Determining key catchments for litter trap installation in urban rivers using a GIS-based approach

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Master of Science in Conservation Biology

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3 Acknowledgements

I am incredibly grateful to my supervisor Peter Ryan for his invaluable input and his time spent working with me on my thesis. I am very glad you overheard me obsessing over GIS with Emma and pitched this project idea to me. I would also like to say a massive thank you to my co-supervisor Patrick O'Farrell for spending the time helping me to develop my model and for always being in a good mood during our meetings, even when I was completely lost. I am privileged to have worked under you both and the skills I have acquired will serve me well in the near future.

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4 Abstract

Litter generated in urban centres has fast become a major problem across the world and poses risks to economic, human and environmental health. It is estimated that around 2.0 billion tonnes of solid waste are produced per year. Rivers and stormwater drainage systems are the primary mechanism through which urban litter is transported into the ocean. In South Africa, widespread littering coupled with poor waste management in many communities results in large amounts of litter entering river systems. South Africa has an extremely diverse socio-economic landscape that results in many challenges, both socio-economically and environmentally. Strategies around waste management must be well-informed, locally applicable and data driven if they are to make a significant impact on reducing urban litter loads. Currently, there are few data on the input and magnitude of urban litter entering into river systems. Measurements of daily litter accumulation rates along urban streets in low, medium and high-income suburbs in Cape Town were modelled using a GIS approach to estimate the amount of plastic litter produced across the different hydrological catchments. There was an inverse relationship between income level and daily street litter generation rate in residential areas. The low-income site generated an order of magnitude more litter daily than the high–income site, with the mid-income site having an intermediate value. The model predicted that on average 26.0 (15.3–36.6) tonnes·day^{-1} of litter is produced in Cape Town with 56% of this litter being loaded into three major river networks; Salt/Black, Eerste and Diep Rivers. Distribution of current litter traps in the city 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 determine weights of urban litter loads and identify key areas for litter trap interventions.

Key words: GIS, Plastic, Catchment delineation, Street litter, Litter traps

5 Introduction

Litter generated in urban centres has fast become a major problem across the world and poses risks to economic, human and environmental health (Farzadkia et al., 2022; Gholami et al., 2020; Paes et al., 2020). Plastic litter is of particular concern given the increased need to use plastic by humans (Karimi & Faghri, 2021).

The average global waste generation rate is estimated at 0.74 kg per person per day and it is estimated that around 2.0 billion tonnes of solid waste are produced per year, and this is expected to rise to 3.4 billion tonnes by 2050 (Kaza et al., 2018). In 1950, approximately 2 million tonnes of plastic waste was produced globally and since then, there has been an annual increase in production of almost 200 times (Ritchie & Roser, 2018). In 2019, 353 million tonnes of plastic waste were produced with approximately 6.1 million tonnes ending up in the aquatic system (OECD, 2022). Litter often remains in the street for varying periods of time, until it is either picked up and disposed of or transported by wind and water (Armitage & Rooseboom, 2000a; Becherucci & Pon, 2014).

Plastics are both lightweight and durable, which means that waste plastics which are not disposed of adequately are readily transported long distances from their sources and ultimately end up in sinks, such as the ocean (Ryan et al., 2009). The proportion of plastic litter in the waste stream tends to increase as one moves away from the litter source areas (Ryan, 2020a). Much of the plastic entering the ocean from coastal cities is transported by either water or wind (Weideman et al., 2020; Axelsson & van Sebille, 2017). Rivers and stormwater drainage systems are the primary mechanism through which urban litter is transported into the ocean (Weideman et al., 2020). Given that many urban centres lie either on the coast or close to rivers, it is vital that urban waste be managed effectively, to avoid continued leakage into the ocean.

There are several alternative urban stormwater and river management techniques that exist and have been explored, particularly in Australia and South Africa (Chittripolu et al. 2011). A review by Chittripolu et al. (2011) looked at various devices designed to remove urban litter from rivers and stormwater systems. Their study concluded that interventions such as fences, booms, weirs and nets are the most cost effective measures to implement on slow flowing streams. However, despite their cost effectiveness, they require periodic maintenance and cleaning.

