MONITORING MACROPLASTIC WASTE SOURCES ALONG THE UMGENI RIVER USING UNMANNED AERIAL VEHICLES

Tadiwanashe Gutsa[1], Thomas Mani [2], Robin de Vries [2], Asanda Qadi[4], Muthukrishnavelaisamy Kumarasamy[3] and Cristina Trois[1]

[1] NRF/DSI/CSIR SARChI Research Chair in Waste and Climate Change, School of Engineering, University of KwaZulu-Natal, Durban, South Africa; [2]The Ocean Cleanup, Rotterdam, The Netherlands; [3]Civil Engineering Programme, School of Engineering, University of Kwazulu-Natal, Durban, South Africa; [4] Mechanical Engineering Programme, School of Engineering, University of Kwazulu-Natal, Durban, South Africa.

ABSTRACT

Rivers are major contributors of plastic waste entering the oceans. A global estimate in the range 0.41-4 million tons of plastic waste enters the oceans annually. The presence of plastic waste in river systems poses a threat to humans and aquatic life. The Umgeni River in Kwazulu-Natal runs through the densely populated city of Durban, with 3.5 million inhabitants and is estimated to emit ~ 400 tons of plastic waste annually into the Indian Ocean, according to a recently published global model. That study identifies the Umgeni River as one of the 1000 rivers in the world responsible for emitting plastic waste into the oceans. The banks of the Umgeni River are lined with plastic waste accumulations, derived from accidental, intentional, and natural accumulation. To our knowledge, no effort to quantify and monitor macroplastic waste sources along the Umgeni Riverbanks exists. This study uses high-resolution aerial imagery and hydrometeorological measuring sensors (rain and water level gauges) in the catchment to (1) locate, monitor, and quantify macroplastic waste hotspots along the Umgeni River; and (2) investigate the influence of hydrometeorological factors driving the spatio-temporal evolution of the plastic hotspots. This study introduces a novel attempt to map and monitor plastic waste accumulations (hotspots) along the Umgeni River through a time-series analysis of the hotspots surface area. A case study of the floods in Durban (8–12 April 2022) highlights the potential of UAV imagery in monitoring riverine macroplastic accumulations and the capacity of extreme weather events in driving their mobilization and transport of macroplastics. This study could assist waste managers and communities with a framework for developing targeted waste removal practices and mitigation measures/tools in riverine environments.

KEYWORDS

Waste management, Aerial imagery, Plastic waste accumulation, Macroplastics, Spatio-temporal, Remote sensing, Hydrometeorological factors, Oceans, Umgeni River, Mitigation measures.

INTRODUCTION

The global annual production of plastics increased from an estimated 245 million tons in 2008 to 370 million tons in 2019. At this accelerating rate, the production of plastics is predicted to increase by 100% in the next 20 years (PlasticsEurope, 2020). In 2015, more than 60% of the global plastic waste ever produced is estimated to have been collected in municipal landfills or entered the natural environment despite the increased efforts in recycling and energy recovery (Geyer et al., 2017). A percentage of the plastic waste that enters the natural environment finds its way into river systems (Horton et al., 2017). Plastic waste generated on land is assumed to contribute most of the plastics accumulating in oceans, with rivers acting as conduits for plastic waste transportation (Jambeck et al., 2015, Schmidt et al., 2017, van Emmerik and Schwarz, 2020). The annual plastic emission into oceans from river systems is estimated in the range 0.41-4 million tons (Lebreton et al., 2017, Schmidt et al., 2017).

