Science of the Total Environment 874 (2023) 162452

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Microplastic accumulation in endorheic river basins – The example of the Okavango Panhandle (Botswana)

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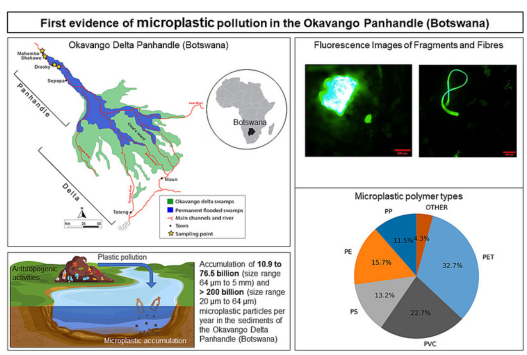
HIGHLIGHTS

- Microplastic concentration in sediment of Okavango Delta ranges from 56.7 to 1756.3 particles per kg dry weight.
- Upscaling of Okavango MP concentration suggests endorheic basins represent significant plastic sink.
- PET, PVC and PE were identified as most abundant polymer types.
- MP concentrations were not related to sediment grain size or percentage of silt and clay.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Yi Yang

Keywords:
Microplastics
Sediments
Endorheic basin
Okavango
Panhandle

ABSTRACT

The Okavango Panhandle is the main influent watercourse of the Okavango Delta, an inland sink of the entire sediment load of the Cubango-Okavango River Basin (CORB). The sources of pollution in the CORB, and other endorheic basins, are largely understudied when compared to exorheic systems and the world's oceans. We present the first study of the distribution of microplastic (MP) pollution in surface sediments of the Okavango Panhandle in Northern Botswana. MP concentrations (64 μm-5 mm size range) in sediment samples from the Panhandle range between 56.7 and 399.5 particles kg^{-1} (dry weight) when analysed with fluorescence microscopy. The concentrations of MP in the 20 μm to 5 mm grain size range (analysed with Raman spectroscopy) range between 1075.7 and 1756.3 particles kg^{-1}. One shallow core (15 cm long) from an oxbow lake suggests that MP size decreases with depth while MP concentration increases downcore. Raman Spectroscopy revealed that the compositions of the MP are dominated by polyethene terephthalate (PET), polypropylene (PP), polyethene (PE), polystyrene (PS), and polyvinyl chloride (PVC). From this novel data set it was possible to estimate that 10.9–336.2 billion particles could be transported into the Okavango Delta annually, indicating that the region represents a significant sink for MP, raising concerns for the unique wetland ecosystem.

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http://dx.doi.org/10.1016/j.scitotenv.2023.162452
Received 21 November 2022; Received in revised form 20 February 2023; Accepted 20 February 2023
Available online 2 March 2023

1. Introduction

The rising amount of plastic pollution is creating detrimental effects not only in populated regions but also in remote, isolated, and relatively pristine environments. Existing studies have identified significant concentrations of microplastics (MP), referred to plastic particles 1–5000 μm in size (Hartmann et al., 2019), even in areas of comparably little human intervention such as high mountain ranges, the world's deep-sea environments or the polar regions (Bergmann et al., 2019; Kukkola et al., 2022; Peeken et al., 2018; Zhang et al., 2021).

Prevalent world-wide MP pollution can be attributed to a rapid increase in synthetic polymer production over the last several decades, with global production reaching 460 million tonnes (OECD, 2022) in 2019. Consequently, in 2019 alone >2.5 million tonnes of primary MP (plastics intentionally produced to this specific size range) were released into the environment as mismanaged plastic waste (OECD, 2022). Secondary MP formed from larger items through processes such as photodegradation, biological degradation, or abrasion, add to the MP input to the environment (Du et al., 2021; Mateos-Cárdenas et al., 2020). Once in the environment, MP particles are transported by a variety of pathways (Allen et al., 2022; Dris et al., 2016; Nel et al., 2020; Schwarz et al., 2019; Waldschlager et al., 2020) including rivers (Eo et al., 2019; Margenat et al., 2021; Tibbetts et al., 2018) where they can remain in sediment for decades (Drummond et al., 2022) and have detrimental effects on food webs (Krause et al., 2021) and aquatic ecosystems (de Sá et al., 2018; Kukkola et al., 2021).

Compared to other regions of the world, MP research in Africa is greatly underrepresented with existing studies often focusing on marine and coastal areas (e.g., Gbogbo et al., 2020; Naidoo and Glassom, 2019; Nel et al., 2017; Shabaka et al., 2019), while extensive inland regions have received little or no attention from the scientific community so far (Alimi et al., 2021; Nel et al., 2021; Talbot and Chang, 2022). More information on the current state of plastic pollution in Africa is imperative as rapid population growth, ongoing urbanization, and an anticipated shift in consumer demand towards more plastic-dominated products will likely increase MP release to the environment in the near future (Jambeck et al., 2018; Nel et al., 2021).

Only a few studies have looked at MP pollution in African rivers (see Alimi et al., 2021; Aragaw, 2021 for recent reviews). For example, Dahms et al. (2020) reported on average 705 particles m^{-3} in river water and 166.8 particles kg^{-1} (>53 μm) in sediment for the Braamfontein Spruit in Johannesburg, South Africa, a heavily urbanized setting. For another South-African setting, the Orange-Vaal river system, Weideman et al. (2020) measured mean concentrations of 1.4 to 2.6 particles L^{-1} (>25 μm) in water, with lower numbers reported for the dry season while Ebere et al. (2019) found concentrations ranging from 440 to 1556 particles L^{-1} (>11 μm) for five streams in South-Eastern Nigeria. Two other studies looked explicitly at MP pollution of river sediment with Nel et al. (2018) encountering varying average concentrations in summer and winter (6.3 vs. 160.1 particles kg^{-1} dry weight > 63 μm) in the Bloukrans River system, South Africa while Toumi et al. (2019) found average concentrations ranging from 2340 to 6920 particles kg^{-1} (>200 μm) dry weight in streams around Bizerte lagoon, Tunisia.