Despite the global presence of many techniques and urban litter intervention devices, there are still many uncertainties around the short and long-term effect of such devices (Helinski et al. 2021). Many of these devices are designed for larger, perennial rivers and would be ineffective in the smaller, more seasonal rivers of Cape Town. Furthermore, intervention devices with more than two working parts may be more expensive and require more maintenance (Helinski et al. 2021). Theft/vandalism of intervention devices is an additional challenge that precludes many solutions which may require expensive infrastructure. However, if intervention devices were implemented in a phased implementation program in key areas, it could potentially lead to the removal of 65% of urban litter entering Cape Town river networks (Wise & Armitage, 2004).

South Africa has a dysfunctional waste management system and as such was listed as the 11th largest global contributor of land-based plastic to the marine environment (Jambeck et al., 2015). The estimate provided by Jambeck et al. (2015), although probably overestimated (Verster & Bouwman, 2020; Weideman et al., 2020), highlights that poor waste management results in large amounts of plastic input into aquatic ecosystems (Ryan, 2020a; Verster & Bouwman, 2020). It is important to find ways of reducing the flux of urban litter into freshwater and marine environments.

Several mechanisms exist, across the country, that are designed to intercept and remove litter from river courses and wastewater systems i.e storm drains. Downstream controls include floating booms and nets across river courses (Armitage and Rooseboom, 2000b) while source controls are mainly catch pits or grids at the entrance to storm drains. Despite these controls, there is limited information pertaining to cost and efficacy around different mechanisms (Helinski et al. 2021). Poor maintenance and a lack of cleaning result in interventions becoming blocked by litter during episodic rain events, leading to additional problems such as localised flooding. Many of these devices are used across South Africa, and are often ineffective due to poor municipal management i.e lack of grids and traps being serviced regularly.

Despite the existence of these interventions, it is important to remember that these are merely stop-gap interventions, and a solution is required to better understand and curb the root cause of littering. The behaviour surrounding littering behaviour is poorly understood in most parts of the developing world (Schenck et al., 2022). Urban litter loads often correlate with the level of urbanisation and overall income-level of an area (Kaza et al., 2018) A clear link appears to exist between human activity and litter generation (Ryan et al. 2020b). South Africa has an extremely diverse socio-economic landscape, that results in many challenges, both socio-economically and environmentally. Strategies around waste management must be well-informed, locally applicable and data driven if they are to make a significant impact on reducing urban litter loads.

Currently in South Africa, there are few data on the input and magnitude of urban litter entering into river systems (Ryan, 2020a ; Ryan & Perold, 2021; Verster & Bouwman, 2020). This study combines litter generation data in different urban land uses with a GIS model to predict litter loads across urban catchments. The aim was to develop a practical approach to identify key areas for litter trap interventions, capable of being applied to other cities, and better understand urban litter.

6 Methods

6.1 Study site

Cape Town (33.9˚S; 18.5˚E), located on the south-western tip of Africa, is South Africa's largest coastal city. The population of around 4.9 million is increasing at almost 2% per year, and this growth rate is projected to continue for at least the next few years, placing additional strain on current infrastructure (Githahu, 2022, Rogerson; Macrotrends, n.d.; World Population Review, 2023).

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 (33.9˚S; 18.6˚E), 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. A large proportion of Cape Town's river networks are seasonal and fill up for only a few months per year. The city experiences a Mediterranean climate, receiving majority of its rainfall in the winter months (June–August). Storms are often brief but intense, resulting in large amounts of rain falling in a very short period (Weidmann, 2022). Rainfall patterns are varied across the Cape peninsula due to the varied topography and experiences 300–1200 mm of rain per year.

There are currently ~120 litter intervention devices located throughout the city. Most are inclined grid traps installed by the local municipality. A few floating boom traps or net systems have been installed by NGOs or concerned citizens and these tend to be better maintained. Litter sampling took place at three sites (Figure 1), covering different income level suburbs: Newlands (33.97˚S, 18.47˚E), an upmarket suburb, Steenberg (34.08˚S, 18.46˚E), a medium–income suburb, and Ocean View (34.15˚S, 18.35˚E), a low–income suburb. At all three sites, sampling took place in mostly residential streets, but with some commercial activity.