Metropolitan cities in low- and middle-income countries are a major source of plastic pollution because of the increase in levels of economic growth, population, and urbanization (Borrelle et al., 2020, Hoornweg and Bhada-Tata, 2012). Specifically, high population density is strongly correlated with solid waste generation (Mai et al., 2020). The municipal solid waste generated in low and middle-income countries is estimated to be comprised of 10% plastic waste (Jambeck et al., 2015). The leakage of plastic waste into the environment in low and middle-income countries is high because of limited waste management infrastructure and indiscriminate plastic disposal (Rech et al., 2015). Sources of plastic waste in rivers include direct dumping at riverbanks, leakage from flooded landfills, direct discharge from boats, leakage from land-based sources through wind, urban runoff, and discharge systems (Daniel González, 2016, Kiessling et al., 2019, Tasseron et al., 2020, van Emmerik and Schwarz, 2020). Because of the complex hydrological interactions and geomorphology of river systems, plastic remains stranded in the waterways for longer durations (Tramoy et al., 2020, van Emmerik et al., 2022, Weideman et al., 2019, Brennan et al., 2018, Weideman et al., 2020). The presence of plastic waste in rivers negatively impacts both human livelihood and animal life (Blettler et al., 2018). Animals are negatively impacted by river plastics through ingestion and entanglement (Gall and Thompson, 2015, Conchubhair et al., 2019). Plastic waste in urban river systems clogs drainage networks which increases localized flood extents and damages the drainage infrastructure (Honingh et al., 2020, Tjia, 2020). Increased flood extents combined with isolated heavy rainfall events driven by the climate change phenomena poses a threat to communities in closer proximity to drainage infrastructure.

Several methods have been used to monitor riverine macroplastics, however, long-term assessments and method standardisation are still rare. Methods adopted for monitoring river plastics vary from low to high spatiotemporal coverage, these include visual observations, physical sampling, satellite imagery, and UAV imagery (Lebreton et al., 2022). Gasperi et al. (2014) and Tasseron et al. (2020) analysed floating macroplastic in urban river systems using visual observations and confirm urban areas as major contributors of river plastic inputs. Rech et al. (2015) and Kiessling et al. (2019) use a citizen science approach to sample plastic litter at riverbanks and classify litter accumulations based on their surface area. These studies show that a citizen science approach can be beneficial for sampling riverbank litter accumulations at large spatial scales and show that the main source of plastics in the sampled rivers were illegal dumping. However, citizen science data still lacks reliability and completeness. Comparatively, open-source satellite imagery provides data to monitor plastic waste accumulations at large spatiotemporal scales. Kruse et al. (2022) use an integrated system of Sentinel-2 satellite imagery and neural networks to monitor terrestrial accumulations of plastic waste in Indonesia and Southeast Asia. The system shows that most plastic waste accumulations are nearby waterways ($< 750m$) and have a high potential of leaking into waterways. However, open-source satellites have an average $10m$ per pixel resolution which has a high chance of missing smaller plastic waste patches and generating creating false positives (Kruse et al., 2022). Despite increased global river plastic monitoring efforts, the behaviour and seasonality of macroplastic accumulation zones on the Umgeni River banks have not been studied. Furthermore, to our knowledge, no long-term systematic monitoring design of plastic accumulation zones in riverbanks exists.

This study presents a simple method of monitoring and quantifying plastic waste accumulations along the Umgeni banks. The method provides a replicable and cost-effective framework for long-term monitoring of riverbank plastic waste accumulations using drones in combination with imaging and mapping software's. The generated data provides an opportunity to investigate the driving forces of plastic waste sources in riverine environments that include rainfall, water level and their seasonal variation. Developing a plastic waste monitoring framework and understanding how plastic waste accumulations evolve over time and with various natural forces allows relevant authorities and communities to prioritize targeted plastic waste removal and mitigation practices, specifically in the outlook of heavy floods in urban catchments.

MATERIALS AND METHODS

Study area

The Umgeni River in Kwazulu-Natal, South Africa is a 255 km long river with a catchment area of 4416 km^2. The Umgeni River emerges from the Drakensberg and has its river mouth at Blue Lagoon estuary in Durban where it joins the Indian Ocean. The river section of the Umgeni catchment in focus stretches 24 km^2 from the Inanda Dam, through the densely populated City of Durban (3.5 million inhabitants) to its river mouth at the Indian Ocean. The lower Umgeni Catchment is characterized by riparian vegetation, meandering channels and tributaries flowing through residential, informal settlements and industrial sites. The study additionally includes the Umhlangane River which runs 21 km through large residential and industrial areas before joining the Umgeni River.

