Booms, grids and nets: intercepting macroplastic debris in rivers

Technical report: Removing plastic and other litter from South African waterways

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EXECUTIVE SUMMARY

This document reports the findings from the DSI/CSIR Waste Roadmap-funded project on booms, grids and nets: intercepting macroplastic debris in rivers, conducted by researchers from the University of Cape Town in 2021-2022. The study improves our understanding of land-based sources and pathways of marine plastic debris, particularly in the context of South African coastal urban areas. The project had three broad aims: to provide a summary of current efforts to intercept litter in South African urban waterways, to assess the efficacy of different devices in relation to urban litter loads based on a comparison of street litter with litter trapped in booms and nets, and to develop a methodology to model litter generation in urban areas to identify key areas where additional installations should be targeted.

Inventory of litter interception devices

The survey of interception devices on waterways in urban source areas was conducted to gather information on their design and servicing protocols. A total of 189 devices were identified along the coast of South Africa, with most concentrated in the major cities of Cape Town and Durban, and a few initiatives in Gqeberha and Gansbaai. However, this is a minimum estimate, because most municipalities failed to respond to inquiries about devices. Within the Cape Town metro, 107 litter traps are managed by the local municipality, with many considered in poor structural and functional condition. Infrequent servicing and maintenance of devices coupled with high litter loads in many river catchments often leads to blockages and overflowing during high flow events. Most devices consistently serviced and maintained are manged by private individuals or groups, often linked to NGOs or research institutions. However, most are generally short-lived, only operating during study or trial phases and thereafter discontinued or removed. A few public organizations have operated over longer periods, relying on public and corporate funding to cover running costs. The bulk of intercepted waste from devices is sent to landfill due to high levels of contamination, which renders it unsuitable for recycling. Some groups separate recyclable materials and partner with recycling initiatives, but this is generally on a small scale. Theft and vandalism of devices, as well as site safety for workers, were common issues raised by operators.

Litter traps: amounts and composition

Site-visits and inspections of devices in Cape Town were conducted to validate and assess their suitability for further sampling. Three sites of contrasting socio-economic settings: Newlands (high income), where two litter booms are installed on the Liesbeek River; Steenberg (middle income), where a series of nets in the canals leading into Marina Da Gama was sampled in tandem with a litter boom; and Ocean View (low income), where a municipal passive sediment trap was sampled together with a net further downstream. All debris was removed from the devices the day prior to a rainfall event; then newly intercepted litter was collected daily and processed. A total of 35 649 intercepted litter items, weighing 131.9 kg, was sampled from the various screening devices across the three study sites. The highest daily litter loads intercepted were by the litter boom and nets at Marina Da Gama (2720 items and 9573 g·day^{-1}), followed by the two litter booms at Liesbeek (1743 items and 6090 g·day^{-1}), and the net and trap in Ocean View (1026 items and 4726 g·day^{-1}). Plastics were the dominant material type by both number (77%) and mass (69%), followed by wood (18%) and glass (5%) in terms of mass. The proportion of plastics in both number and mass was highest in Ocean View (91% by number, 73% by mass), followed by Marina Da Gama (82% by number, 67% by mass) and

Liesbeek (59% by number, 68% by mass). Wooden objects by mass were higher in Ocean View (13%) and Marina Da Gama (25%) compared to Liesbeek (9%), where glass (9% by mass) and metal (8% by mass) contributed a larger proportion to the total mass.

Most of the mass of intercepted plastics were single-use items (66%), with user items contributing 25% of the mass but only 5% by number. Flexible packaging such as food wrappers and bags dominated the macroplastic litter in urban waterways in terms of numbers of items (45%), but bottles, lids, and tubs (mostly PP and PET) made up more than half of single-use plastics by mass (53% by mass), despite comprising only 8% of single-use items by number. The proportion of flexible packaging by mass showed an inverse relationship with income level, decreasing five-fold from Ocean View (54%) to Liesbeek (10%). Flexible packaging at Liesbeek featured heavily, both numerically (76% by number) and by mass (54% by mass) of single-use plastics. Foamed plastics (chiefly expanded polystyrene, EPS) made up more than half of single-use items by number in both Steenberg (53% by number) and Liesbeek (56%), in contrast to Ocean View (18%). Although being the most common macroplastic item numerically (47% by number), foamed plastics constituted a much lower proportion of single-use plastics by mass (15% by mass). These differences in litter composition among sites likely reflect differences in trap efficiency as well as in the types of litter entering each catchment.

Street litter: composition and flux

Given the challenges of estimating litter fluxes in episodic rivers, street litter surveys were conducted in the same catchments where interception devices were sampled, to better estimate litter inputs, and to compare the waste streams in both environmental compartments: streets (source) and river (sink). Overall, 25 420 items weighing 69.7 kg were collected during street litter surveys. The low-income site generated an order of magnitude more litter daily (147.7 items and 396.6 g·100 m^{-1}·day^{-1}) than the high-income site (6.4 items and 27.8 g·100 m^{-1}·day^{-1}), with the mid-income site having intermediate values (42.8 items and 95.5 g·100 m^{-1}·day^{-1}). Plastics were the most common material type both numerically (49% of all litter) and by mass (47% of litter), followed by card/paper (16%) and glass (14%) in terms of mass. Cigarette butts comprised 28% of street litter items by number, but only accounted for 3% of the mass of litter.

Flexible packaging dominated single-use plastics in street litter by number (87%) and made-up half of the total mass (50% by mass) across the three sites. In contrast, flexible packaging in rivers constituted lower proportions of single-use plastics both numerically (45% by number) and by mass (33% by mass) across the study sites. Only 3% of single-use plastics in street litter by number were foamed plastics, despite being the leading contributor in rivers numerically (47% by number). This results in part from the ready fragmentation of EPS (especially sheets and trays used for food packaging) in freshwater systems, which can be seen in the greater average mass per foamed item in street litter (2.01 g) compared to riverine/intercepted litter (0.89 g). There was a decrease in the relative mass proportions of flexible packaging from street to river litter in both Steenberg (street 60%; river 37%) and Liesbeek (street 40%; river 10%), but not in Ocean View (street 50%; river 54%).

Litter trap efficiency

The sampling of multiple devices in sequence at each site allowed a broad assessment of trap efficiency in terms of composition and litter load captured by each device. The upstream litter boom at Marina Da Gama intercepted a larger proportion of buoyant items by number (68% by number) compared to the nets below (53% by number), but over five sampling events, three times as much litter was captured in the nets (25.7 kg) compared to the litter boom (8.5 kg), indicating that simple floating booms trap at most one quarter of the litter load. Just under half of all items intercepted by the litter boom were <5 cm in length (49%), the same proportion captured by the last net with the finest mesh (49%, mesh size 60 mm). The first two nets immediately downstream of the boom, which have the largest mesh size (both 120 mm), intercepted the highest proportion of large items in the two larger size classes: 12% >20 cm and 28% 10-20 cm in net 1, followed by 9% >20 cm and 22% 10-20 cm in net 2. The proportion of items <5 cm intercepted generally increased as the net mesh size decreased moving downstream.

Trials using marked items of varying size indicated a lower retention efficiency for small items in both litter booms and nets. However, retention rate also depended on the amount of other litter already in the device (retention generally better when nets and booms are clogged with litter). Flow rate presumably also influences retention rates, but trials were only conducted at relatively low flow rates.

Modelling litter flux

The data from the street litter surveys in the three catchment areas, combined with previous estimates of litter amounts in Cape Town storm drains, were used to develop a spatial model of the amount of plastic and other litter generated in each hydrological catchment across the Cape Town metro area. The model predicted that on average 26.0 (15.3–36.6) tonnes of street litter is produced in Cape Town daily, with 56% of this litter being loaded into three river networks; Salt/Black, Eerste and Diep Rivers. Key litter trap installation sites were identified in the Salt/Black River catchment area. The distribution of current litter traps in the city (mostly municipal traps installed in the 1980s and 1990s) was poorly correlated (R^2 = 0.28) to the catchments receiving the largest plastic litter weight daily. The findings from this study will help better inform the City of Cape Town management with regards to focusing their urban litter mitigation efforts. The approach used could be readily applied in other urban areas to predict weights of urban litter loads and identify key areas for litter trap interventions.

Conclusions and recommendations

Interception devices offer considerable potential to reduce the leakage of plastic and other litter from land-based sources into the sea. However, the simple floating boom design used by most projects are substantially less efficient at capturing litter than nets or other designs that trap litter deeper into the water column. It appears that device design is constrained more by the need to reduce the risk of loss through theft or vandalism than functionality. All devices struggle to operate effectively in high flow conditions, which means that even if they were installed throughout coastal urban waterways, they would have limited success in reducing spikes in litter reaching coastal waters and polluting urban beaches during very high rainfall events. As such, management should focus primarily on reducing litter loading into urban catchments through improved solid waste management, incentives to recycle and re-design of litter-prone items (especially packaging for convenience foods and drinks, and tobacco-related litter).

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1. Introduction

South Africa is one of the worst polluters of the marine environment with plastics globally (Jambeck et al., 2015). Most of this plastic comes from land-based sources, resulting from chronic littering and poor waste management in many municipal areas (Verster & Bouwman, 2020). The quantification of litter flows in areas lacking waste delivery services remains a key goal in the country's national waste management strategy, which is vital in the identification of problematic waste types and areas where mitigation efforts should be focused. Much of this plastic waste is carried to the sea by rivers or waste-water systems (Ryan, 2020; Weideman et al., 2020a; Ryan & Perold, 2021). Until we can resolve the many challenges to effective solid waste management on land, one of the most effective interventions is to remove macroplastic items from storm water and rivers before it reaches the sea. Various devices have been designed to do this, ranging from floating booms and nets to grids and floating litter traps. With increasing awareness of the threats posed by plastic waste in aquatic systems, new initiatives are being implemented in urban catchments to intercept litter, led by NGOs as well as municipalities. However, we lack an overview of how extensive these efforts are, and more critically, we don't know how effective these efforts are in capturing plastic macrolitter. Each group typically has their own design of litter trap and servicing protocol, developed largely through trial and error to find a system that appears to be effective and also is not at high risk of being stolen and/or vandalised. We need a systematic review of litter interception initiatives and their efficacy, including an assessment of the fate of materials collected. Ideally, most of the material caught in these devices should be recycled or composted, and if done properly, could help to support the sustainable servicing of the screening systems. By providing an inventory of current screening initiatives, this project also identifies areas where further screening measures could usefully be implemented.