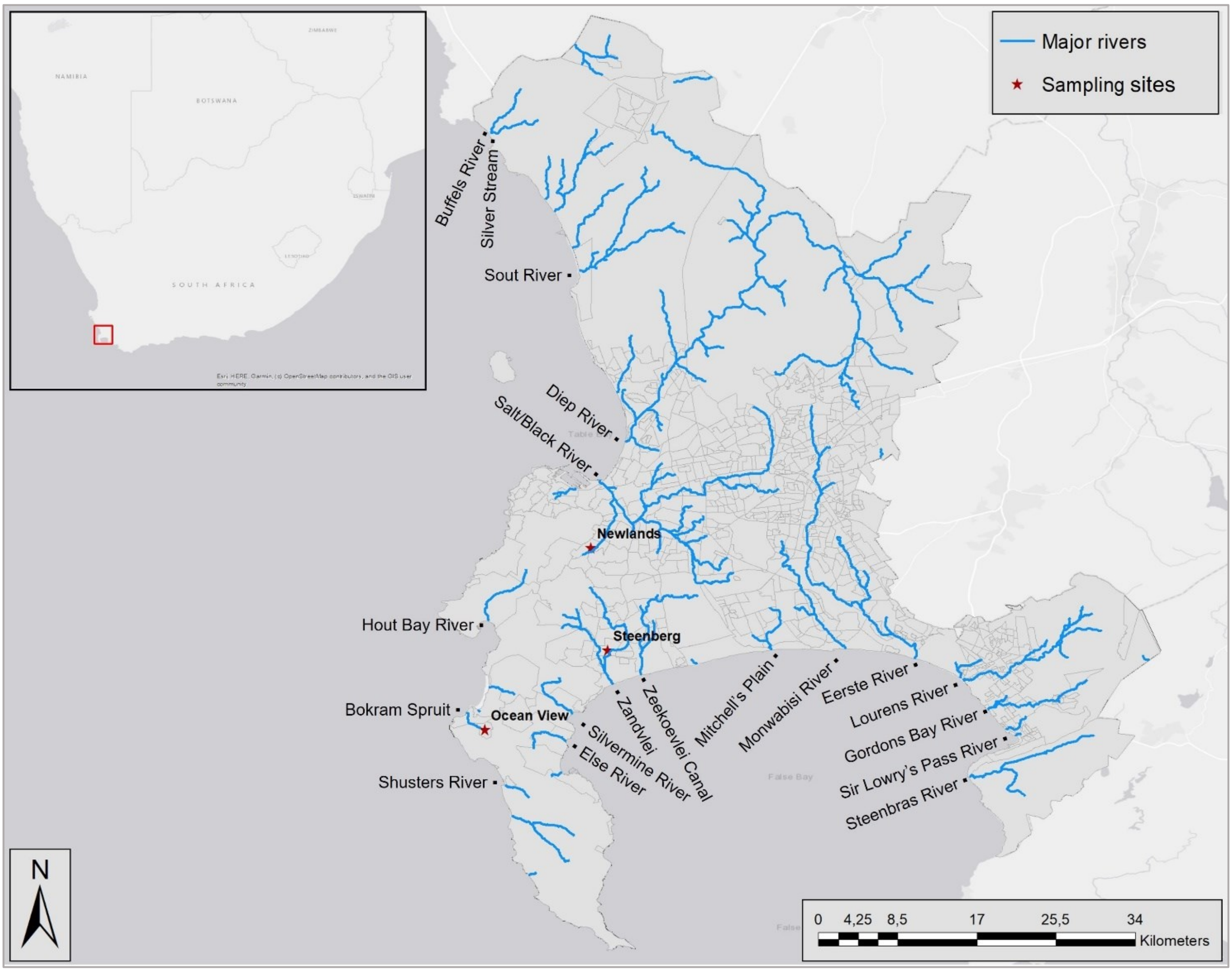

Figure 1. Map of the study area showing the three sampling locations in Cape Town. Major rivers and associated tributary locations.

6.2 *Hydrologic flow model*

Catchment boundaries are often delineated at a national level and as such are not suitable to use for an analysis such as this. Using ArcHydro (Environmental Systems Research Institute, 2022) and the 30-m STRM DEM (Shuttle Radar Topography Mission Digital Elevation Model) (Farr & Kobrick, 2000), finer scale catchments and river networks were delineated for the city. Cape Town is made up of 229 sub-catchments and approximately 36 catchments. These catchment delineations are based off the input parameters mentioned previously and may vary depending on the method used. The major river networks of the city run through 198 of these sub-catchments and into the ocean. The remaining 31 sub-catchments are coastal catchments whose drainage lines do not appear in the hydrologic flow model. These coastal regions are grouped into False Bay, Atlantic Seaboard and West Coast sub-catchments, which drain directly into the ocean via diffuse storm drains and small rivers (Figure 2).