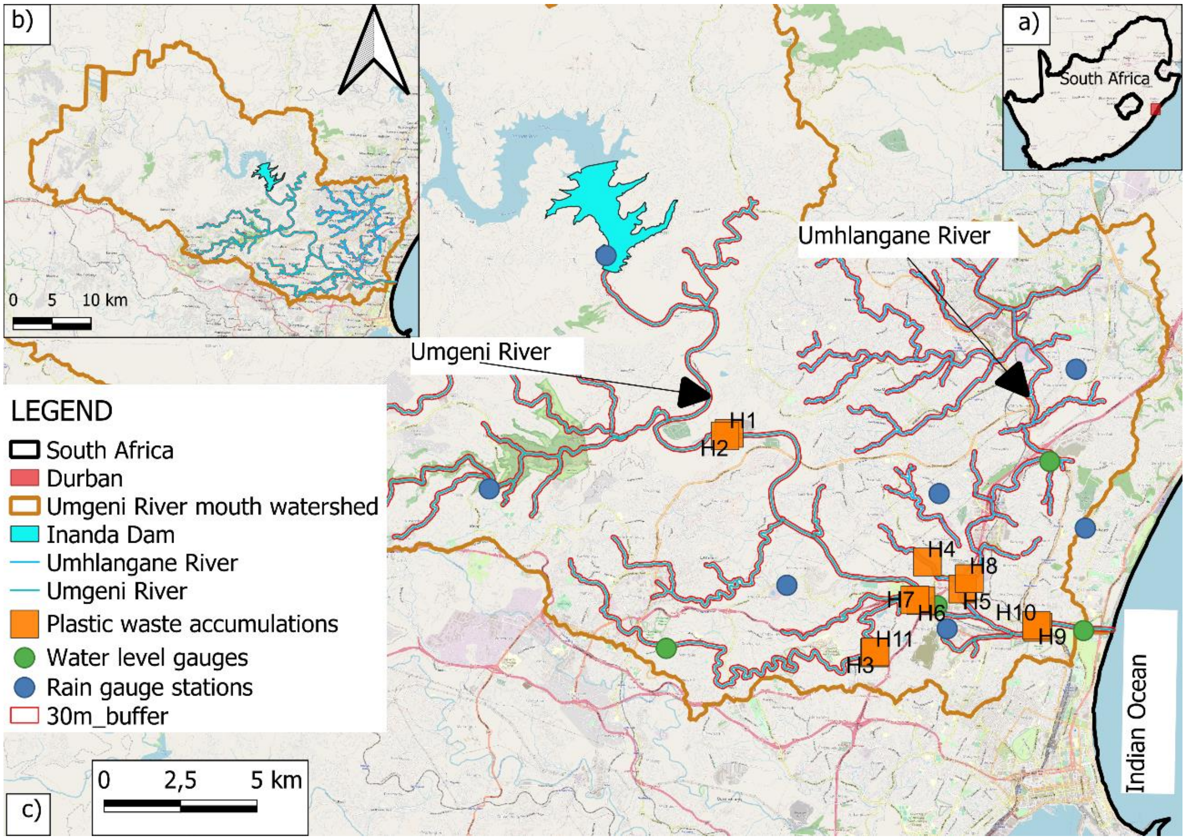

Figure 1: a) Map of South Africa and location of Durban (red square) b) the Umgeni watershed and c) the focal section of the Umgeni River system, hotspot locations and environmental sensors used for this study.

Aerial image acquisition

Aerial imagery was collected along the banks of the Umgeni River using (i) Sentinel 2-satellite, (ii) light aircraft and (iii) a DJI Mavic Air 2 Drone. The imagery was collected within a spatial perimeter of 30m buffer along the Umgeni River waterbody and its tributaries. The 30m spatial buffer was selected in order to cover plastic accumulation hotspots with high potential leakage into the waterbody. The selection of plastic accumulation hotspots to monitor followed three steps as follows: 1. Satellite imagery was used to visually distinguish and identify potential hotspots in the natural environment. 2. Aerial imagery captured from light-weight aircraft was used to corroborate and validate the hotspots. 3. Ground-truthing field survey was used to select final hotspots suitable for continuous monitoring based on a set of criteria that includes land use; and distance from waterbody and accessibility (n=11, Figure 1). The locations and extents of the 11 hotspots were selected carefully such that they can be surveyed in one day missions to avoid distortions that may be introduced by hydrometeorological events during multiple-day surveys.