1.1 Background and Rationale

South Africa has been listed as the 11th largest contributor of land-based plastic pollution to marine environments globally, based largely on the high proportion of mismanaged waste (Jambeck et al., 2015). Although the amount of plastic leaked into marine systems from South Africa probably is appreciably less than that predicted by Jambeck's model (Ryan, 2020; Verster & Bouwman, 2020; Weideman et al., 2020), it is clear that poor waste management on land results in significant plastic inputs into wetlands and the sea (Department of Science and Technology, 2014; Ryan, 2020; Verster & Bouwman, 2020). These local sources of plastic waste are concentrated around urban areas, where land-based litter loads are larger due to the large concentrations of people living and working in cities (Jambeck et al., 2018; Ryan, 2020). This land-based litter has the potential to travel into nearby rivers via stormwater drains and catchments (Weideman et al., 2020) and be transported to the ocean (Maclean et al., 2021). However, there are limited data on the input, transport, and magnitude of plastic wastes in rivers, especially in a South African context (Ryan, 2020; Verster & Bouwman, 2020; Weideman et al., 2020a, 2020b; Ryan & Perold, 2021). This paucity of data makes it difficult to draft and implement strategies to reduce litter loads in rivers, and therefore the ocean.

For inland litter sources, a large proportion of macrolitter is probably trapped in rivers, failing to reach the sea at least under normal flow conditions (Weideman et al., 2020). During extreme weather events and associated flooding, large amounts of litter including some old debris may be released, as recently seen in Durban (Pichegru & Ryan, 2022). A recent study in France found that plastic litter may spend decades trapped in the lower reaches of rivers (Tramoy et al., 2020). Such long retention times might promote the formation of microplastics (Tramoy et al., 2020; Verster & Bouwman, 2020) but also offer the opportunity to capture and remove macroplastics before they reach the sea. Numerous mechanisms have been designed to remove litter from wastewater, including both source controls on storm water drain inlets (e.g. grids across inlet entrances or catch pits inside inlets) and downstream structural controls (e.g. floating booms, nets, grids, etc.; Armitage & Rooseboom, 2000). Source controls are expensive to implement because they are more diffuse, and are not suitable for areas with limited infrastructure, which is likely where most of the urban litter in South Africa originates (Verster & Bouwman 2020).

Accordingly, this project focused on downstream structural controls that can remove macroplastic litter from rivers before it reaches the sea (e.g. Sidek et al., 2016). This approach is in line with the shift in focus by groups such as The Ocean Cleanup, which has moved from attempting to clean up the mid-ocean gyres to intercepting litter in heavily polluted rivers (https://theoceancleanup.com/rivers/). However, the hi-tech approach advocated by The Ocean Cleanup requires large, perennial rivers, and is expensive to install and protect. Much of the urban litter in South Africa is carried by small, seasonal streams, and attempts to erect screening systems are often foiled by theft and/or vandalism. For example, three litter catch nets on the Soet River in Strand, Cape Town, were removed on the first night after installation (Gregg Oelofse, City of Cape Town, pers. comm.). As a result, most NGOs are resorting to using simple floating booms to trap litter (e.g. https://www.businessinsider.co.za/litterbooms-in-cape-town-2020-6), which might be not very effective in trapping the bulk of litter in river systems.

There is limited information on the cost, maintenance required and efficacy of different device types (Helinski et al., 2021). To date, few studies have looked at the operational effectiveness of different interception devices including floating booms. Under controlled, laboratory conditions, booms capture some 90% of buoyant macrolitter items (Gkanasos et al., 2021), but under field conditions, Bletter et al. (2022) estimated a trapping efficiency around 37%, with low retention rates for submerged plastics. High abundances of sinking plastic products in freshwater systems have been reported by multiple studies around the world (Morritt et al., 2014; Rech et al., 2014; Schöneich-Argent, Dau & Freund, 2020; Morales-Caselles et al., 2021), suggesting the limited efficiency of devices only targeting floating litter.

A range of device types is currently being used across South Africa, likely chosen without much consideration of plastic loading and the most prevalent plastic types commonly littered within each catchment. Device design influences servicing requirements as well as device efficiency for trapping different litter types by size and buoyancy (density). And in order to better understand efficiency, we need to understand the amounts and types of plastics and other debris transported in waterways, and in particular their vertical profile (Helinski et al., 2021). Waste management strategies must be well-informed and supported by adequate data if they are to substantially reduce plastic pollution of our marine and freshwater systems. Monitoring accumulation of debris on land as well as in rivers is important in acquiring such data and can generate more knowledge of local variation in litter accumulation as well as litter characteristics. Removing plastics and other litter from urban wastewater is important not only to reduce plastic reaching the sea, but also to improve the health of freshwater ecosystems, which are crucial for human well-being.

1.2 Objectives

The project had three objectives:

1) to provide an inventory of the various measures currently used to intercept macroplastics in urban waterways in coastal South Africa;

2) to assess the efficacy of litter barriers under South African conditions through both direct observation and experimental measures; and

3) to develop a methodology to identify key sites for further deployments to reduce plastic leakage into the sea.

2. Methodology

2.1 Inventory of litter interception devices

A survey of litter interception devices on waterways in the major urban source areas was conducted using a questionnaire (Annexure 1) to gather information on the design and management: who collects the accumulated litter, how often, what happens to the litter, who funds the servicing, etc. The survey was mostly conducted remotely (via email and Zoom calls) due to Covid-19 travel restrictions at the start of the study, with follow up visits in-person to a subset of sites in Cape Town. The data obtained were summarized by region, type of device and managing body. Communication with most coastal municipalities was challenging, often with limited response and/or engagement, thus our inventory is a minimum representation of municipally-administrated devices.

2.2 Field Sampling

2.2.1 Riverine/intercepted litter

Cape Town is South Africa's largest coastal city, home to more than 4 million people (World Population Review, 2020), and is a key source of plastic leakage into the environment (Collins & Hermes, 2019; Ryan, 2020; Weideman et al., 2020). The city is drained by approximately 36 rivers, which run through a varied landscape ranging from mountain ranges to flat, lowland areas. Many of the rivers found in the Cape Flats region, a large, low lying, flat region located to the southeast of the CBD, are canalised. Some of the coastal regions lack rivers and have storm drain systems that empty directly into the ocean. The city experiences a Mediterranean climate, receiving most rainfall in winter (June–August), and a large proportion of city's river networks are seasonal, only flowing for a few months per year. Rainfall patterns vary considerably across the Cape Peninsula due to the varied topography, ranging from 300–1200 mm per year. Storms are often brief but intense, resulting in heavy rain for a short period.

Using information gathered from the inventory, litter was sampled from interception devices in three suburbs of Cape Town. The sampling of intercepted litter involved clearing the devices of all litter the day prior to a rain event and collecting all retained litter the next day. Three contrasting areas were selected to cover a range of socio-economic settings and land-use types (Fig. 1). Matching street litter in the same catchments was sampled to compare the two waste streams and generate more consistent estimates of litter input in each catchment. Information of each site is detailed below:

Newlands/Liesbeek: an upmarket, medium-density residential area. Two litter booms installed by an NGO on the Liesbeek River, a tributary to the Black River (Fig. 2), were sampled on six occasions. These booms have a total urban catchment of some 1027 ha. Daily accumulations of street litter were surveyed along 1760 m of mostly residential streets, but which also included streets adjacent to a school, a public park, and an on-ramp onto a section of dual-carriageway. Street litter accumulation was sampled on two occasions for a total of 31 days.

Steenberg/Marina Da Gama: a middle-income community. A series of five nets, decreasing in mesh size from 120 mm to 60 mm, installed by a local resident in one of the canals leading into Marina Da Gama was sampled on seven occasions (Fig. 3). Municipal grids have been installed in some of the tributaries leading into this canal, but often become blocked due to infrequent servicing (Fig. 4). In addition, a litter boom was installed by an NGO immediately above the net system specifically to assess the trapping efficiency of booms compared to nets. Both devices were sampled in tandem during five rain events. These nets and booms have a total urban catchment of some 2338 ha. Daily accumulation of street litter was sampled along 600 m of roads in a mixed-commercial/residential area and a light industrial area on two occasions for a total of 15 days.

Ocean View: a low-income, high-density township established in the 1960s to accommodate people displaced by the Group Areas Act. A net with a 90 mm mesh size installed by a student from the University of Stellenbosch in conjunction with the Kommetjie community was sampled on six occasions (Fig. 5). An old municipal silt trap is located just upstream of the net (Fig. 6), which was sampled on two days during the net sampling. These devices have a total urban catchment of some 108 ha. Daily accumulation of street litter was estimated along 740 m of roads in two sub-areas, which were mostly residential with a few ‘spaza’ shops. Sampling occurred on two occasions for a total of 18 days.