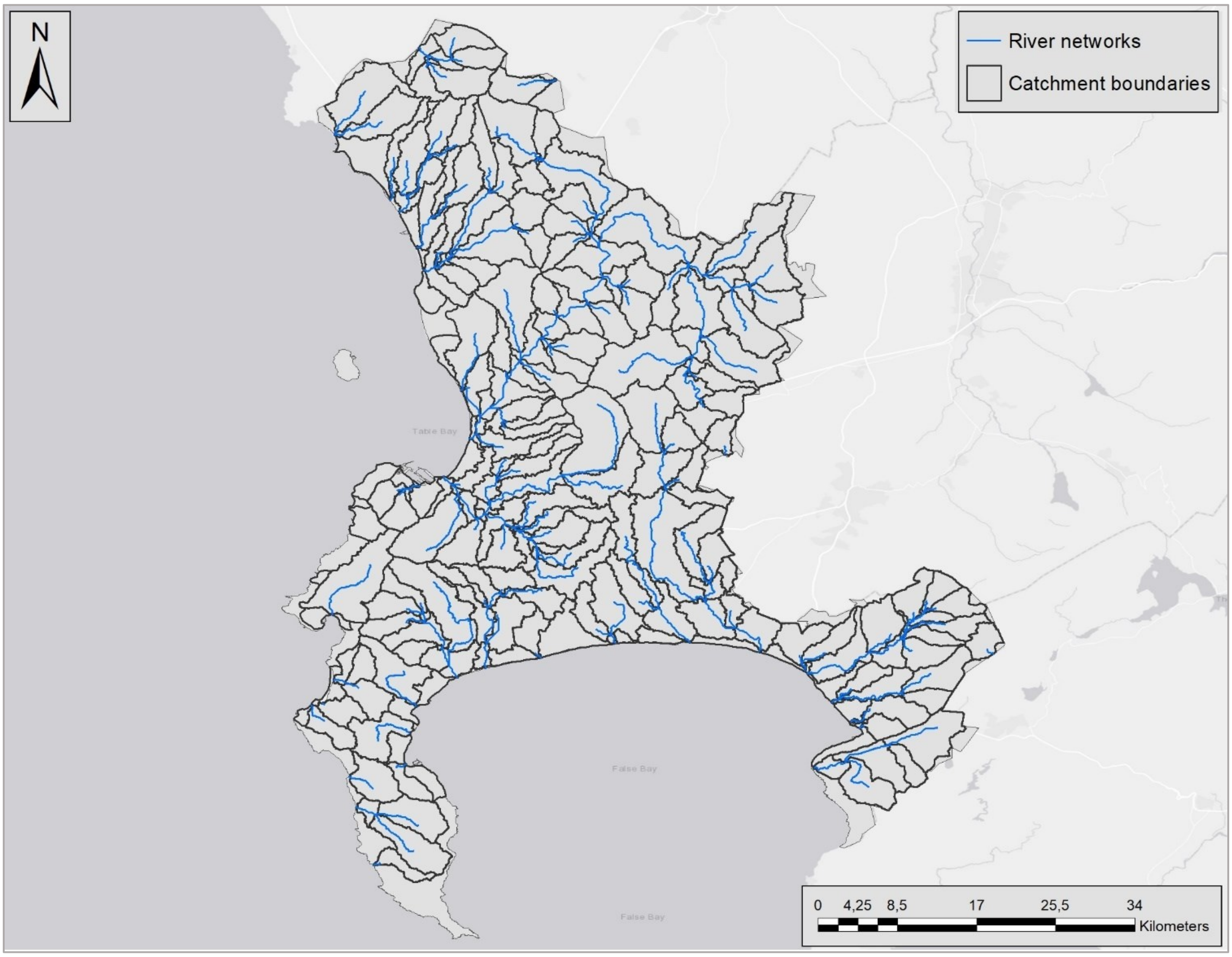

Figure 2. *Hydrologic flow model for the city. Black lines represent catchments and sub-catchments, blue lines show central river networks.*

6.3 Income level

The national 2011 census information (Stats SA, 2011) was used in this study as it was the most recent published census to date in South Africa. The census 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 was regrouped into three categories; low (< R76 000 per annum); medium (R76 000–2.457 million per annum) and high (> R2.457 million per year) income categories.). 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 (Table 1) were used as reference points to determine a base set of criteria for which to group all other suburbs into high, medium and low-income level.