The 11 selected hotspots are monitored bi-weekly using a DJI Mavic Air 2 drone under optimal weather conditions (no rainfall and wind gusts). The drone is programmed to fly automated grid flight paths with GPS correction at each hotspot (Table 1) using the Dronelink application (version 3.0.1). The drone is equipped with 12-and 48-megapixel camera modes with a mechanical shutter mounted to a three-axis gimbal, 24 mm (35 mm format equivalent) focal length with 84 degrees field of view, and a ½ inch image sensor. Images were captured at an altitude of 14m above ground level to provide ground sampling distance (GSD) of 0.5cm and overview images captured at an altitude of 120 m . The parameters for the grid flight are set as follows: camera is pointed nadir 90 degrees to the ground, ISO adjusted according to specific daylight, aperture at f/2.8, image overlap is 80% frontal and 70%-lateral, flight speed at 5 m/s and image interval at 2 seconds.

Aerial image processing and analysis

The aerial drone images acquired during the grid flight missions were processed using Pix4D cloudAdvanced and mapped using QGIS (version 3.24) software. Every image captured contains DJI metadata such as geo-location tags, timestamp, and image resolution. Grid flight images for each hotspot were stitched together using Pix4D to generate an orthomosaic tile with a GSD of 0.5 cm in the WGS 84/ UTM Zone 35S Coordinate Reference System (CRS). A GSD of 0.5 cm provides sufficient visual detail to detect plastic items down to the size of e.g. a bottle cap and allows for human classification of plastic items by eye. The generated orthomosaics have a spatial positioning error of ± 2 m because no tie points are used to rectify the imagery hence it relies on the DJI aircraft geo-location tags only.

Through visual inspection of the orthomosaic tiles, plastic waste accumulations were critically differentiated and tagged based on a decision tree classifier (Figure 2). The decision tree classifies waste accumulations into three classes as follows: visible dense plastic waste cluster; visible scattered plastic waste cluster; and visible construction rubble cluster. Each cluster is tagged by marking its boundary and assigning it a unique code.

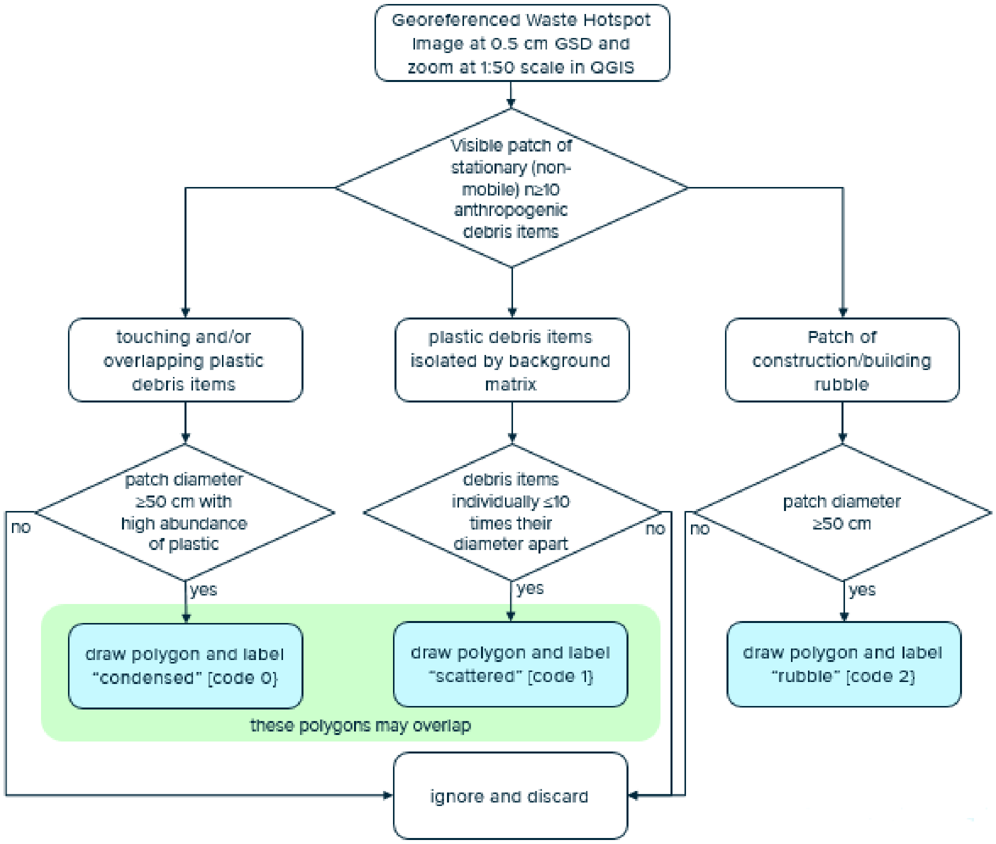

Figure 2: Decision tree classifier used to cluster and tag waste accumulations.