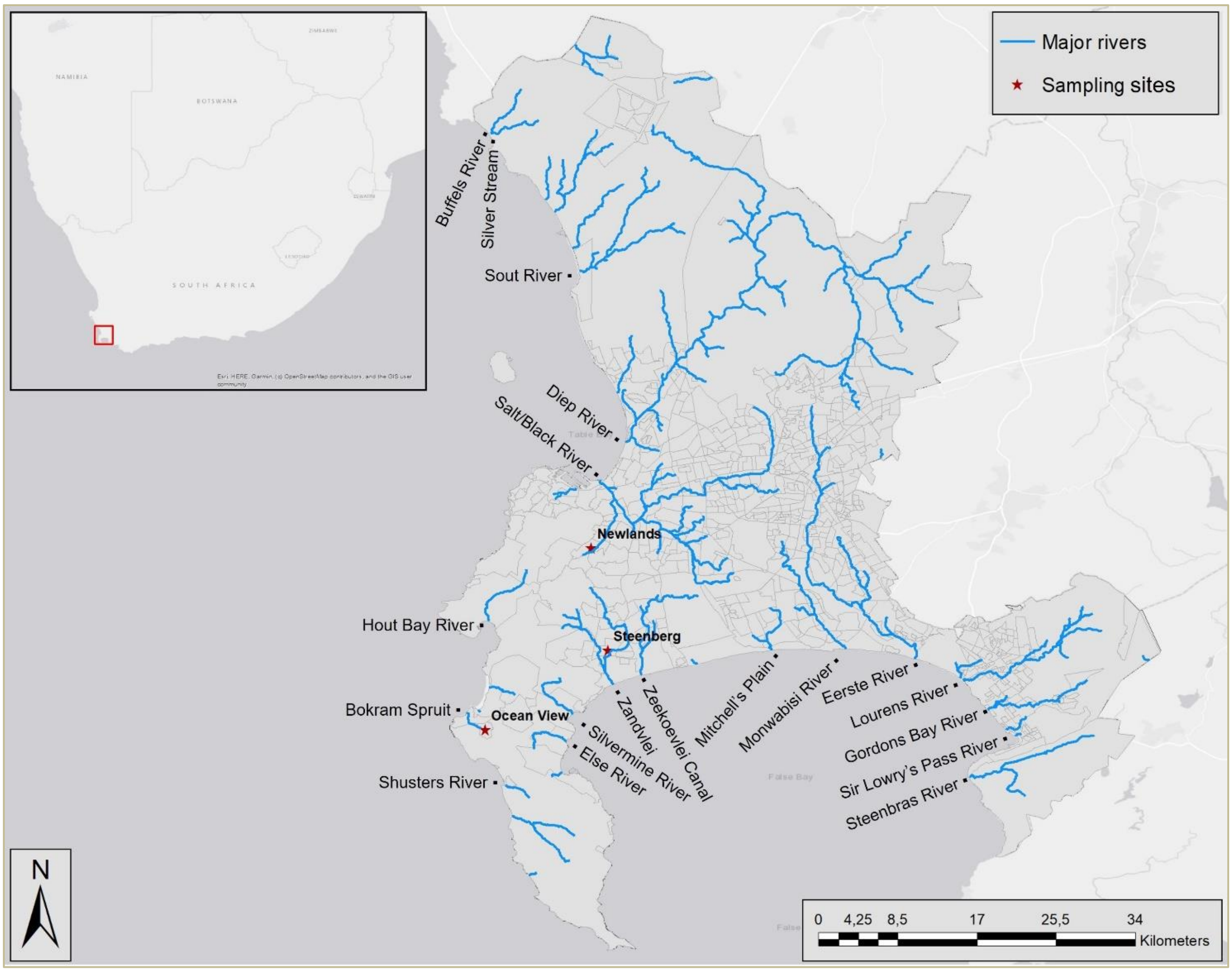

Figure 1. Map of the study area showing the three sampling locations in Cape Town. Major rivers and associated tributary locations.

Figure 2. A litterboom installed by an NGO on the Liesbeek River, Cape Town as part of a Dutch-South African research collaboration.

Figure 3. A series of five nets with increasingly finer mesh installed by Marina Da Gama residents on the canal leading into Zandvlei, Cape Town, lower down the same river in Figure 4.

Figure 4. An inclined grid screen installed by the City of Cape Town municipality on a canalised section of river leading into Zandvlei, Cape Town (top). If serviced regularly, this system works fairly well under low to moderate flow conditions, but rapidly becomes blocked during high flow conditions, requiring an overflow basin with bollards to trap larger debris items.

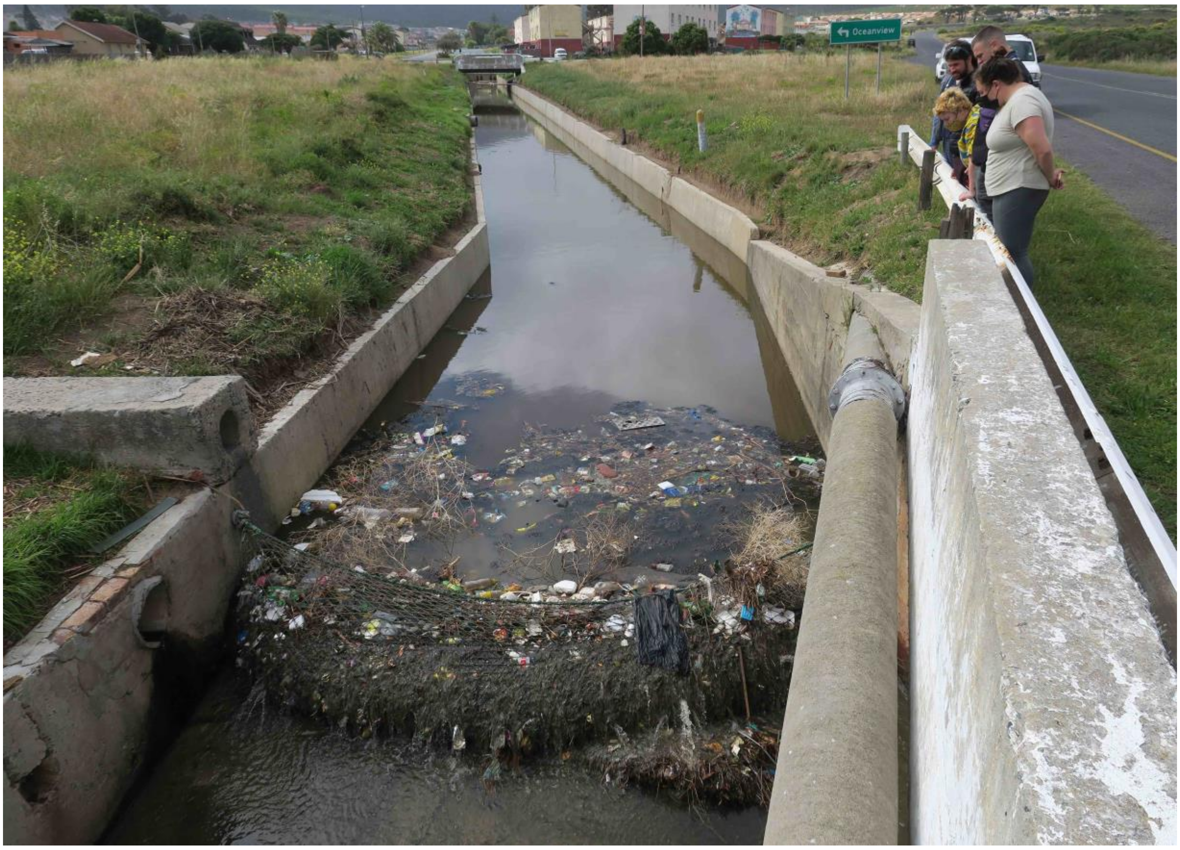

Figure 5. A net installed in Ocean View, Cape Town by a student from the University of Stellenbosch as part of a research project in collaboration with the Kommetjie community. The net is 150 m downstream from a passive municipal litter trap in Figure 6.

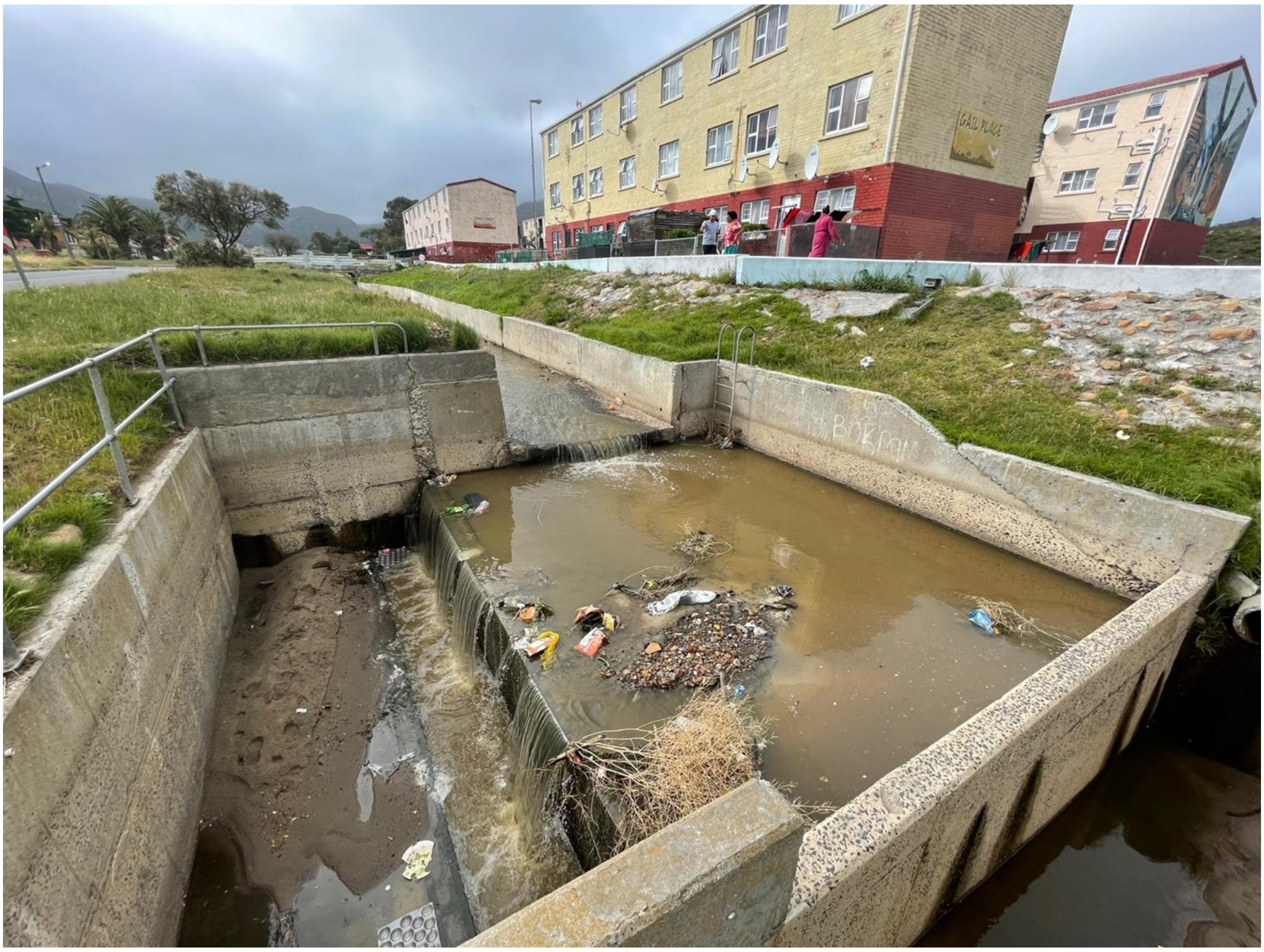

Figure 6. Municipal silt trap in Ocean View, Cape Town installed in the 1990s that is not serviced regularly and largely non-functional (shown here blocked with sediment, vegetation, and other debris). The trap is 150 m upstream of the net shown in Fig. 5.