Despite endorheic basins covering one fifth of the Earth's surface (Wang et al., 2018a), plastic transport and deposition in such systems has not yet been well studied, leaving a critical knowledge gap of a potentially significant long-term plastic sink, as these basins are not connected to the world's oceans. In this study, we identify and quantify the concentration, size and type of MPs present in the sediments of the Okavango Panhandle, located in the middle Kalahari, northern Botswana (Fig. 1). The Panhandle in Botswana is a 70 km long trough at the apex of the Okavango Delta, the largest endorheic alluvial fan in Africa. The Delta is one of the world's largest arid-zone wetland systems, and a remote hotspot of biodiversity that provides livelihoods and natural resources for the population of eastern Namibia and northern Botswana (Mendelsohn and Martins, 2018). It is fed by a large drainage basin, the Cubango Okavango River Basin (CORB), which stretches over three countries (Angola, Namibia and Botswana) and covers an area of 171,000 km^2. The catchment is characterised by a very low level of human transformation (Mendelsohn and Martins, 2018). The Delta is thus the terminal sink for sediments and with that, many sediment-bound pollutants, potentially including MP, are produced across such a large basin. Using new bedload sediment data published by Milzow et al. (2009), we also provide early estimates of total annual MP numbers being transported into the Delta. Our results provide a first estimate of the local MP pollution problem and the global relevance of MP accumulation in this endorheic basin. Our study therefore establishes a baseline for future large-scale and more comprehensive studies as well as for potential policy decisions concerning waste management, risk assessment and environmental monitoring.

2. Materials and methods

2.1. Study site description

The CORB stretches from the Angolan highlands in the north-west to the central Kalahari Desert in the south-east, culminating in the Okavango Delta (Fig. 1A). This study was conducted in the inlet area of the Okavango, known as the Panhandle, a 70-km-long stretch of the Okavango River that feeds into the Delta (Fig. 1A-B). The landscapes surrounding the Okavango Panhandle and its catchment have been modified by human activities over the last decades, reflecting an increase in population and tourism, which are thought to be linked to an increase in plastic pollution and plastic loss to the environment.

The soils of the CORB are predominantly sandy arenosols derived from the unconsolidated Kalahari surficial sands (Jones, 2010). Consequently, the bedload in the Okavango River is primarily comprised of well sorted, fine to medium grained sand (median size ca. 300 mm) (McCarthy et al., 1992; Tooth et al., 2022), with a low bedload to suspended load ratio of ca. 3:1 (McCarthy et al., 1991). Further detailed descriptions of the study area in the wider regional context are reported in the supplementary information (S1).

The Panhandle exhibits sinuous, mostly meandering channels and numerous oxbow lakes creating a wide alluvial plain. At certain times of the year, flood water surcharges the main channel, inundating larger parts of the area of the Panhandle (Tooth et al., 2022). The mean discharge of the Okavango River measured at the Mohembo gauging station (18° 16′ 32.6388” S, 21° 47′ 14.3232″ E) at the head of the Panhandle is about 266 $m^3 s^{-1}$ (mean over archive data from 1974 to 2022, http://www.okavangodata.ub.bw/ori, data from daily discharge measurement by Dept. Water and Sanitation, Botswana). The annual peak flow is between 400 and 700 $m^3 s^{-1}$ and is normally sustained for a few weeks between March and April before dropping to the seasonal lows of <100 $m^3 s^{-1}$ (Mendelsohn and Martins, 2018).

Sediment samples were taken at eight distinct locations (Fig. 2, Table S1). Two of the samples (OK10/21 and OK11/21) were collected near Mohembo from point bars along the meandering section of the main channel (Fig. 2B). Another sample was taken further downstream along the main channel near Xaro Lodge (OK09/21 in Fig. 2C). An oxbow lake (1) adjacent to the main river north of Xaro lodge was sampled (OK12/21) at the cut bank (Fig. 2C). At another oxbow lake (2), further downstream from Xaro Lodge (Fig. 2C), four additional samples were taken, with OK06/21 representing the intra-point bar erosion surface, OK08/21 representing a side bar while OK05/21 was taken at the cut bank (inset in Fig. 2C). OK07/21 was taken in one of the oxbow limbs from water lily's roots. OK05/21 included not only a surface sample (OK05/21E) but a short core that was also taken using a push corer with a metal barrel. The core was divided into three subsections (OK05/21A-C, 0–5, 5–10 and 10–15 cm depth). Two composite field blanks were collected during the sampling campaign.