The classification of the clusters depends on the ability of the human eye to identify plastic items based on their characteristics and features (for example colour and shape). In addition, the surface area of each cluster on an orthomosaic tile was automatically computed using the Pix4D polygon annotation tool. The annotated orthomosaic tiles were exported to QGIS to produce scaled and true north-oriented hotspot maps (Figure 3).

RESULTS

Of the 26 plastic accumulation hotspots identified on the satellite imagery, 11 were selected for continuous monitoring over the course of the study (Table 1). The distance of a waste hotspot to the water body was measured as distance from the nearest boundary of the hotspot to the river during the ground truth survey. In total 141 flight missions were carried out from December 2021 to June 2022.

Table 1: Details of monitored hotspots. Each hotspot is monitored twice per month.

Hotspot ID	Area (m^2)	Land use	Distance from waterbody (m)	Period surveyed	Estimated flight time (minutes)
H1	421	Peri-urban residential	10	7 months	04:40
H2	880	Peri-urban residential	7	7 months	06:05
H3*	442	Informal residential	0	7 months	01:36
H4	485	Formal residential	4	7 months	03:49
H5	558	Industrial	0.5	7 months	01:52
H6	3960	Informal residential	15	7 months	13:52
H7	710	Informal residential	0.5	7 months	07:02
H8*	672	Informal residential	4	7 months	02:25
H9	520	Recreational	0.5	7 months	04:50
H10	1265	Recreational	1	7 months	04:42
H11	229	Formal residential	0	5 months	01:54

A time-series analysis of the computed waste cluster surface areas from each orthomosaic tile was used to determine the evolution of the waste hotspots over time. The hotspot's surface area data were compared with rainfall and water level data to investigate their correlation and thus potential influence on the evolution of the plastic accumulations.

CASE STUDY OF THE RECENT DURBAN FLOODS (8–12 April 2022).

In this paper a case study of the recent Durban floods is used to present the impact of flooding on riverbank plastic waste accumulations. The city of Durban experienced heavy rainfall between the 8th and 12th of April that resulted in severe flooding during which coastal areas received rainfall above $200mm$. The devasting floods triggered mudslides and washed away homes causing the death of more than 400 people and left thousands homeless (reliefweb, 2022). This analysis covers flight missions for two hotspots (marked with asterisk in Table 1) captured on the 7th of April 2022 (3 days before the flood) and 6th of May 2022 (3 weeks after the flood). The hotspot maps in Figure 3 show waste accumulations at two hotspot locations before and after the flood.

Figure 3: a) and b) Hotspot maps showing waste cluster abundance at site H8 on the 7th of April (before flood) and on the 6th of May (after flood); and c) and d) plastic waste cluster abundance at site H3 on the 7th of April 2022 (before flood) and on the 6th of May 2022 (after flood).

Water level and rainfall data during the flooding event were correlated with the waste cluster surface area changes (Figure: 4). The total cluster surface area for both hotspots H8 and H3 were reduced by more than 50% after the flood event. This might be due to the flushing away of macroplastics waste during the floods. Similarly, van Emmerik et al. (2019) report a strong correlation between plastic waste transport in rivers during flood events induced by heavy rainfalls in the Seine River, France. Their study shows that plastic waste transport was 10-fold during high flow conditions compared to low flow conditions.