***Table 1**. Relative proportion of each income category; Newlands, Steenberg and Ocean View.*

Suburb	**Income category (%)**		
	High	Medium	Low
Newlands	4	62	34
Steenberg	1	31	68
Ocean View	0	13	87

Based off these proportions, all suburbs with >87% low income category were placed into the low–income level. Suburbs with >4% high–income and <34% low–income category were classified into the high–income level. All remaining suburbs were classified into the medium–income level. This process provided a general high, medium and low–income level to all suburbs across the city, thus allowing the corresponding litter generation rate obtained from the three sampling sites to be applied. Suburbs of low–income level were clustered mostly 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 (Figure 3). Overall, low, medium and high–income areas made up 35, 60 and 5%, respectively, of the total residential area of the Cape Town.

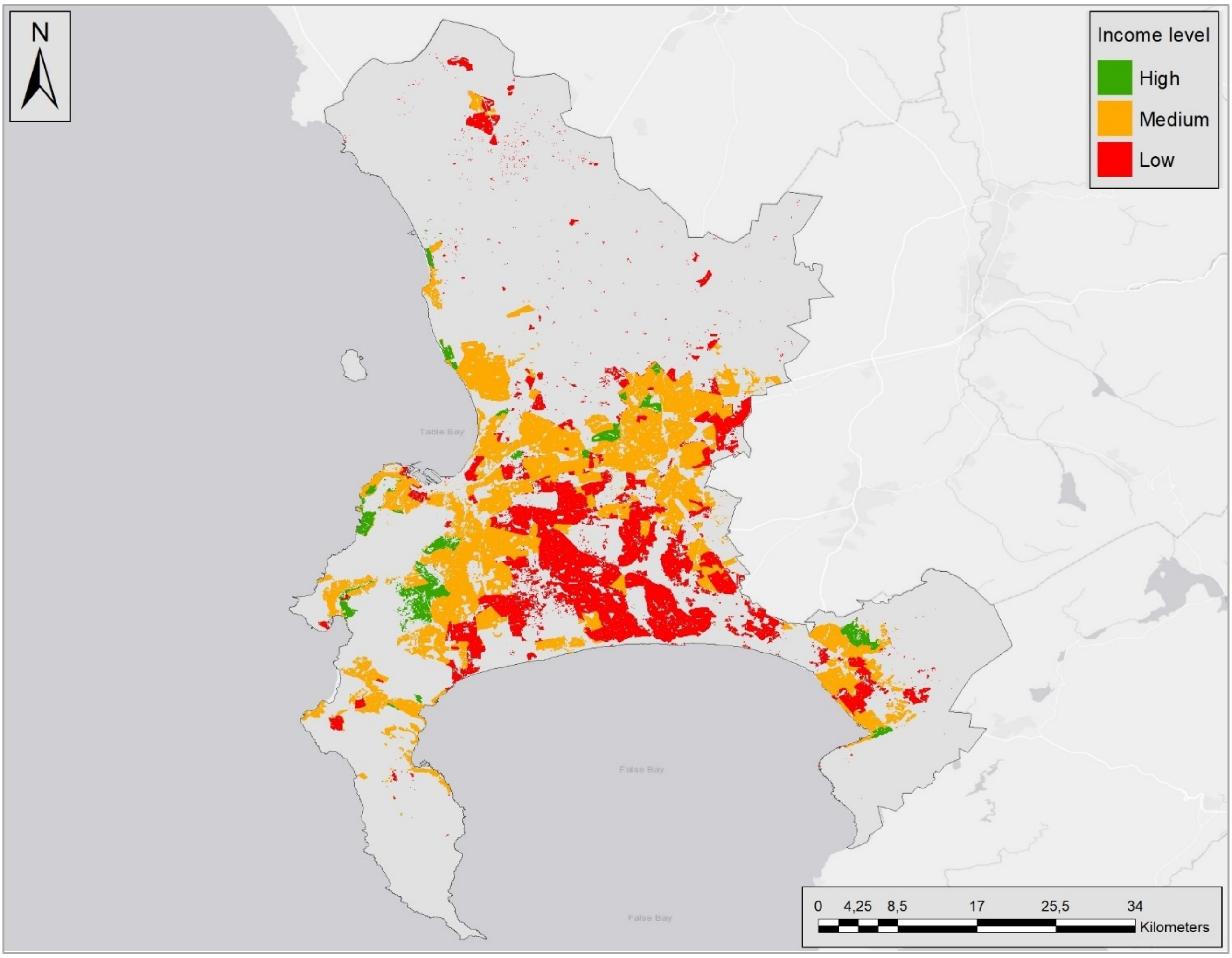

Figure 3. *Mapped income level of all residential areas. Green areas represent high–income areas, orange areas show medium–income and red the low–income areas.*