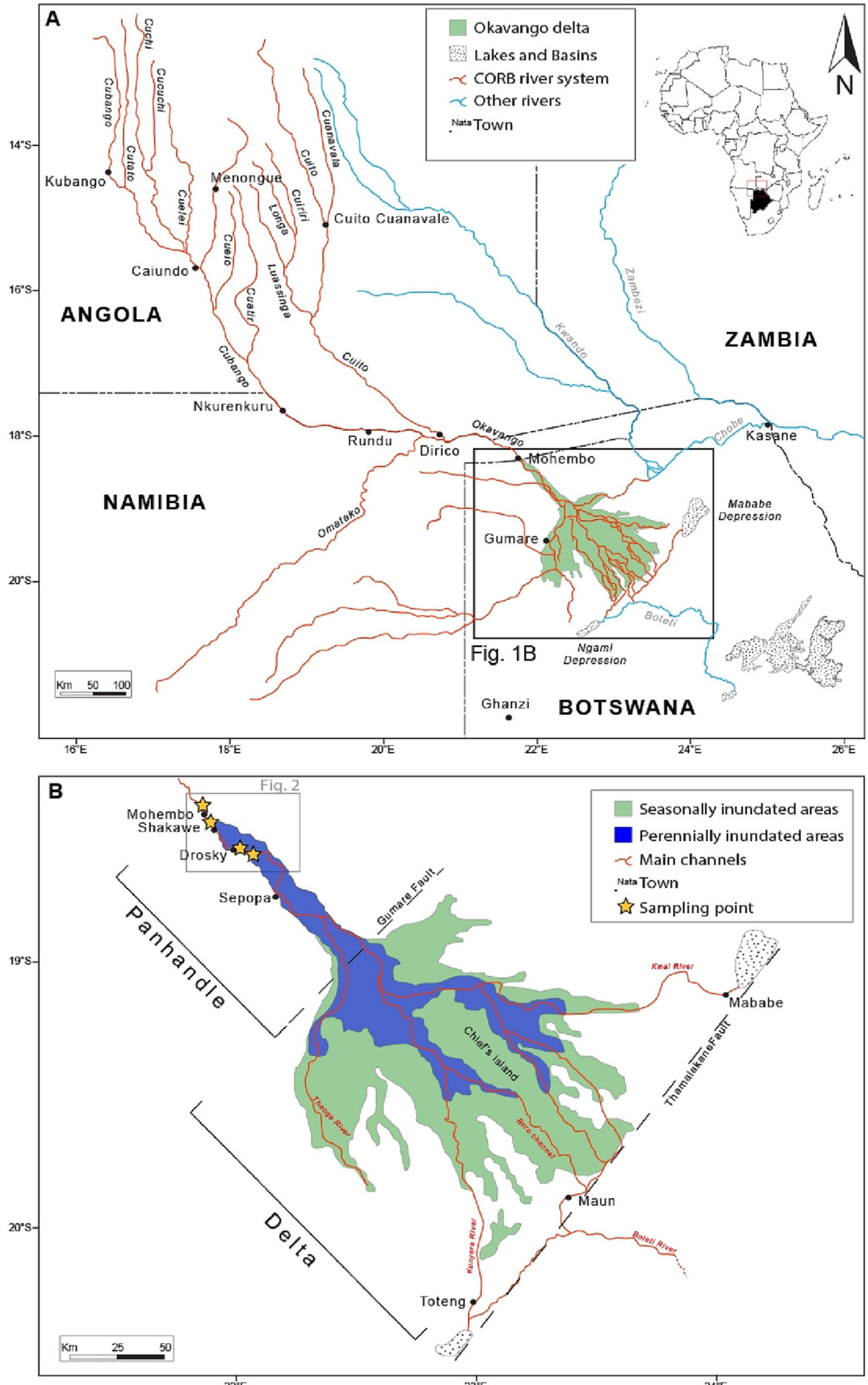

Fig. 1. A. Map of the Cubango-Okavango River system showing rivers (red) and the Okavango Delta wetlands (green). B. Close-up view of the Okavango Delta region with sample sites (yellow stars in the Panhandle region) and main channels (red) indicated. In this map seasonally inundated areas of the Delta are shown in green while perennially inundated areas are in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