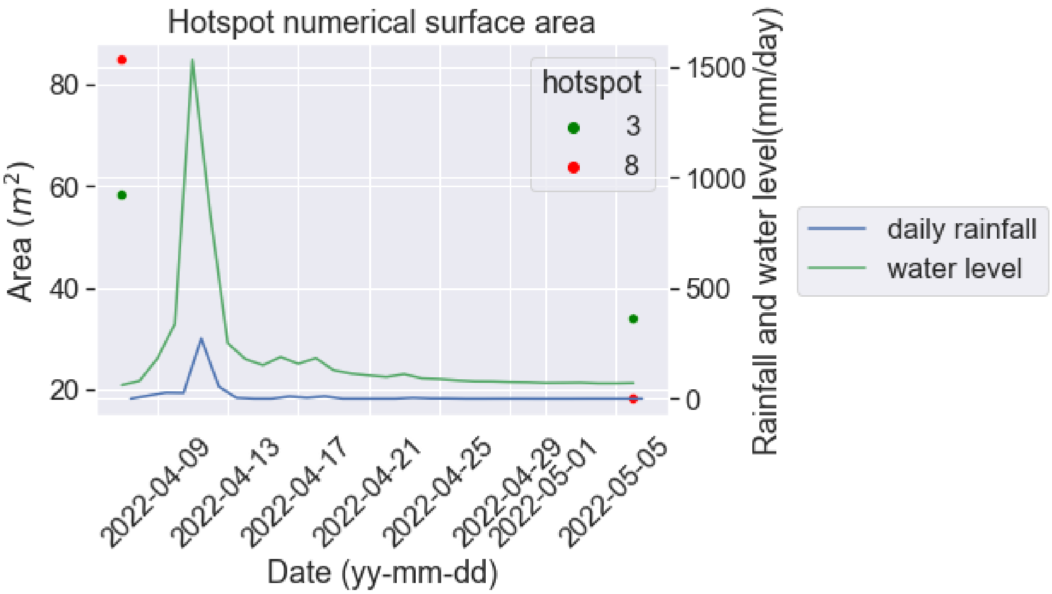

Figure 4: Waste cluster areas for hotspot H8 and H3 aligned with mean daily rainfall and mean daily water level.

A bi-weekly time-series (December 2021 to May 2022) of the cluster surface area at hotspot H3 in Figure 4 shows that during rainfall and river water level peak in January there is a reduction in the waste aggregation. After the first peak period a gradual increase in waste aggregations is evident between 2022-01 and 2022-04 which drops considerably during the flood period (2022-04 to 2022-05).

This analysis although still in its primary stages, highlights the potential to use aerial images to quantify riverbank plastic pollution at a coarse scale over extensive areas. The monitoring method used is replicable, cost-effective, provides high-resolution data and can be used regularly to monitor important segments of urban river catchments relevant to plastic pollution for longer durations.

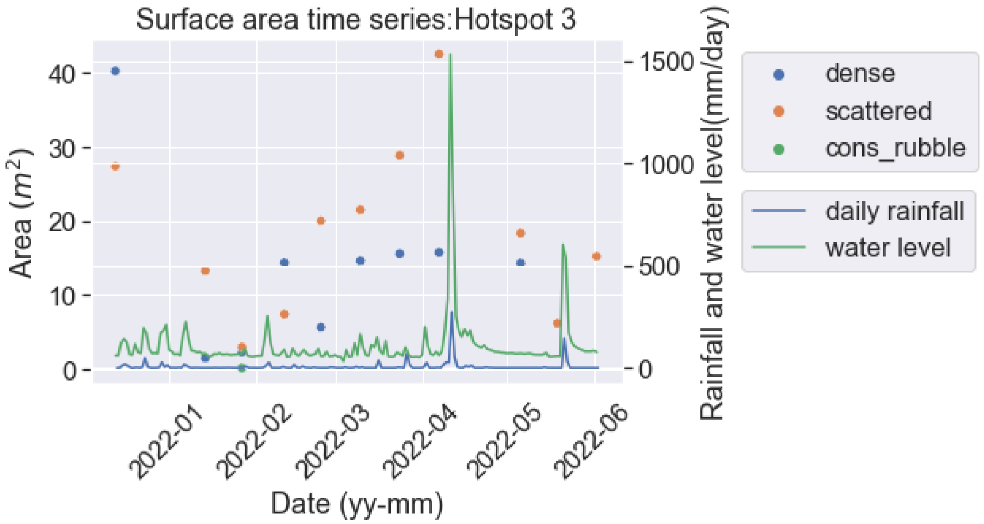

Figure 5: Cluster area bi-weekly time series at hotspot H3 for all three clusters from December to May 2022, and the corresponding daily rainfall and water level time series during the same time period.