At most sites, limited rainfall resulted in litter loads only being sampled for one day following a rainfall event. However, three consecutive days of sampling following more substantial rain events were conducted once at Marina Da Gama and once at Ocean View on separate occasions. When sampling the devices, all anthropogenic litter items >1 cm were carefully removed to prevent any other retained items from being lost from the device (i.e. being pushed under, over or through the device). Retained organic waste was removed during the cleaning and appropriately discarded on site (only anthropogenic litter items were stored for later processing). Litter samples were dried at 40˚C in an oven overnight, grouped into four size classes: <5 cm, 5-10 cm, 10-20 cm, >20 cm and individually weighed. Items were weighed to nearest 0.1 g (for items <120 g) or 1 g (<2 kg) using top pan balances; heavier items (>2 kg) were weighed using a 20 kg spring balance to the nearest 0.1 kg. All litter items were identified as far as possible and categorized according to material type (plastic, glass, metal, wood, rubber, etc.) and function (packaging, other disposable items, multiple-use 'user' items, etc.). Plastic items were further classified according to their function and type: single-use packaging (e.g. food wrap, drink bottles and lids, polystyrene packing chips and take-away clam shells, carrier bags, etc.), disposable items (e.g. earbud sticks, cigarette lighters, straws, etc.), user items (e.g. flip flops, toys, stationary etc.), miscellaneous hard pieces/fragments and hygiene/medical-related products (condoms, sanitary pads, wet wipes etc.). Brands and production/best before dates also were recorded, but are not reported here.

2.2.2 Matching street litter

Daily accumulation surveys of street litter were conducted in the same catchments where we sampled the river interception devices as detailed above. This allowed more consistent estimates of litter inputs, given the challenges of estimating litter flux in rivers, and also allowed comparison with the river litter to better understand differential transport of litter material types from land into water courses. Stretches of roadside verge were entirely cleared of all litter items >1 cm the day prior to each survey to ensure the subsequent collections only sampled newly arrived litter (following Ryan et al., 2020). After the initial pre-clean, daily surveys were repeated for 5-10 days. All newly-arrived litter items were collected and processed following the same method described above for litter collected from river interception devices.

2.2.3 Measure of trap efficacy

The efficacy of selected devices was estimated in two ways: i) by inferring retention rates from a comparison of litter above and below different types of litter traps; and ii) by directly measuring retention rates using marked litter items. In the first approach, all debris in the device was removed and the catch system thoroughly cleaned. The initial idea was to install a fine-mesh net immediately downstream from the screening system to measure the retention rates of different types of litter (in terms of size and buoyancy). However, after a trial installation in Marina Da Gama, and several attempts to install a curtain net on the Liesbeek litter booms, it became evident that any fine-mesh netting across a waterway during moderate-high flow conditions was likely to break, and this trial was discontinued. However, the paired trap design at Marina Da Gama (litter boom above 5 nets) and Ocean View (sediment trap above net) allowed a minimum estimate of trap efficiency for the upper trap in each case.

Trap retention also was tested by releasing marked litter items of known size and buoyancy above interception devices, and the retention rates recorded from the litter recovered. The deployment of the marked blocks mirrors previous studies on the dispersal and stranding rate of plastics entering the sea from rivers (Maclean et al., 2021; Ryan & Perold, 2021). In this study, smaller blocks were included. Two sizes of blocks (12 × 8 cm and 6 x 4 cm) of three types were labelled with unique identifying codes. The three types of blocks were expanded polystyrene (EPS) 3 cm thick (average ± SD density of 0.016 ± 0.001 $g{\cdot}cm^{-3}$), pine wood blocks 1.2 cm thick (0.40 ± 0.05 $g{\cdot}cm^{-3}$) and high-density polyethylene (HPDE) blocks 0.3 cm thick (0.96 ± 0.01 $g{\cdot}cm^{-3}$).

2.3 GIS model

Using the data generated from the inventory and field sampling, a GIS model was built to estimate litter loads across the Cape Town metro area and identify key sites for additional installations of interception devices. This model was based on data from existing screening devices and variables such as catchment land-use, population density, waste servicing and rainfall to predict where installations would be most effective.

Using ArcHydro (Environmental Systems Research Institute, 2022) and the 30-m STRM DEM (Shuttle Radar Topography Mission Digital Elevation Model) (Farr & Kobrick, 2000), fine-scale catchments and river networks were delineated. The Cape Town metro region covers approximately 36 catchments and 229 sub-catchments, with the major river networks running through 198 of these sub-catchments into the ocean. The remaining 31 sub-catchments are coastal areas whose drainage lines do not appear in the hydrologic flow model, typically resulting in storm drains leading directly into the sea. These coastal regions were grouped into three broad regions: False Bay, Atlantic Seaboard and West Coast sub-catchments, which drain directly into the ocean via diffuse storm drains and small rivers (Fig. 7).

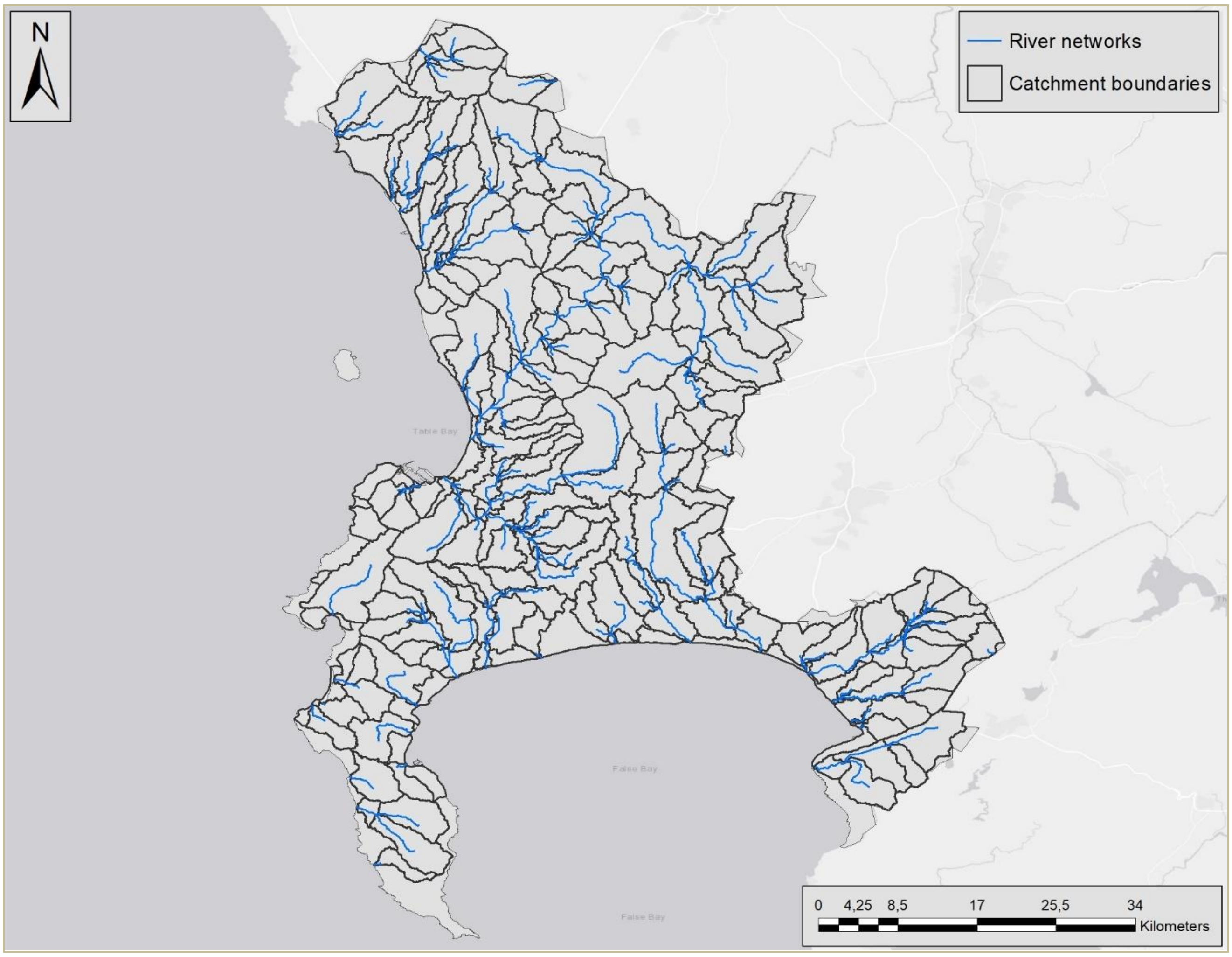

Figure 7. Hydrologic flow model for Cape Town. Black lines represent catchments and sub-catchments, blue lines show central river networks.

The most recently published national census (StatsSA, 2011) provided nine income brackets and the number of people within each bracket for all suburbs in Cape Town. To align with the three-tiered sampling of street litter, socio-economic data were regrouped into three categories; low (< R76 000 per annum); medium (R76 000 – R2 457 000 per annum) and high (> R2 457 000 per year) income categories based on the approach by Maphupha (2018). The number of people in each of the three income categories was used to determine the relative proportion of each income category across all suburbs. Using Newlands, Steenberg and Ocean View as reference points, the relative proportions of each income category were used as reference points to determine a base set of criteria for which to group all suburbs into high, medium, and low-income level. Suburbs of low–income level were mostly clustered on the Cape Flats due to urban sprawl being constrained by the mountains and ocean. Medium–income suburbs occurred predominantly on the outer rim of these low–income areas. High–

income areas were clustered mainly along the coast and mountain margins. Overall, low, medium and high–income areas made up 35, 60 and 5%, respectively, of the total residential area of the Cape Town.

The National Land Cover (NLC) of South Africa was resampled to two land-use classes, residential and industrial areas. The road network for the city was overlaid onto the landcover map to provide the road network for all residential areas. Using suburb borders, the total length of roads in each residential suburb was determined. Residential litter generation rates were applied to each suburb based on their income level. Using road length, the total litter weight produced per residential suburb was estimated from the litter masses from the street litter surveys (Section 3.X). For industrial areas, the mass of all litter items collected from a storm drain net in Paarden Eiland (2.5 ha catchment) were added together and used to calculate a litter generation rate ($g \cdot ha \cdot day^{-1}$) based on data from Weideman et al. (2020). All daily litter generation rates were calculated with upper and lower plausible bounds based on approximate 95% confidence intervals estimated from the observed daily variance in litter accumulation rates at each site. The combined industrial and residential litter weights provided an estimate of the total litter weight ($kg \cdot day^{-1}$) produced per suburb across Cape Town. These litter generation rates were then mapped onto the drainage sub-catchments generated for Cape Town to estimate the total litter weights ($kg \cdot day^{-1}$) for each river and its major tributaries. Locations of all litter interception devices currently installed around the city were plotted onto the major river networks and compared to estimated litter loads.