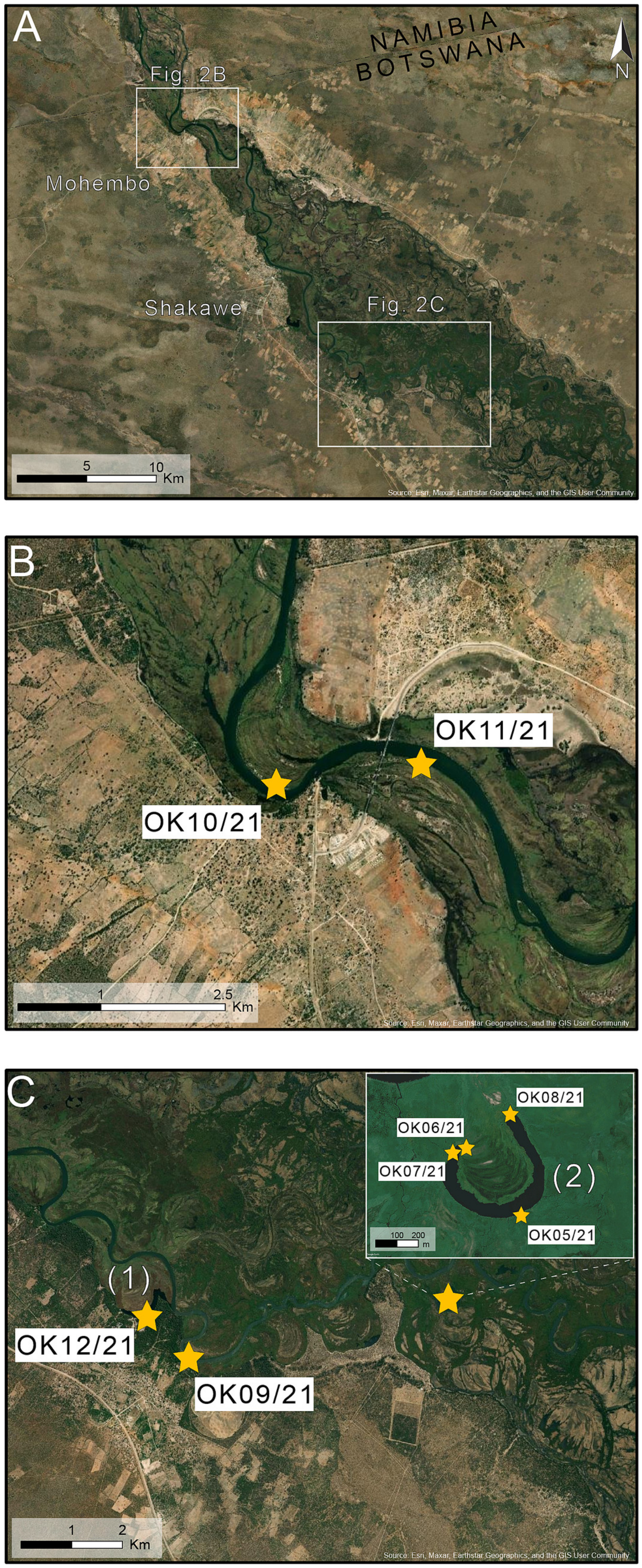

Fig. 2. Satellite images of the Okavango Delta Panhandle showing sampling locations in the upper Panhandle, near Mohembo (B) and south of Shakawe (C). Sample sites are indicated by the yellow stars. The numbers between brakets in C indicate the oxbow lakes as named in the main text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Sediment sampling and characterisation

Surface sediment samples were collected with glass jars using the scooping technique at eight locations along the Cubango River (Panhandle) between Mohembo and Sepopa (Fig. 2 and Table S1) in May 2021.

Samples were dried at 50 °C to remove pore water until constant weight was achieved. A subsample (approximately 50 g, Table S2) of the dried sediment was then placed in a pre-weighed ceramic crucible and heated at 550 °C for 5 h to determine the total organic matter content as loss on ignition (LOI). Grain size distribution was determined for the subsample with organic matter removed by means of laser diffraction using a Malvern Mastersizer 2000MU A with an ultrasound probe to disperse the sediment and deionized (DI) water without any further dispersant. Before using the Mastersizer, samples were pre-sieved with a 2 mm stainless-steel mesh to remove larger particles.

2.3. Microplastic extraction, digestion and identification

For the identification of MP, two optimal sample processing pathways have been utilised for respective detection by fluorescence microscopy and Raman spectroscopy (see workflow in Fig. 3). This workflow allowed us to combine advantages of both techniques, i.e., fluorescence microscopy allows for quick enumeration of larger particles on a bigger portion of each sample (approximately 35 g, see Table S2) while Raman spectroscopy helped us identify smaller particles and provided information on polymer type albeit on a smaller portion of each sample (approximately 10 g, see Table S2). The detailed methodology is presented in the supplementary information (S2).

Pre-filtered zinc chloride ($ZnCl_2$), with a minimum density of 1.45 g cm^{-3}, was used for density separation of MP from the bulk sediment sample. Density separation of sediment samples for fluorescent microscopy was carried out in Sediment-Microplastic Isolation (SMI) units (Coppock et al., 2017) modified after Nel et al. (2019). The separated supernatant potentially containing MP particles was then subjected to digestion over at least 24 h with Fenton's reagent (30 % H_2O_2 and Fe^{2+}_{aq} 0.05 M) to remove organic material. After digestion, samples were filtered through a 64 μm sieve and the captured sample material was then backwashed into beakers using DI water before it was stained with Nile Red (5 μg mL^{-1}). The mixture was subsequently filtered over a 47 mm glass fibre disk (Whatman GF/D). Putative MP were assessed using an Olympus MVX-ZB10 microscope and Olympus U-HGLPS mercury lamp. MP were identified using a set threshold of 100 fluorescence a.u. (arbitrary units) and following a simple yet effective identification key as reported in Kukkola et al. (2023).

Sediment samples for Raman spectroscopy investigation, were first digested with pre-filtered 30 % hydrogen peroxide (H_2O_2), followed by density separation using $ZnCl_2$ in a cleaned glass graduated cylinder. Following density separation, the supernatant was filtered with a 25 mm Anodisc (Whatman). Raman spectroscopy measurements were carried out on a Renishaw Qontor Raman microscope equipped with a 785 nm laser, power was set to 10 % (approximately 15 mW at the sample). One spectrum for each putative MP was collected. The spectra were then compared with in-house references, along with SLOPP and SLOPP-E libraries (Munno et al., 2020); a match of over 70 % was considered for the identification as MP.

3. Results and discussion

3.1. Sediment characterisation

The organic matter content of the samples varied from 0.04 % (OK08/21) to 4.50 % (OK11/21) with an average of 1.47 % and a standard deviation of 1.44 %. In general, samples with higher silt (and clay) content such as OK11/21 contained up to 100 times more organic matter than those samples containing mostly fine and medium sand such as OK08/21. Percent organic matter content was strongly linearly correlated with percent grain size <63 μm (silt and clay), with a Pearson correlation coefficient of 0.93 (Fig. S12).

Grain size distribution (GSD) curves are shown in Figs. S1 to S11 while grain size parameters d_{10}, d_{50} and d_{90} are given in Table S1. Samples generally showed primary grain size modality of 200–300 μm (OK06/21, OK08/21, OK09/21, OK10/21 and OK12/21) with a secondary modal peak within the silt range (25–40 μm). The exception was for the central oxbow lake grain size distribution, where sediment showed complete mixing without clear or significant modality with sediment of equal proportions across the grain size range of 40–800 μm (full GSD of 0.5–2000 μm).