CONCLUSIONS

With the increasing amount of plastics entering the oceans, there is an urgent need for management practices to prevent and remove these plastics. Identifying macroplastic hotspots along riverbanks and the extent of accumulation can assist waste managers in strategizing targeted cleanup campaigns, resource allocation, and optimizing in-situ river plastic retainment. This research uses the Umgeni River system as a case study to determine and monitor a specific type of river plastic waste source – hotspots – and understand their spatial evolution in relation to hydrometeorological factors and extreme weather events. Furthermore, the study aims to introduce a simple method of classifying land-based macroplastic aggregations. The research output is intended to be transferred to other river systems across South Africa and the world. Future work aims to use aerial imagery for waste characterization and developing replicable risk-management and climate change mitigation tools which integrate mismanaged solid waste and hydrological data.

ACKNOWLEDGEMENTS

Tito's Handmade Vodka is acknowledged for the partial funding of this project through the 3 RIVERS 3 YEARS research program lead by The Ocean Cleanup. The Ocean Cleanup is a non-profit organization advancing scientific understanding and developing solutions to rid the oceans of plastic, headquartered in Rotterdam, the Netherlands.

This study is supported by the South African National Research Foundation (NRF) through the SARCHI Chair Waste and Climate Change (UID 115447). The authors acknowledge the funding received from the Department of Science and Innovation of South Africa under the Waste RDI Roadmap Programme (Grant #42).

REFERENCES

BLETTLER, M. C., ABRIAL, E., KHAN, F. R., SIVRI, N. & ESPINOLA, L. A. 2018. Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water research,* 143**,** 416-424.

BORRELLE, S. B., RINGMA, J., LAW, K. L., MONNAHAN, C. C., LEBRETON, L., MCGIVERN, A., MURPHY, E., JAMBECK, J., LEONARD, G. H. & HILLEARY, M. A. 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science,* 369**,** 1515-1518.

BRENNAN, E., WILCOX, C. & HARDESTY, B. D. 2018. Connecting flux, deposition and resuspension in coastal debris surveys. *Science of the total environment,* 644**,** 1019-1026.

CONCHUBHAIR, D. Ó., FITZHENRY, D., LUSHER, A., KING, A. L., VAN EMMERIK, T., LEBRETON, L., RICAURTE-VILLOTA, C., ESPINOSA, L. & O'ROURKE, E. 2019. Joint effort among research infrastructures to quantify the impact of plastic debris in the ocean. *Environmental Research Letters,* 14**,** 065001.

DANIEL GONZÁLEZ, G. H., GIJSBERT TWEEHUYSEN, BERT BELLERT, MARLOES HOLZHAUER, ANDREJA PALATINUS, PHILIPP HOHENBLUM AND LEX OOSTERBAAN 2016. Riverine Litter Monitoring-Options and Recommendations.

GALL, S. C. & THOMPSON, R. C. 2015. The impact of debris on marine life. *Marine pollution bulletin,* 92**,** 170-179.

GASPERI, J., DRIS, R., BONIN, T., ROCHER, V. & TASSIN, B. 2014. Assessment of floating plastic debris in surface water along the Seine River. *Environmental pollution,* 195**,** 163-166.

GEYER, R., JAMBECK, J. R. & LAW, K. L. 2017. Production, use, and fate of all plastics ever made. Sci Adv 3: e1700782.

HONINGH, D., VAN EMMERIK, T., UIJTTEWAAL, W., KARDHANA, H., HOES, O. & VAN DE GIESEN, N. 2020. Urban river water level increase through plastic waste accumulation at a rack structure. *Frontiers in earth science,* 8**,** 28.

HOORNWEG, D. & BHADA-TATA, P. 2012. What a waste: a global review of solid waste management.

HORTON, A. A., WALTON, A., SPURGEON, D. J., LAHIVE, E. & SVENDSEN, C. 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the total environment,* 586**,** 127-141.