3. Results

3.1 Inventory of interception devices in South Africa

A total of 189 interception devices were identified in urban centres along the South African coast (Table 1). Most were concentrated in the greater metros of Cape Town and Durban, with a few devices installed in Gqberha and smaller towns. It is important to note that new interventions are constantly being implemented, while others are no longer operational. Doubtless there are many devices, especially those managed by local municipalities, in other urban centres, which were not reported during our survey. Communication and information sharing with local government proved challenging throughout the study, limiting our inventory results. As such, the inventory presented in this report is a minimum list of initiatives currently operating in the country.

Approximately 107 litter screening devices of varying design have been installed by the City of Cape Town municipality, most of which are in canalized waterways. A 2020 report by the Catchment, Stormwater and River Management Branch of the City of Cape Town (unpublished) concluded that many devices were in poor structural and functional condition and need to be replaced. Of those in good condition, infrequent servicing and maintenance often leads to blockages and local flooding. Large volumes of waste are mobilized during rainfall or high flow events, such that even the structurally sound devices are not equipped for the sheer volume of waste carried down the waterway (Fig. 4). Simple floating pipes angled across a waterway, known as litter booms, are among the most common devices used in the country (Fig. 2). A combined 59 litter booms have been installed between two NGOs in Durban and Cape Town on some of the country's worst polluting rivers. Private installations are often linked to research activities and student projects (Fig. 5) and can thus be short-lived and maintained only throughout the duration of a study.

Table 1. Litter intervention devices on urban catchments in coastal urban areas in South Africa

Organisation	Location	Device type	No. of devices	Service frequency	Notes
City of Cape Town	Cape Town metro	grids, grates, fences, traps	107	irregular	
Durban Green Corridors	Durban	litter boom	32	daily	
The Litterboom Project	Durban, Cape Town	litter boom	27	daily	
Pristine Earth Collective	Sea Point	storm drain sock	8	daily	
Nelson Mandela Bay Municipality	Gqeberha (PE)	trap	6	irregular	
Sustainable Seas Trust	Gqeberha (PE)	net	4	weekly	
Kommetjie residents	Ocean View	net	2	irregular	
Shark Spotters	Muizenberg	storm drain sock	1	daily	net stolen after a few weeks
Dyer's Island Conservation Trust	Gansbaai	storm drain sock	1	daily	
Marina Da Gama residents	Marina Da Gama	net	1	after rain	series of 5 nets
Total			189		

Theft and vandalism of devices were reported by most respondents as the primary challenges and threats to operation and sustainability. This was seen first-hand during the study whereby devices were stolen shortly after installation. Most of the captured waste removed from the devices is sent to landfill due to high levels of contamination that prevent recycling. Some of the waste, primarily sought-after polymers such as HDPE and PET bottles, is diverted to recycling initiatives. Maintenance costs for private initiatives are typically in the form of sponsorship and donations to cover the labour costs of servicing the devices. The cost of installation for most devices is generally low, with the few exceptions where drilling or anchor points are needed to secure the device, and materials required (netting, pipes etc.) for the assemblage of the device are either donated or sourced through the fishing industry. Much of costs associated with operating and servicing devices falls to labour costs.

3.2 Litter traps: amounts and composition

A total of 35 649 items weighing 131.9 kg were sampled after being intercepted by the various screening devices across the three study sites (Table 2). Plastics were the dominant material type by both number (77%) and mass (69%), followed by wood (18%) and glass (5%) in terms of mass (Table 3). The proportion of plastics in both number and mass was highest in Ocean View (91% by number, 73% by mass), followed by Marina Da Gama (82% by number, 67% by mass) and Liesbeek (59% by number, 68% by mass). Wooden objects by mass were higher in Ocean View (13%) and Marina Da Gama (25%) compared to Liesbeek (9%), where glass (9% by mass) and metal (8% by mass) were more prominent (Table 3).

Table 2. The total number and mass (kg) of intercepted items from devices in the three study areas in terms of income levels. The number of sampling events (n) and type of devices surveyed are also shown.

	Number of items			Mass of items (kg)		
	Lower	Middle	Upper	Lower	Middle	Upper
Device type	net; trap	boom; net	2 booms	net; trap	boom; net	2 booms
Days sampled (n)	6	7	6	6	7	6
Total litter load	6 153	19 038	10 458	28.4	67.0	36.5

Most of the mass of plastics were single-use products (66%), with user items contributing an additional 25% of the mass but only 5% by number (Table 4). Over half of the mass of single-use plastics were categorized as other packaging (53% by mass), despite making up only 8% of single-use items by number (Table 5). The proportion of flexible packaging by mass showed an inverse relationship with income level, decreasing five-fold from Ocean View (54%) to Liesbeek (10%) (Table 5). Foamed plastics (mainly EPS) made up more than half of single-use items by number in both Steenberg (53% by number) and Liesbeek (56%), in contrast to Ocean View (18%). Flexible packaging at this site featured heavily, both numerically (76% by number) and by mass (54% by mass) of single-use products.

At Marina Da Gama, litter loads intercepted peaked the day immediately after a rain event for both the litter boom (552 items, 0.8 kg) and the nets (3 547 items, 8.2 kg); dropping on day two for both devices: litter boom (220 items, 1.0 kg); nets (611 items, 1.0 kg); followed by day three: litter boom

(178 items, 0.3 kg) and nets (201 items, 0.3 kg). In Ocean View, the first two days of the three-day sampling period there was rainfall, resulting in a consistent litter load intercepted by the net: day one (640 items, 4.2 kg); day two (750 items, 3.2 kg) followed by negligible litter intercepted on day three (73 items, 0.9 kg).

Table 3. Proportion by number and mass of different materials captured by litter interception devices in three urban areas in Cape Town. Sample size refers to the total number and mass (kg) of items at each site.

Material	% number				% mass			
	Lower	Middle	Upper	Total	Lower	Middle	Upper	Total
Plastic	91.3	82.3	59.3	77.1	73.3	66.8	67.7	68.5
Butts	2.5	13.5	37.8	18.7	0.1	1.0	2.8	1.3
Card/paper	3.9	1.9	0.7	1.9	4.2	1.2	0.4	1.6
Glass	0.3	0.1	0.1	0.1	1.1	4.1	8.7	4.7
Metal	0.8	5.4	0.9	0.6	1.2	1.8	8.1	3.4
Wood	0.6	1.5	0.9	1.2	12.5	24.6	8.8	17.6
Other	0.6	0.3	0.2	0.3	7.6	0.5	3.5	2.9
Sample size	6 153	19 038	10 458	35 649	28.4	67.0	36.5	131.9

Table 4. Percentage of plastic litter by number and mass in street and riverine litter in each of the three catchments. Plastic litter was subdivided into single-use packaging, disposable items, user items, miscellaneous hard fragments, and hygiene-related products.

	% N				% Mass			
	Lower	Middle	Upper	Total	Lower	Middle	Upper	Total
River/canal								
Plastic	91.3	82.3	59.3	77.1	73.3	66.8	67.7	68.5
Single-use	92.5	91.8	84.3	90.2	73.3	63.4	66.6	65.7
Disposable	3.5	2.9	5.8	3.7	6.7	5.4	7.5	6.1
User	1.6	2.0	2.7	2.1	17.7	29.9	22.5	25.4
Hygiene	1.6	1.3	2.7	1.7	1.4	1.2	1.7	1.8
Miscellaneous	0.8	1.9	4.5	2.2	0.9	1.0	1.6	1.1
Street								
Plastic	51.9	33.5	44.6	48.6	47.1	43.8	48.8	46.9
Single-use	82.7	83.4	70.5	81.9	58.6	70.9	40.0	57.7
Disposable	2.4	7.6	7.3	3.2	2.5	12.0	9.9	4.5
User	5.3	4.1	14.6	5.8	32.6	13.5	45.4	31.9
Hygiene	5.0	3.7	2.6	4.7	3.2	3.0	3.7	3.2
Miscellaneous	4.7	1.2	5.0	4.3	3.2	0.5	0.8	2.6

Table 5. Percentage of single-use plastic by number and mass in street and riverine litter in each of the three catchments. Single-use items were subdivided into flexible packaging (food wrappers, carrier bags, etc.), other packaging (bottles, tubs, lids, etc.) and expanded polystyrene (fast food clam-shells, cups, trays, etc.).

	% N				% Mass			
	Lower	Middle	Upper	Total	Lower	Middle	Upper	Total
River/canal								
Single-use	92.5	91.8	84.3	90.2	73.3	63.4	66.6	65.7
Flexible packaging	75.7	41.0	25.7	44.9	53.6	37.4	10.4	32.9
Other packaging	5.6	5.8	18.2	8.4	39.3	42.7	79.9	52.6
Foamed plastics	18.7	53.1	56.1	46.7	7.1	19.9	9.7	14.5
Street								
Single-use	82.7	83.4	70.5	81.9	58.6	70.9	40.0	57.7
Flexible packaging	87.6	87.5	78.6	87.1	50.2	59.6	40.5	49.8
Other packaging	9.4	6.8	13.7	9.4	47.8	26.5	57.1	46.5
Foamed plastics	3.0	5.8	7.7	3.1	2.0	13.9	2.4	3.8

3.3 Street litter: composition and flux

Overall, 25 420 items (mean across all sites = 66.1 ± 69.3 items·100 m^{-1}·day^{-1}) weighing 69.7 kg (175.4 ± 194.4 g·100 m^{-1}·day^{-1}) were collected during the study. Litter densities were highest in Ocean View (147.7 items·100 m^{-1}·day^{-1}, 396.6 g·100 m^{-1}·day^{-1}), followed by Steenberg (42.8 items·100 m^{-1}·day^{-1}, 95.5 g·100 m^{-1}·day^{-1}) and Newlands (6.4 items·100 m^{-1}·day^{-1}, 27.8 g·100 m^{-1}·day^{-1}) (Table 6).

Plastics were the most common material type both numerically (49% of all litter) and by mass (47% of litter), followed by card/paper (16%) and glass (14%) in terms of mass (Table 7). Although cigarette butts made a large contribution in terms of numbers (28%), they accounted for only 3% of the total mass of street litter. The proportion of plastics by both number and mass was highest in Ocean View (52% by number, 47% by mass), with similar proportions found in Steenberg (34% by number, 44% by mass) and Newlands (45% by number, 49% by mass). Single-use plastics were the leading contributor to the plastic waste stream across all locations by both number (82% of all plastic items) and mass (58% of all plastic items) (Table 5). However, user-items comprised almost half of the mass of all plastics in Newlands (45% by mass) and contributed a similar proportion in Ocean View (33% by mass) compared to Steenberg (14% by mass).