Upstream samples OK10/21 and OK11/21 showed significant differences in grain sizes although <2 km apart along the stream course. While

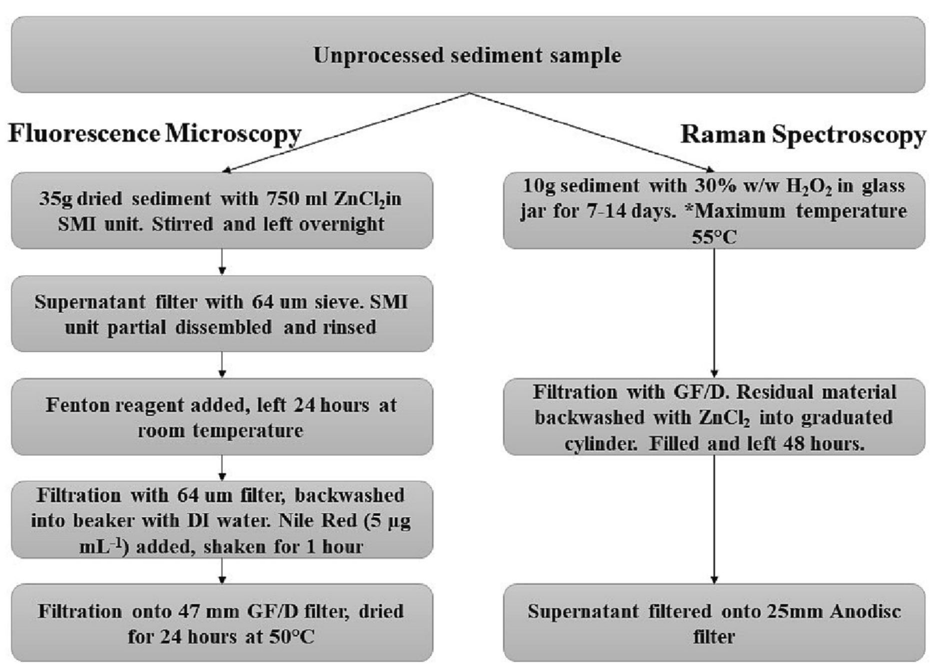

Fig. 3. Flow diagram of the extraction and digestion process of sediments samples for microplastic identification by fluorescence microscopy and Raman spectroscopy.

OK10/21 sediments were comprised of >95 % sand (following the ISO14688-1:2017 classification) with >60 % being fine sand (63–200 μm) and the rest medium sand (200–630 μm), OK11/21 sediments contained >60 % of particles in the silt and clay region (<63 μm). Sample OK09/21, from further downstream (Fig. 2) was comprised of mostly medium sand (about 60 %) with the rest being fine sand. Both OK10/21 and OK09/21 contained about 10–30 times less organic matter than OK11/21. It is also worth noting that OK11/21 was downstream of the Mohembo ferry point which may cause disturbance in the grain size distribution. As both OK10/21 and OK11/21 are from point bar deposits, we exclude sedimentological reasons for this change in grain size distribution.

Grain size analysis from the downstream oxbow lake (2) samples shows two different trends. While OK08/21 and OK06/21 taken from an old point bar and close to the meander neck, respectively, were comprised mostly of medium sand, locations in the centre of the oxbow channel (OK07/21) and the cut bank (OK05/21) showed lower sorting with considerable amounts of silt (30–60 %) as well as fine to coarse (630–2000 μm) sand. Interestingly, sample OK12/21 taken at the cut bank of the more upstream oxbow lake (1) near Xaro Lodge (hence comparable with OK05/21) showed mostly medium sand with a minor fraction of fine sand and only very little silt (97 % between 112 and 800 μm with a small silt component of 3 %) while OK05/21 presented well mixed sediment, with a relatively consistent proportion of fine silt through to coarse sand in the surface sediment and throughout the short core. OK12/21 also exhibits a much narrower distribution range with d_{10} being 3.5 times smaller than d_{90} while for OK05/21 this factor is up to 157.1. More details regarding the grain size distribution can be found in the SI.

3.2. Microplastic concentrations

In total, 71 particles (>64 μm) were identified as MP during fluorescence microscopy (Table S3). Concentrations (Fig. 4) varied from 56.7 particles kg^{-1} sediment (dry weight) at OK06/21 to 399.5 particles kg^{-1} at OK09/21 with an average concentration over all locations of 190.6 particles kg^{-1}. With Raman spectroscopy, 104 particles (>20 μm) were identified as plastics with concentrations ranging from 1075.7 particles kg^{-1} at OK12/21 to 1756.3 particles kg^{-1} at OK09/21 (Fig. 4 and Table S4). Raman spectroscopy consistently found more MP in the sediment than fluorescence microscopy due to the lower limit of identification. However, both analytical methods generally presented a similar MP spatial trend. It has been suggested that MP abundance increases with smaller size (Triebskorn et al., 2019), which was also observed in this study. On the other hand, it is possible that some of the plastics present (such as PVC) might not have been staining well, leading to the underestimation of certain plastic types with fluorescence microscopy (Stanton et al., 2019).

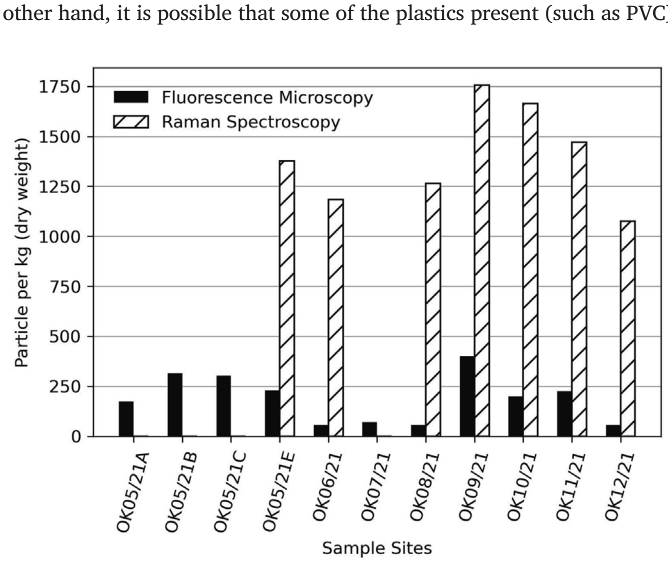

Fig. 4. Sediment microplastic concentrations (particle per kg dry weight of sediment) across the Okavango Panhandle identified with fluorescence microscopy (black bars) and Raman spectroscopy (white bars with black lines).