JAMBECK, J. R., GEYER, R., WILCOX, C., SIEGLER, T. R., PERRYMAN, M., ANDRADY, A., NARAYAN, R. & LAW, K. L. 2015. Plastic waste inputs from land into the ocean. *Science,* 347**,** 768-771.

KIESSLING, T., KNICKMEIER, K., KRUSE, K., BRENNECKE, D., NAUENDORF, A. & THIEL, M. 2019. Plastic Pirates sample litter at rivers in Germany–Riverside litter and litter sources estimated by schoolchildren. *Environmental Pollution,* 245**,** 545-557.

KRUSE, C., BOYDA, E., CHEN, S., KARRA, K., BOU-NAHRA, T., HAMMER, D., MATHIS, J., MADDALENE, T., JAMBECK, J. & LAURIER, F. 2022. Satellite Monitoring of Terrestrial Plastic Waste. *arXiv preprint arXiv:2204.01485*.

LEBRETON, L., KOOI, M., MANI, T., MINTENIG, S. M., TEKMAN, M. B., VAN EMMERIK, T. & WOLTER, H. 2022. Plastics in Freshwater Bodies. *Plastics and the Ocean.*

LEBRETON, L. C., VAN DER ZWET, J., DAMSTEEG, J.-W., SLAT, B., ANDRADY, A. & REISSER, J. 2017. River plastic emissions to the world's oceans. *Nature communications,* 8**,** 1-10.

MAI, L., SUN, X.-F., XIA, L.-L., BAO, L.-J., LIU, L.-Y. & ZENG, E. Y. 2020. Global riverine plastic outflows. *Environmental Science & Technology,* 54**,** 10049-10056.

PLASTICSEUROPE 2020. Plastics–the facts 2020. *PlasticEurope,* 1**,** 1-64.

RECH, S., MACAYA-CAQUILPÁN, V., PANTOJA, J., RIVADENEIRA, M., CAMPODÓNICO, C. K. & THIEL, M. 2015. Sampling of riverine litter with citizen scientists—findings and recommendations. *Environmental monitoring and assessment,* 187**,** 1-18.

RELIEFWEB 2022. South Africa: Floods and Landslides Apr 2022. OCHA.

SCHMIDT, C., KRAUTH, T. & WAGNER, S. 2017. Export of plastic debris by rivers into the sea. *Environmental science & technology,* 51**,** 12246-12253.

TASSERON, P., ZINSMEISTER, H., RAMBONNET, L., HIEMSTRA, A.-F., SIEPMAN, D. & VAN EMMERIK, T. 2020. Plastic hotspot mapping in urban water systems. *Geosciences,* 10**,** 342.

TJIA, J. 2020. Assessing the impact of plastic waste accumulation on flood events with citizen observations: A case study in Kumasi, Ghana.

TRAMOY, R., GASPERI, J., COLASSE, L., SILVESTRE, M., DUBOIS, P., NOÛS, C. & TASSIN, B. 2020. Transfer dynamics of macroplastics in estuaries–new insights from the Seine estuary: part 2. Short-term dynamics based on GPS-trackers. *Marine Pollution Bulletin,* 160**,** 111566.

VAN EMMERIK, T., MELLINK, Y., HAUK, R., WALDSCHLÄGER, K. & SCHREYERS, L. 2022. Rivers as plastic reservoirs. *Front. Water,* 3**,** 1-8.

VAN EMMERIK, T. & SCHWARZ, A. 2020. Plastic debris in rivers. *Wiley Interdisciplinary Reviews: Water,* 7**,** e1398.

VAN EMMERIK, T., TRAMOY, R., VAN CALCAR, C., ALLIGANT, S., TREILLES, R., TASSIN, B. & GASPERI, J. 2019. Seine plastic debris transport tenfolded during increased river discharge. *Frontiers in Marine Science,* 6**,** 642.

WEIDEMAN, E. A., PEROLD, V. & RYAN, P. G. 2019. Little evidence that dams in the Orange–Vaal River system trap floating microplastics or microfibres. *Marine Pollution Bulletin,* 149**,** 110664.

WEIDEMAN, E. A., PEROLD, V. & RYAN, P. G. 2020. Limited long-distance transport of plastic pollution by the Orange-Vaal River system, South Africa. *Science of the Total Environment,* 727**,** 138653.