Flexible packaging dominated single-use plastics by number (87%) and made up half of the total mass (50% by mass) across the three sites (Table 5). Only 3% of single-use plastics in street litter were foamed plastics by number, despite being the leading contributor in rivers numerically (47% by number). Foamed plastics in street litter were on average twice as heavy (2.01 g) as those intercepted by devices (0.89 g). There was a decrease in the relative mass proportions of flexible packaging at both Steenberg (60% by mass in street; 37% by mass in river) and Liesbeek (40% in street; 10% in river), in contrast to Ocean View (50% in street; 54% in river).

Table 6. The total number and mass of street litter items in the three study areas, as well as the mean ± standard deviation of the number ($n \cdot 100\ m^{-1} \cdot day^{-1}$) and mass ($g \cdot 100\ m^{-1} \cdot day^{-1}$) of items littered daily. The number of days (n) and distance (m) each site was surveyed are also shown.

	Number of items			Mass of items (g)		
	Lower	Middle	Upper	Lower	Middle	Upper
Days sampled (n)	(18)	(15)	(31)	(18)	(15)	(31)
Distance (m)	740	600	960	740	600	960
Total	19 670	3 850	1 900	52 827.7	8 597.9	8 262.5
Mean ± SD	147.7 ± 41.4	42.8 ± 15.9	6.4 ± 2.5	396.6 ± 164.0	95.5 ± 47.6	27.8 ± 0.7

Table 7. Proportion by number and mass of different materials comprising street litter in three areas in Cape Town. Sample size refers to the total number and mass (kg) of items collected at each site.

	% N				% Mass			
	Lower	Middle	Upper	Total	Lower	Middle	Upper	Total
Plastic	51.9	33.5	44.6	48.6	47.1	43.8	48.8	46.9
Butts	27.0	39.3	12.7	27.8	2.6	4.6	0.8	2.6
Card/paper	14.3	15.8	25.5	15.4	14.2	25.5	19.6	16.3
Glass	0.7	0.5	5.1	1.0	13.8	9.9	15.4	13.5
Metal	2.8	5.5	8.3	3.6	3.6	12.2	9.8	5.4
Wood	2.4	4.4	1.6	2.6	14.7	0.7	0.8	11.5
Other	1.0	0.9	2.2	1.0	3.8	3.3	3.3	3.7
Sample size	19 670	3 850	1 900	25 420	52.9	8.6	8.3	69.7

3.4 Litter trap efficiency

Litter booms generally retained smaller items than nets (Fig. 8). However, over the five rain events when they were sampled in tandem, the nets at Marina Da Gama intercepted three times more litter (25.7 kg) than the litter boom (8.5 kg) located upstream of the nets, indicating the low efficiency of booms for retaining a high proportion of litter loads. The litter boom intercepted a larger proportion of buoyant items by number (68% by number) compared to the nets (53% by number; Table 8). Just under half of all items intercepted by the litter boom were <5 cm in length (49% size class 1), the same proportion captured by the last net with the finest mesh (net 5; 49% size class 1). The net immediately downstream of the boom intercepted the highest proportion of items in the larger size classes (28% size class 3; 12% size class 4), followed by net 2 (22% size class 3; 9% size class 4). The proportion of items intercepted in size class 1 generally increased as the net mesh size decreased moving downstream (Fig. 9).

Table 8. Proportions of buoyant and non-buoyant items intercepted in the litter boom and nets at Marina Da Gama. Sample size refers to the total number and mass (kg) of items collected.

	% number		% mass	
	boom	net	boom	net
Buoyant	68.2	53.1	41.3	36.8
Non-buoyant	31.8	46.9	58.7	63.2
Sample size	2 616	10 293	8.5	25.7

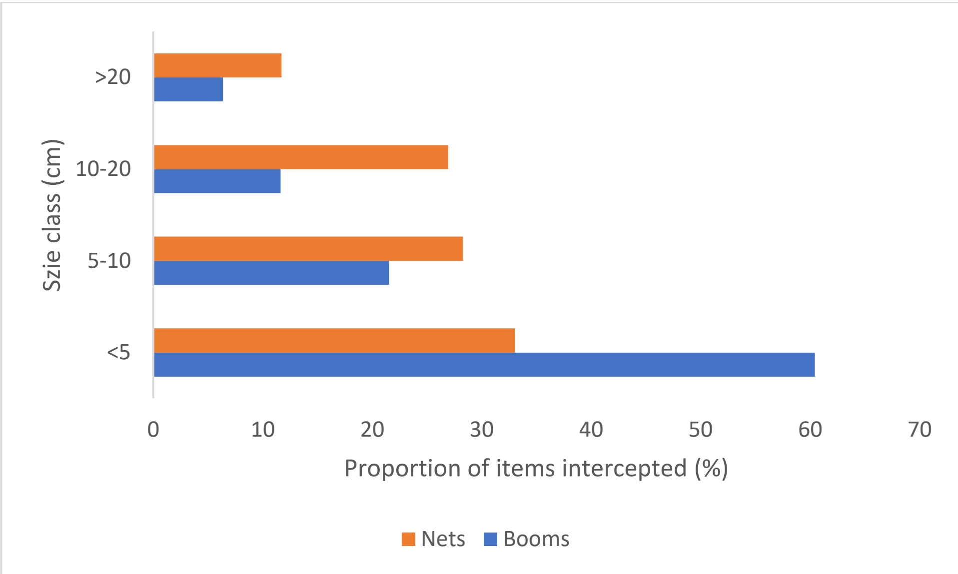

Figure 8. Proportions of items in each of the four size classes (cm) intercepted by litter booms and nets across all sites.

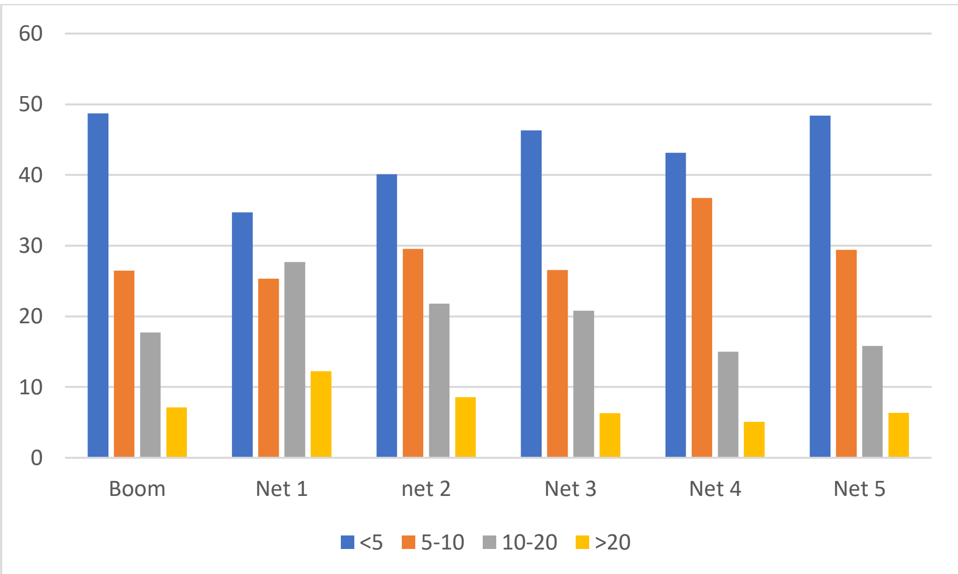

Figure 9. Proportions of items in each of the four size classes (cm) intercepted by the litter boom and series of nets at Marina Da Gama.

3.5 Modelling litter flux

Based on the plausible street litter estimates (Table 9), the spatial model estimated that Cape Town generates an average of 26.0 (15.3–36.6) tonnes·day^{-1} of litter (Figure 10). Residential areas account for 91% of the generated litter, with industrial areas making up the remaining 9%. Plastics comprise 45% or 11.9 (5.90–17.9) tonnes·day^{-1} of the waste stream by mass, with paper, glass and wooden materials contributing 16%, 13% and 11% respectively to the mass. However, this probably underestimates the importance of plastic litter in river systems, which is closer to 70% by mass (Section 3.2.1).

Table 9. Plausible litter generation rates for the three sample locations; high–income area (Newlands), medium–income area (Steenberg) and low–income area (Ocean View).

Income level	Litter generation rate (g·100 m road^{-1}·day^{-1})	Plastic litter generation rate (g·100 m road^{-1}·day^{-1})
High	66.8 (58.8–74.8)	35.3 (20.7–50.0)
Medium	204.7 (132.6–276.9)	89.7 (51.9–127.6)
Low	861.7 (575.7–1147.7)	425.6 (222.9 – 628.3)

Approximately 90% of all litter drains into eight river networks and the three diffuse coastal regions (Table 10). The three catchments with the highest litter loads; Salt/Black River, Eerste River and Diep River, receive 56% of the total litter input, resulting in an average of 14.5 (8.1–20.8) tonnes·day^{-1} total litter and 6.5 (3.1–9.9) tonnes·day^{-1} of plastic litter (Figure 10; Table 11). Overall, the 31 diffuse coastal sub-catchments generate 1.8 (1.0–2.5) tonnes of litter·day^{-1} (7% of the total), with most entering False Bay, followed by the Atlantic Seaboard and West Coast. For the Salt/Black River, six sub-catchments contribute the bulk of the projected litter load (Fig. 10), but these contain relatively few municipal interception devices (Fig. 11). Overall, the spatial distribution of litter traps in the city is poorly correlated (R^2 = 0.28) with the catchments receiving the highest plastic input daily (Figure 12).

Table 10. The projected litter inputs into river catchments in the Cape Town metro area, listed in descending order of total loads.