Both methods identified the highest MP concentration at OK09/21 (399.3 and 1756.3 particles kg^{-1} for fluorescence microscopy (FM) and Raman spectroscopy (RS), respectively), which is in close proximity to Xaro Lodge, a tourist accommodation site. Other areas of high MP concentration include OK10/21 (199.3 for FM and 1664.2 particles kg^{-1} for RS) and OK11/21 (225.4 for FM and 1470.3 particles kg^{-1} for RS), both collected from the point bar of the Okavango active channel near Mohembo village (Fig. 2). Interestingly, although OK11/21 sediment contained a high percentage of silt and a much higher amount of organic matter than sediment at OK10/21, MP concentrations were not very different. Both methods identified low concentrations in the upstream oxbow lake 1 (sampled at the cut bank) as well as in/close to the meander necks in oxbow lake 2, downstream (Fig. 2C). Surprisingly, surface samples (OK05/21E) from the cut bank area of the downstream oxbow lake showed much higher concentrations (1.2× for Raman spectroscopy and 4× for fluorescence microscopy) than OK12/21 at the cut bank of the upstream oxbow lake. Those higher concentrations were also consistently found in the core taken at the lower oxbow lake cut bank (OK05/21A-C), indicating that this area has continuously been exposed to higher MP input, with possible main sources being local fishery activities, and direct aeolian deposition.

Although grain size has previously been identified as one of the factors influencing sediment MP concentrations under certain conditions (Enders et al., 2019; Vermeiren et al., 2021), here, the results from both fluorescence microscopy and Raman spectroscopy showed no apparent correlation between MP concentrations and grain size represented by d_{10} and d_{50} (Fig. S13), as well as, between MP concentrations and the percentage of fine material (silt and clay <63 μm, Fig. S14).

Another factor that has been linked to higher MP concentrations is a higher degree of urbanization (de Carvalho et al., 2021; Wagner et al., 2019). We also observed the highest concentrations near Xaro Lodge (OK09/21) and Mohembo village, both areas with higher human activity. However, the complexity of rural and urban human settlements and activities along the river makes it difficult to attribute these concentrations to very specific sources. Floodplain-channel interflows and the filtration capacity of floodplain plants imply that much of the observed MP distribution is probably locally driven.

In an African context, our results seem comparable to those of Dahms et al. (2020) for freshwater sediments of the Braamfontein Spruit, an urban river in South Africa or to results from Abidli et al. (2018) for Lake Tunis sediments. Other Africa-related studies report much higher MP concentrations in freshwater sediments (Abidli et al., 2017; Toumi et al., 2019), even when particles below 100 μm were not considered. While no upstream information is available from surrounding countries Namibia, Angola and Zambia we report here considerable amounts of MP in stream sediment, with average concentrations only about 1.4 times lower than those found in the Nakdong River (Eo et al., 2019), South Korea, a densely populated catchment for the same size range while results from the rather remote Tibetan Plateau (Jiang et al., 2019) indicate lower MP sediment concentrations although the actual size range found there was not reported. In general, a comparison of results across studies is hampered by the multitude of different field sampling, extraction, and identification techniques, and different studies reporting different lower size limits. In an African context, an additional limitation is the relatively low number of studies performed in freshwater systems not least due to the challenges of carrying out large-scale sampling campaigns and in-depth MP analysis in low and middle-income countries as discussed by Nel et al. (2021).

3.3. Microplastic size, shape and colour

Here we report the longest length and area for MP fragments identified with fluorescence microscopy only, as they constitute almost 92 % of all particles identified during fluorescence microscopy. In the samples studied, MP fragment length ranged between 70 and 1065 μm with a mean length of 260 μm, a median of 184 μm and a standard deviation of 228 μm (Table S3).

Median fragment lengths at OK05/21 in the downstream oxbow lake were 246 μm at the sediment surface (OK05/21E, n = 8) and 209 μm within the top 5 cm (OK05/21A, n = 6). Median lengths were 98 μm at 5–10 cm depth (OK05/21B, n = 11) and up to 121 μm (OK05/21C, n = 10) at 10–15 cm, indicating an overall decrease in median length from the sediment surface with depth. We hypothesise that either smaller fragments are transported deeper into the sediment by porewater infiltration or that fragments underwent considerable degradation in deeper sediment layers, but further sampling will be required to thoroughly test this. In contrast, median fragment lengths in the active channel seem larger, with 266 μm at OK11/21 (n = 4) at a point bar, and 270 μm at OK09/21 (n = 14) at a cut bank, although the latter location is near a tourist lodge. The measured area of the MP fragments ranged between 1890 μm^2 (OK05/21B) and 520,181 μm^2 (OK09/21) with an average of 45,037 μm^2, a standard deviation of 92,588 μm^2 and a median of 12,261 μm^2, indicating that many fragments encountered are rather small. As with the longest length, it is clearly visible at OK05/21 that the median particle area decreases from 28,730 μm^2 at the surface (OK05/21E) to 4244 μm^2 at 5–10 cm (OK05/21B) and 5886 μm^2 at 10–15 cm (OK05/21C).

