Wang Q, Guan C, Han J, Chai M, Li R. Microplastics in China Sea: analysis, status, source, and fate. Sci Total Environ. 2022;803. https://doi.org/10.1016/j.scitotenv.2021.149887.
58. Crawford CB, Quinn B. Microplastic separation techniques. In: Crawford CB, Quinn B, editors. Microplastic pollutants. Amsterdam, Boston, Heidelberg, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sydney, Tokyo: Elsevier; 2017. p. 203–18.
59. Zobkov MB, Esiukova EE. Microplastics in a marine environment: review of methods for sampling, processing, and analyzing microplastics in water, bottom sediments, and coastal deposits. Oceanology. 2018;58:1–137. https://doi.org/10.1134/S0001437017060169.
60. Miller ME, Motti CA, Menendez P, Kroon FJ. Efficacy of microplastic separation techniques on seawater samples: testing accuracy using high-density polyethylene. Biol Bull. 2021;240:1–52. https://doi.org/10.1086/710755.
61. Primpke S, Wirth M, Lorenz C, Gerdts G. Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. Anal Bioanal Chem. 2018;410:21–5131. https://doi.org/10.1007/s00216-018-1156-x.
62. Tamminga M, Hengstmann E, Fischer EK. Nile red staining as a subsidiary method for microplastic quantification: a comparison of three solvents and factors influencing application reliability. J Earth Sci Environ Stud. 2017;2:2–165. https://doi.org/10.15436/JESES.2.2.1.
63. Konde S, Ornik J, Prume JA, Taiber J, Koch M. Exploring the potential of photoluminescence spectroscopy in combination with Nile Red staining for microplastic detection. Mar Pollut Bull. 2020;159:111475. https://doi.org/10.1016/j.marpolbul.2020.111475.
64. Gerolin CR, Pupim FN, Sawakuchi AO, Grohmann CH, Labuto G, Semensatto D. Microplastics in sediments from Amazon rivers, Brazil. Sci Total Environ. 2020;749:141604. https://doi.org/10.1016/j.scitotenv.2020.141604.
65. Rodrigues MO, Abrantes N, Gonçalves FJM, Nogueira H, Marques JC, Gonçalves AMM. Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antuã River, Portugal). Sci Total Environ. 2018;633:1549. https://doi.org/10.1016/j.scitotenv.2018.03.233.
66. Horton AA, Dixon SJ. Microplastics: an introduction to environmental transport processes. WIREs Water. 2018;5:2. https://doi.org/10.1002/wat2.1268.
67. Eppehimer DE, Hamdhani H, Hollien KD, Nemec ZC, Lee LN, Quanrud DM, et al. Impacts of baseflow and flooding on microplastic pollution in an effluent-dependent arid land river in the USA. Environ Sci Pollut Res Int. 2021;28:33–45375. https://doi.org/10.1007/s11356-021-13724-w.
68. Hoellein TJ, Shogren AJ, Tank JL, Risteca P, Kelly JJ. Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. Sci Rep. 2019;9:1–3740. https://doi.org/10.1038/s41598-019-40126-3.
69. Cheng NS. Exponential formula for bedload transport. J Hydraul Eng. 2002;128:10–942. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:10(942).
70. Nel HA, Dalu T, Wasserman RJ. Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an austral temperate urban river system. Sci Total Environ. 2018;612:950. https://doi.org/10.1016/j.scitotenv.2017.08.298.
71. Xia F, Yao Q, Zhang J, Wang D. Effects of seasonal variation and resuspension on microplastics in river sediments. Environ Pollut. 2021;286:117403. https://doi.org/10.1016/j.envpol.2021.117403.
72. Rillig MC. Microplastic in terrestrial ecosystems and the soil? Environ Sci Technol. 2012;46:12–6453. https://doi.org/10.1021/es302011r.
73. He B, Smith M, Egodawatta P, Ayoko GA, Rintoul L, Goonetilleke A. Dispersal and transport of microplastics in river sediments. Environ Pollut. 2021;279:116884. https://doi.org/10.1016/j.envpol.2021.116884.
74. Chen H, Qin Y, Huang H, Xu W. A regional difference analysis of microplastic pollution in global freshwater bodies based on a regression model. Water. 2020a;12:7–1889. https://doi.org/10.3390/w12071889.
75. Kataoka T, Nihei Y, Kudou K, Hinata H. Assessment of the sources and inflow processes of microplastics in the river environments of Japan. Environ Pollut. 2019;244:958–65. https://doi.org/10.1016/j.envpol.2018.10.111.
76. Martí E, Martin C, Galli M, Echevarría F, Duarte CM, Cózar A. The colors of the ocean plastics. Environ Sci Technol. 2020;54(11):6594–601. https://doi.org/10.1021/acs.est.9b06400.
77. Pagter E, Frias J, Kavanagh F, Nash R. Differences in microplastic abundances within demersal communities highlight the importance of an ecosystem-based approach to microplastic monitoring. Mar Pollut Bull. 2020;160. https://doi.org/10.1016/j.marpolbul.2020.111644.
78. Egessa R, Nankabirwa A, Ocaya H, Pabire WG. Microplastic pollution in surface water of Lake Victoria. Sci Total Environ. 2020;741:140201. https://doi.org/10.1016/j.scitotenv.2020.140201.
79. He B, Wijesiri B, Ayoko GA, Egodawatta P, Rintoul L, Goonetilleke A. Influential factors on microplastics occurrence in river sediments. Sci Total Environ. 2020;738:139901. https://doi.org/10.1016/j.scitotenv.2020b.139901.
80. Rochman CM, Hentschel BT, Teh SJ. Long-term sorption of metals is similar among plastic types: implications for plastic debris in aquatic environments. PLoS One. 2014;9:1. https://doi.org/10.1371/journal.pone.0085433.
81. He B, Duodu GO, Rintoul L, Ayoko GA, Goonetilleke A. Influence of microplastics on nutrients and metal concentrations in river sediments. Environ Pollut. 2020a;263(A):114490. https://doi.org/10.1016/j.envpol.2020.114490.
82. Nizzetto L, Futter M, Langaas S. Are agricultural soils dumps for microplastics of urban origin? Environ Sci Technol. 2016b;50:20–10777. https://doi.org/10.1021/acs.est.6b04140.
83. Zubris KAV, Richards BK. Synthetic fibers as an indicator of land application of sludge. Environ Pollut. 2005;138:2–201. https://doi.org/10.1016/j.envpol.2005.04.013.
84. Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci Total Environ. 2017;586:127. https://doi.org/10.1016/j.scitotenv.2017.01.190.
85. Lambert S, Wagner M. Microplastics are contaminants of emerging concern in freshwater environments: an overview. In: Wagner M, Lambert S, editors. Freshwater microplastics, The handbook of environmental chemistry, vol. 58. Cham: Springer International Publishing; 2018. p. 1–23.
86. Zhang H. Transport of microplastics in coastal seas. Estuar Coast Shelf Sci. 2017;199:74. https://doi.org/10.1016/j.ecss.2017.09.032.
87. Ferronato N, Torretta V. Waste mismanagement in developing countries: a review of global issues. Int J Environ Res Public Health. 2019;16:6. https://doi.org/10.3390/ijerph16061060.
88. Rochman CM. Microplastics research-from sink to source. Science. 2018;360:6384–28. https://doi.org/10.1126/science.aar7734.

Publisher's Note