Rank	River network	Length (km)	Catchment area (ha)	Built up area (ha)	Litter weight (tonnes·day^{-1})	Plastic weight (tonnes·day^{-1})	Percent total litter load (%)	
							Catchment	Cumulative
1	Salt/Black River	97	25964	19311	7.51 (4.21–10.82)	3.37 (1.60–5.15)	28.9	28.9
2	Eerste River	57	18193	11288	4.36 (2.59–6.12)	2.00 (0.99–3.01)	16.8	45.7
3	Diep River	188	63144	9506	2.61 (1.35–3.87)	1.12 (0.51–1.73)	10.1	55.8
4	Manwabisi River *	19	4387	3118	2.57 (1.71–3.43)	1.26 (0.66–1.87)	9.9	65.7
5	Mitchell's Plain **	8	3202	2659	1.91 (1.25–2.57)	0.93 (0.48–1.38)	7.3	73.0
6	False Bay Coast	–	7705	2986	0.97 (0.60–1.34)	0.45 (0.23–0.67)	3,7	76,8
7	Atlantic Seaboard	–	3903	1740	0.46 (0.24–0.69)	0.20 (0.09–0.31)	1,8	78,6
8	West Coast	–	4064	1161	0.32 (0.17–0.47)	0.14 (0.06–0.21)	1,2	79,8
9	Zandvlei	28	8826	4766	1.25 (0.79–1.72)	0.58 (0.30–0.87)	4,8	84,6
10	Zeekoevlei Canal	20	6006	3361	1.09 (0.67–1.51)	0.51 (0.26–0.76)	4,2	88,8
11	Gordons Bay River	15	4133	1107	0.46 (0.28–0.63)	0.22 (0.11–0.32)	1,8	90,6
12	Other rivers	216	77655	9556	2.44 (1.43–3.46)	1.10 (0.55–1.66)	9,4	100

* River ends in a holding pan

** River ends in a wastewater treatment plant

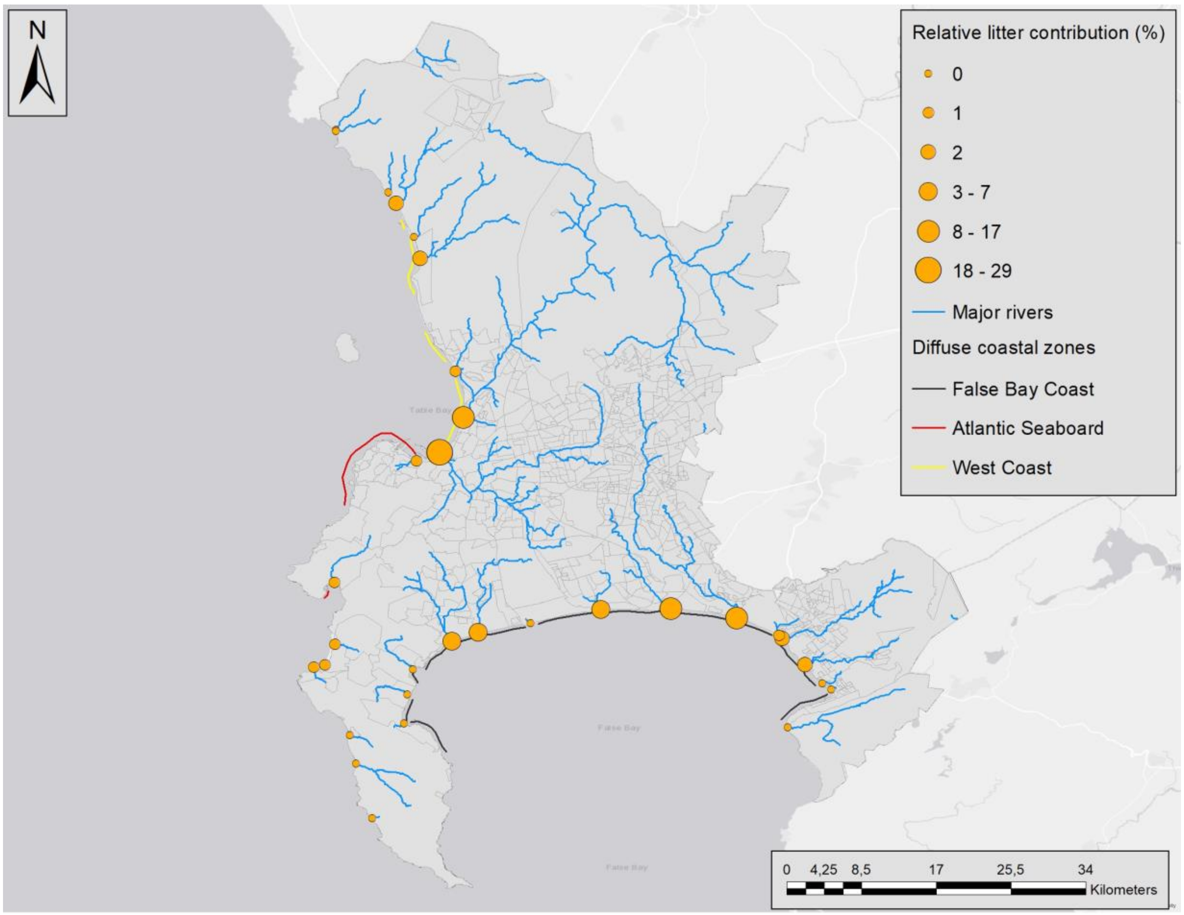

Figure 10. Daily average litter weight (kg·day^{-1}) produced across all residential and industrial areas in Cape Town (A) and the resultant projected inputs into the sea (B)

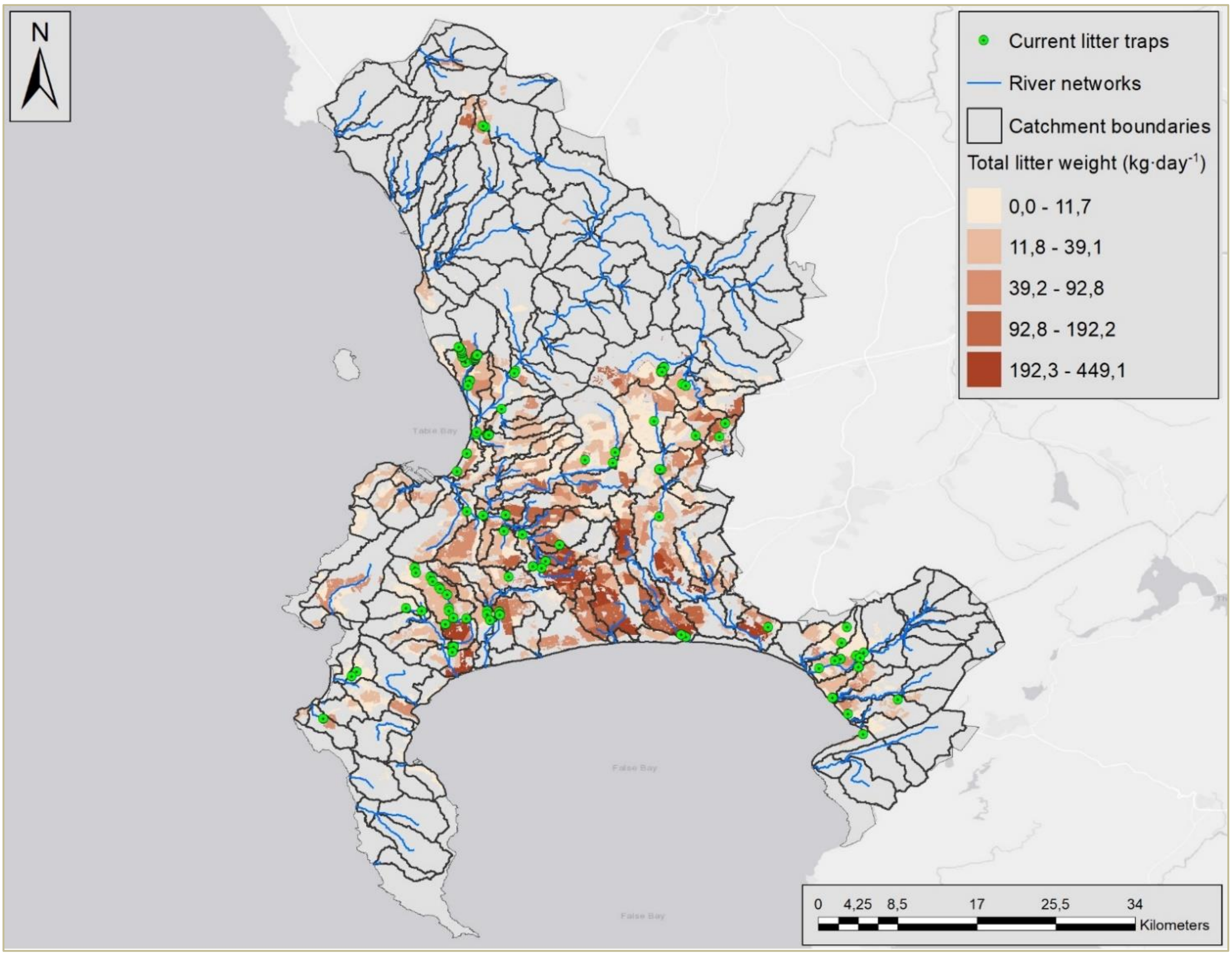

Figure 11. Current litter trap intervention locations (green dots) in relation to the top plastic litter producing catchments (yellow polygons) in Cape Town.

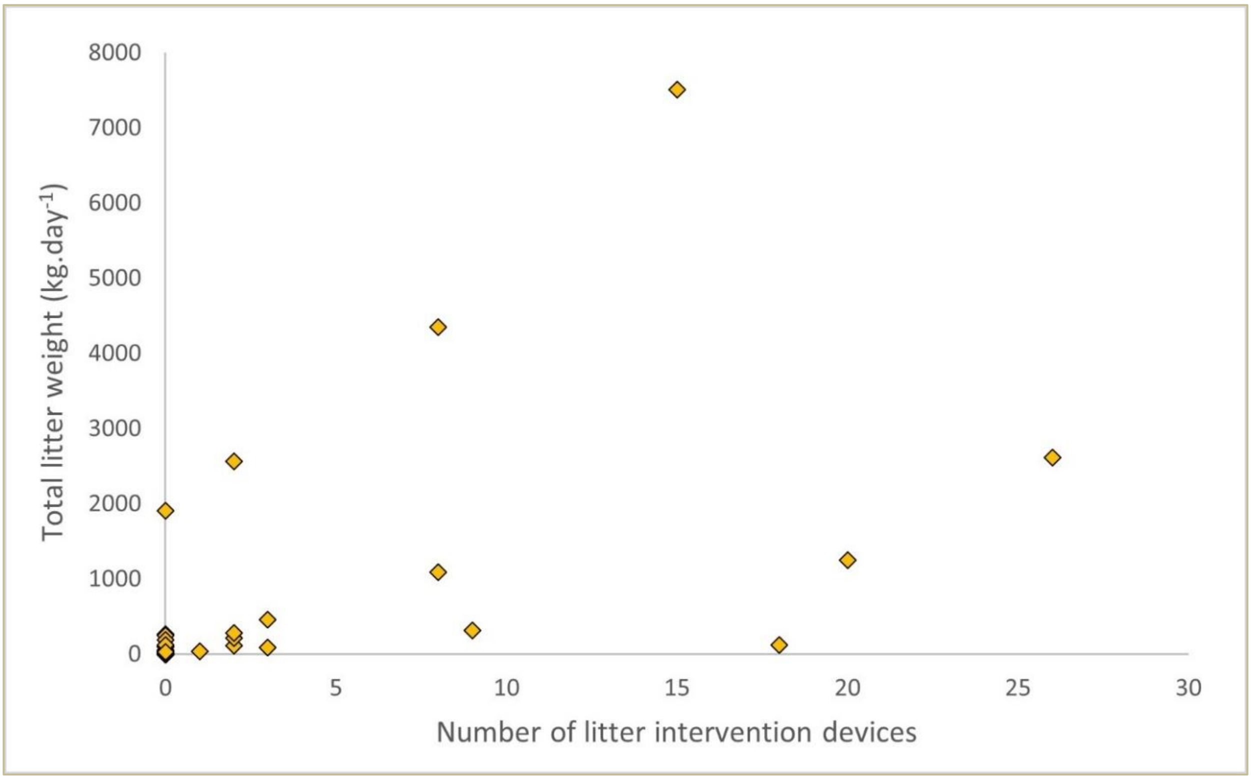

Figure 12. Number of litter intervention devices versus the total litter weight produced in each major catchment (kg·day^{-1}). Each point represents a litter intervention device located across the city.