Of the 71 particles identified with fluorescence microscopy, fragments (n = 65) were the dominant structural shape, with only five fibres and one sphere identified (Table S3). Of the 65 fragments identified, 32 were in a film-like state, suggesting that these might be fragments from consumer items such as plastic bags and food containers, or likely related to material in fishing activities that are more local to the area. A limited number of fibres was identified at OK10/21 and OK11/21 along the river point bar sites, OK12/21 the oxbow lake 1, with no fibres found in the oxbow lake (2) sites (Table S3). Of the 104 particles identified with Raman spectroscopy, all were identified as fragments (Table S4). Similar to our results, fragments were identified as the most abundant MP shape in river sediment in some recent studies (Kabir et al., 2022; Klein et al., 2015; Wang et al., 2018b) while other studies found predominantly fibres (e.g., Lin et al., 2018). A clear reason for that has yet to be established. However, as fibres are often released into to the environment from human activities such as washing clothes, with more pronounced release patterns closer to urban areas (Browne et al., 2011), the lack of larger population centres in the remote Panhandle region or upstream thereof is hypothesised to contribute to the much lower fibre concentrations observed in this work.

The predominant MP colour for fragments identified by fluorescent microscopy was clear (n = 26), followed by pink (n = 19), blue (n = 9), brown (n = 4) and grey (n = 4), while further samples were identified as white and purple. Clear fragments could result from several different sources, such as food packaging, however, in the context of this specific geographical location, one of the most likely contributors could be local fishing activities where clear-coloured monofilament nets are frequently used. Clear particles have also been identified as the dominant colour in previous studies (e.g., Martí et al., 2020). This is assumed to be the result of enhanced and faster UV degradation of lighter coloured plastics over darker ones as described by Zhao et al. (2022). However, colour assignment is often subjective and varies with microscope used, instrument settings and the user (Delgado-Gallardo et al., 2021; Hanvey et al., 2017).

3.4. Microplastic polymer type

Using Raman spectroscopy, the main MP polymer types identified were polyethene terephthalate (PET), polypropylene (PP), polyethene (PE), polystyrene (PS), and polyvinyl chloride (PVC) as shown in Fig. 5. Polymer types identified in the least abundance include polyurethane (PU), acrylonitrile butadiene (ABS), and polycarbonate (PC). Across all sediment samples, PET and PVC were most prevalent, composing approximately 55 % of the polymer types identified. For the cumulative results, MP types in the Panhandle region were 32.7 % PET, 22.7 % PVC, 15.7 % PE, 13.2 PS, 11.5 % PP, and 4.3 % other. Oxbow lake sites 1 and 2 showed similarities in polymer type, with OK12/21 showing the presence of more diverse polymer types as identified in others, which might be due to the proximity to the tourist lodge. A similar trend in increased MP polymer diversity was observed for OK11/21 in the main channel as compared to OK10/21 further upstream. Our findings are in line with those of Alimi et al. (2021) who discuss that PS, PP, PE, PET, PVC and polyamide (PA) seem to be the most common polymer types identified in investigated African freshwater, marine and beach sediments.

3.5. Potential impacts of our results

Long-term mean Okavango Delta sediment deposition has been reported at 870,000 metric tonnes annually, whereby 22 % can be related

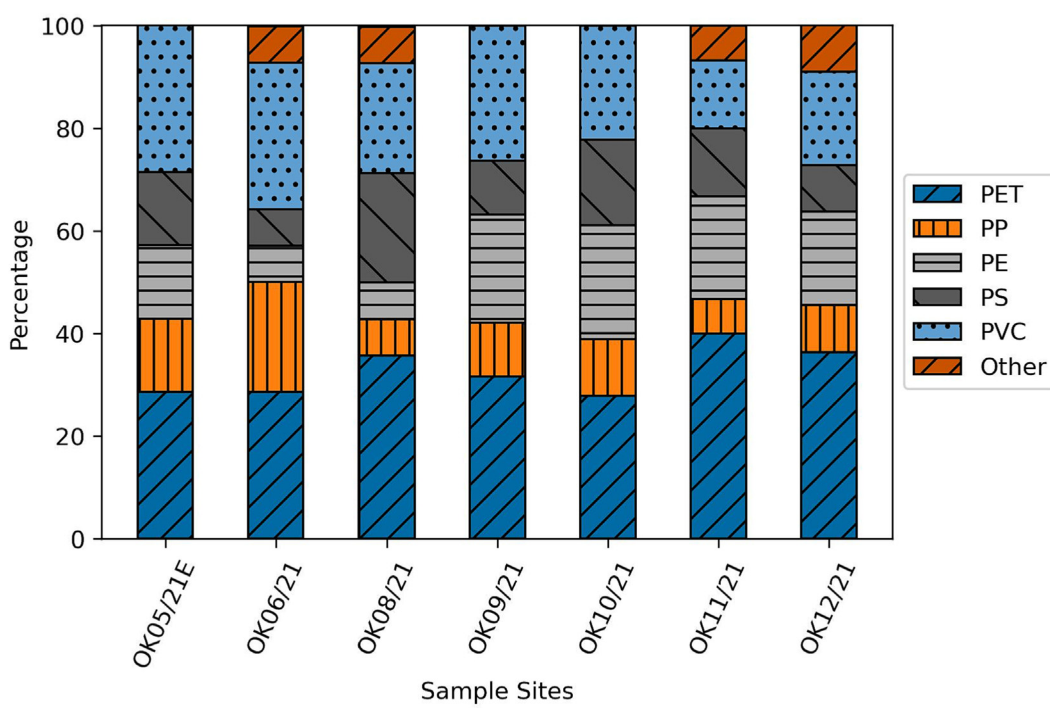

Fig. 5. Microplastic polymer types identified across the Okavango Panhandle using Raman spectroscopy.

to bedload sediment (Milzow et al., 2009). Extrapolating our MP concentrations identified with fluorescence microscopy, an annual range of 10.9 to 76.5 billion MP particles (64 μm - 5 mm) would be deposited by the river within the Okavango Delta. Using findings from Raman spectroscopy, this range would increase to 205.9–336.2 billion MP particles (20 μm – 5 mm). These first estimates of MP deposition in the Okavango Delta come with considerable uncertainty, as they are based on only a few sampling locations, without considering spatial and temporal variations in water flow across the Panhandle. Also, aeolian input (or export) of MP into (from) the fan is not considered. Nonetheless, these results suggest that MP deposition in endorheic basins may represent a significant mechanism that is currently overlooked in studies of the global MP cycle. Our results point to a critical need to further elaborate the role of other endorheic basins around the world as long-term MP sinks as they cover one-fifth of the Earth's surface (Wang et al., 2018a). Our study provides evidence that even across a rather remote area as the Okavango Delta, considerable export of MP particles can be observed with transported MP loads prone to increase in the future as plastic use and MP deposition into the environment are also likely to increase. This may have a significant impact on the local ecosystem for a number of reasons.