4. Discussion

Interception devices offer considerable potential to reduce the leakage of plastic and other litter from land-based sources into the sea. However, the simple floating boom design used by most projects are substantially less efficient at capturing litter than nets or other designs that trap litter deeper into the water column. Due to the poor response from most municipalities, our inventory of existing devices in South African rivers and urban waterways was not comprehensive. That said, it is unlikely that many municipalities have initiatives focused mainly on waste removal from rivers (as opposed to broader screening aimed at removing debris and silt from rivers). Passive municipal devices, guided by research on litter trapping methods best suited for South Africa (Armitage & Roseboom, 2000), were explored as early as the 1990s but were largely not adopted, and many of those devices installed have been neglected and no longer function effectively. Devices specifically designed to intercept litter are largely managed by private individuals or groups, though constrained more by the need to reduce the risk of loss through theft or vandalism than functionality. With the generally poor oversight and maintenance of municipal devices by local government, private initiatives are chiefly responsible for any effective and consistent removal of waste intercepted in rivers, notwithstanding the relatively poor trapping efficiency of designs commonly chosen. The City of Cape Town has however shown increased support for such initiatives, recently signing a memorandum of agreement with a local NGO (https://www.goodthingsguy.com/environment/the-litterboom-project-gets-official-city-support-in-cape-town) and collaborating on similar projects (https://www.capetown.gov.za/Media-andnews/Litter%20nets%20catch%20waste%20from%20stormwater%20system%20along%20Sea%20Point%20coastline).

Three times as much litter was intercepted by the nets immediately below the litter boom at Marina Da Gama, indicating that litter booms trap at most one quarter of the litter load. A large amount of litter transported within freshwater systems sits below the water surface (Morritt et al., 2014; van Emmerik & Schwarz, 2020), such that litter booms and similar devices targeting buoyant items only retain a small proportion of the litter load. Broadly speaking, litter booms are probably the best option for larger, perennial rivers in South Africa where other design types are constrained by the risk of theft or vandalism. Booms are made from cheap, readily available materials and do not require any installation of permanent structures into the waterbed (Nikiema et al., 2022), with operational costs mostly However, in terms of litter trapping efficiency, booms are generally limited to capturing buoyant items only (Bletter et al., 2022). The efficacy tests at Marina Da Gama confirmed this, with a larger proportion of buoyant items by number intercepted by the boom compared to the nets below, but even more importantly, the much greater mass of litter retained in the nets below the boom. Trials using marked items of varying size indicated a lower retention efficiency for small items in both litter booms and nets, although a large number of cigarette butts and items <5 cm in length were retained by the litter boom at Marina Da Gama during low flow conditions. Retention rate however also depended on the amount of other litter already in the device (retention generally better when nets and booms are clogged with litter), where retained debris offered additional trapping effects. Flow rate presumably also influences retention rates, but trials were only conducted at relatively low flow rates.

Plastic items, particularly single-use packaging, are among the most prevalent litter types in urban street litter (Becherucci & Seco Pon, 2014; Ryan et al., 2020; Cowger et al., 2022), and are readily transported by stormwater run-off (Weideman et al., 2020). Compared to other debris types, plastics are persistent and travel well by wind and water (Ryan, 2020), resulting in a general increase in their contribution to the waste stream when moving from land to freshwater environments. The was evident at all sites, where a higher proportion of litter by both number and mass intercepted by the devices were plastic items compared to the urban waste stream in the same catchment areas. Tobacco-related litter also featured heavily, and the dominance of cigarette butts in terms of numbers has also been reported in similar studies (Seco Pon & Becherucci, 2012; Ryan et al., 2020). More than 5 trillion cigarette filters or 'butts' are produced annually, and an unacceptably large proportion are not disposed of adequately (Torkashvand et al., 2020). Butts can persist in the environment for as long as 18 months (Novotny & Zhao, 1999), and most filters are made of cellulose acetate, a synthetic polymer, that remains in the environment long after the butts are no longer visible pollutants. Over 150 toxic compounds including heavy metals, nicotine and polycyclic aromatic hydrocarbons are gradually released from used filters (Araújo & Costa, 2019), posing a serious risk to the environment, particularly aquatic environments and their biota (Slaughter et al., 2011).

Overall, the higher street litter densities in Ocean View were not surprising given the limited waste management infrastructure in disadvantaged communities (Verster & Bouwman, 2020). Previous estimates of litter inputs in Ocean View and other low-income areas in Cape Town were significantly higher than in middle and high-income areas (Marais et al., 2004). Despite the sample area comprising mostly residential housing and a few 'spaza' shops, four times as much litter by mass was generated daily in Ocean View compared to the more frequented and commercial-intensive site in Steenberg. This may partly be attributed to the presence of refuse bins and street sweeping by municipal workers, as was noted during the street litter surveys in Steenberg.

The model predicted that roughly 26 tonnes of urban litter is generated across Cape Town daily, with more than half of this feeding into three main river networks: Salt/Black, Eerste and Diep Rivers. However, modelling the pathways of urban litter into freshwater systems relies on the simple pipeline assumption that most street litter enters drainage lines. Many factors influence the transport of litter items, including their point of entry into the environment and how easily they are transported by wind or water. This is further complicated by the presence of street sweeping and other clean-up initiatives, removing litter items before they can wash into rivers. The retention time of litter in urban waterways is highly variable, where some items may remain in the environment for several decades before being removed from the system or washed out to sea (Tramoy et al., 2020). Such uncertainties mean that we can't easily match litter loads in rivers with daily street litter loads, especially in drainage systems characterised by episodic flow events. Sequential sampling after rain events generally confirmed that there is an initial pulse of litter associated with the initial flush following a dry spell (see also Ryan and Perold, 2021). The apparent mismatch between street litter loads and litter loads intercepted by the river devices reflects differences in catchment areas. Although street litter densities were highest in Ocean View, daily litter loads intercepted were the lowest at this site because of the relatively small catchment of this system (approximately 108 ha). The highest loads were intercepted by the litter boom and nets at Marina Da Gama mainly because of the large catchment size of this site (2338 ha).

Inaccuracies in the grouping of suburbs into high, medium, and low-income level were both a product of the method used to group suburbs and the use of the 2011 census data. Further studies may better group suburbs into income levels by using a weighted average based on the nine income groupings in the census. Lack of a sensitivity analysis around this point is also a key component that must be taken into account. Secondly, extrapolation of four litter generation rates across a diverse socio-ecological landscape meant that a lot of the variation in litter production may not have been accurately accounted for. Finally, model validation proved challenging as no data was collected with regards to the mechanisms that remove or retain litter from the streets and very little data exists on these points in South Africa.

The city of Cape Town employs the use of several intervention devices, however there is a mismatch between the location of interventions and projected litter loads across the urban landscape. This is primarily due to a lack of government capacity, limited information regarding intervention device efficacy (Helinski et al., 2021) and a lack of data around litter loading into urban rivers (Ryan & Perold, 2021). Understanding the magnitude of urban litter loads in key areas will help provide the data needed to underpin more efficient management plans.

5. Conclusions and recommendations

Given the potential of litter interception devices as stop-gap measures to further leakage of land-based plastics and other litter into the sea, urban managers need to be well-informed to maximize the efficiency of existing devices. It appears that device design is constrained more by the need to reduce the risk of loss through theft or vandalism than functionality. Increased public-private partnerships will certainly aid in this regard, removing obstacles often faced by private groups interested in installing a device. All devices struggle to operate effectively in high flow conditions, which means that even if they were installed throughout coastal urban waterways, they would have limited success in reducing spikes in litter reaching coastal waters and polluting urban beaches during very high rainfall events. As such, management should focus primarily on reducing litter loading into urban catchments through improved solid waste management, incentives to recycle and re-design of litter-prone items (especially packaging for convenience foods and drinks, and tobacco-related litter). Moreover, it is vital that we find solutions that target the root cause of littering. The largest source of litter in the environment is due to human behaviour, and there is a clear link between litter generation and human activity (Ryan et al., 2020). There are a range of factors that contribute to littering such as the absence of bins and waste infrastructure, lack of education and awareness, as well as personal traits and values (Niyobuhungiro & Schenck, 2022; Schenck et al., 2022). South Africa faces unique socio-economic and environmental challenges, which means that plastic policies and interventions will need to be tailored to local conditions (Verster & Bouwman, 2020).

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ANNEXURE 1

Questionnaire

1. What type(s) of screening devices are currently being used to intercept litter?
2. How do the screening device(s) work, and to what depth in the water column do they trap litter?
3. What is the smallest item size retained? (based on mesh size or grid spacing)
4. What are the device(s) made of?
5. Who designed the device(s)? (own design, or copied from another other source?)
6. Where are they located?
7. When were they first installed?
8. What factors did you consider when deciding where to install the screening devices?
9. How often is litter collected from the traps?
10. Who is responsible for collecting the litter?
11. How much does litter collection cost and how is this funded?
12. Is there a seasonal difference in litter amounts?
13. If so, are servicing protocols adjusted accordingly? How?
14. What flow/pressure can the devices withstand? Do they have a built in mechanism that stops them being washed down the river when they break?
15. Is a record kept of the quantity of litter collected at each service?
16. What happens to the material following its removal? (fate of captured litter)
17. Is there scope for the use of this material to offset maintenance costs? (sustainability)
18. Have there been any instances of theft and/or vandalism to your devices?
19. What are some of the biggest challenges in maintaining these devices?
20. Are there plans for additional devices to be installed?
21. Do you have a website or information relating to the project?

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