MP threaten fluvial ecosystems as they may enter the food chain and become sources of chemical contaminants and vectors of pathogens (Benson et al., 2022; Kukkola et al., 2021). This can have detrimental consequences for the ecosystems and can result in feeding disruption, problems with reproductive performance, disturbances in energy metabolism and even in the death of certain species (Anbumani and Kakkar, 2018). The food web in the Okavango Panhandle and Delta is controlled by the seasonality of floods, which delivers riverine nutrients, such as organic and inorganic matter/debris, leading to an increase in phytoplankton biomass and, therefore, zooplankton in the water system (Høberg et al., 2002). The resulting increase of zooplankton then supports the growth of fish communities in the shallow flood plains (Mosepele et al., 2022). Previous research has identified that zooplankton readily ingests MP, which can negatively impact reproduction, growth and life span (Botterell et al., 2019; Cole et al., 2013; Galloway et al., 2017). Therefore, harm at this level of the ecosystem may have cascading effects and negatively impact larger species within the aquatic and terrestrial environment (Høberg et al., 2002), and ultimately affect humans who derive their main source of food from the Okavango. As first results indicate that MP is already present in the Okavango Panhandle it is imperative to establish the specific effects on the local ecosystem in future studies. As the Okavango Delta is an endorheic basin, MP transported by the Okavango River can only accumulate in the fan (unless exported by non-fluvial means), and further studies are needed to fully quantify the extent of MP contamination and to identify potential management and remediation strategies that help to preserve the fragile ecosystem. Future studies should include upper, middle and lower reaches of the CORB in a basin-wide attempt to map MP distribution in sediment, surface water and selected species.

4. Conclusion

Considerable MP pollution of Okavango Panhandle sediment is found across all sampled locations including two oxbow lakes and the main Okavango channel near Mohembo. A comparison of results obtained with fluorescent microscopy to those obtained with Raman spectroscopy indicates that a large part of the particles is smaller than 64 μm. PET, PVC, PE, PS, and PP in decreasing order of prevalence are the main polymer types identified, with almost 92 % of MP particles identified as fragments. Direct MP sources have not been identified in this study but the main contributor is assumed to be hydrodynamic MP transport from upstream regions, with local input due to aeolian deposition, tourism and fishery activities. Due to high UV irradiation and little shading in the study area, MP breakdown into smaller sizes can be expected to be frequent and rapid.

Tentative estimates indicate 10.9–336.2 billion particles could be annually transported into the Okavango Delta. Taking the upper limit, this would be equivalent to between 0.7 and 2.2 % of all MP estimated to be floating in the World's oceans in 2014 (15–51 trillion particles <200 μm) as discussed by van Sebille et al. (2015). This indicates that the World's endorheic basins might constitute an important part of the global plastic cycle and further research is warranted. Whilst our study is a pilot, it indicates that MP pollution in sediment is prevalent in the Okavango Delta region, which may have detrimental effects on the fluvial ecosystem and wider wildlife. Further analysis is required to build a spatial and temporal understanding of MP pollution in the region. This study will form an integral part of the preliminary sediment assessment of the CORB commissioned by OKACOM (The Permanent Okavango River Basin Water Commission) that will eventually lead to a permanent monitoring system for sediment distribution into the basin.

CRediT authorship contribution statement

Liam Kelleher: Methodology, Investigation, Data Analysis, Writing – Original draft, Visualization.
Uwe Schneidewind: Methodology, Investigation, Data Analysis, Writing – Original draft, Visualization.
Stefan Krause: Conceptualization, Writing – Review and Editing, Funding acquisition.
Lee Haverson: Methodology, Investigation.
Steve Allen: Investigation, Writing – Review & Editing.
Deonie Allen: Data Analysis, Writing – Review & Editing.
Anna Kukkola: Investigation, Writing – Review & Editing.
Mike Murray-Hudson: Resources, Writing – Review and Editing.
Vittorio Maselli: Conceptualization, Writing – Review and Editing.
Fulvio Franchi: Conceptualization, Resources, Writing – Review and Editing, Visualization, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fulvio Franchi reports financial support was provided by Permanent Okavango River Basin Water Commission. Stefan Krause reports financial support was provided by Leverhulme Trust. Uwe Schneidewind reports financial support was provided by German Research Foundation.

Acknowledgements

This work was conducted as part of the reconnaissance work for the “OKACOM Sediment Assessment of the Cubango/Okavango River Basin”, commissioned by OKACOM, The Permanent Okavango River Basin Water Commission. FF and MMH would like to thank Casper Bonyongo (OKACOM) for the coordination of the logistic in the field. Thanks are due to the colleagues from the Department of Water and Sanitation (Botswana) for availing their facilities at Mohembo. Funding from the Leverhulme Trust via the “PlasticRivers” - The fate and transport of microplastics in rivers (RPG-2017-377) project is gratefully acknowledged. U.S. would like to acknowledge funding from the German Research Foundation (DFG – grant number 403826296).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162452.

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