6.4 Litter generation rate

To estimate the litter loads in each residential suburb, 500–1200 m of streets (including pavements and adjacent verges) were cleaned thoroughly to remove all accumulated litter. The ends of the street and any side streets were cleaned further than where litter collection took place to limit the amount of litter collected that had been externally transported into the study area. Majority of the data was collected by PhD student Kyle Maclean in preparation of his thesis. The length of street cleaned was determined by the amount of litter in the area, in order to ensure an adequate sample of litter during subsequent collections. Thereafter, we returned for 7–10 consecutive days (depending on the site) on two separate occasions to collect all anthropogenic litter items greater than ~ 1 cm. Litter items were collected on half of the road i.e from the centre of the road to the edge of the residential properties Litter items were dried at 40 ˚C overnight, then weighed and categorised based on material type (plastic, glass, paper, wood, metal and other). Items were weighed to nearest 0.1 g (<120 g) or 1 g (<2 kg) using top pan balances; heavier items were weighed using a 20 kg spring balance.

Weights of litter were used to calculate the litter generation rate per residential site ($g \cdot 100$ m road$^{-1} \cdot$day^{-1}).The length of street cleaned at each site was multiplied by the average distance from the centre of the road to the start of the residential property i.e half the road's width. This gave the area corresponding to the length of road where litter was collected. This area was then reconciled to give the litter generation rate per hectare at each site. The litter generation rate was calculated for industrial areas using raw data from Weideman et al. (2020). Weights of all litter items collected from a storm drain on Paarden Eiland (2.5 ha study area) were added together and used to calculate a litter generation rate ($g \cdot ha \cdot$day^{-1}). This was used for all industrial areas across the city. These litter generation rates estimate the rate of litter generated by the built up areas i.e. residential and industrial area in Cape Town. 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.

6.5 Litter loads

6.5.1 Residential and industrial

The National Land Cover (NLC) (South African National Land-Cover (SANLC) 2020 | Department of Environmental Affairs, n.d.) of South Africa was resampled to two land-use classes, residential and industrial areas. The road network for the city was overlayed onto the new landcover map providing the road network for all residential areas. Using suburb borders, the total area of residential and industrial land-use was calculated. Similarly, 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 calculated. For the industrial areas, the industrial litter generation rate was applied to the area of industry in each suburb. Combined industrial and residential litter weights provided an estimate of the total litter weight ($kg \cdot$day^{-1}) produced per suburb across Cape Town.

6.5.2 River networks

Using the sub-catchments generated for Cape Town, total litter weights (kg·day–1) were obtained for each by adding together the weights of all contributing suburbs. Sub-catchment litter weights were further added together, based on common river networks, providing the total weight of litter loaded into each major river network. Locations of all litter interception devices currently installed around the city (K.Maclean, personal communication, September 1, 2022) were plotted onto the major river networks.

7 Results

7.1 Estimated litter loads

There was an inverse relationship between income level and daily street litter generation rate in residential areas. The low-income area (Ocean View) generated an order of magnitude more litter daily than the high–income site (Newlands), with the mid-income site (Steenberg) having an intermediate value (Table 2). Industrial areas had a total litter generation rate of 460 (49–871) g·ha·day^{-1} and a plastic generation rate of 144 (8–281) g·ha·day^{-1}.

Table 2. *Litter generation rates for the three sample locations; high–income area (Newlands), medium–income area (Steenberg) and low–income area (Ocean View).*

Residential income level	Total 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)

The model indicates that Cape Town produces an average of 26.0 (15.3–36.6) tonnes·day^{-1} of litter (Figure 4). Plastic litter makes up approximately 45% or 11.9 (5.90–17.9) tonnes·day^{-1} of this weight, while paper, glass, wood, other and metal made up the remaining 16.3%, 12.9%, 10.6%, 6.3% and 5.3%, respectively. Residential areas contributed approximately 91% of this litter, while industrial areas contributed the remaining 9%.

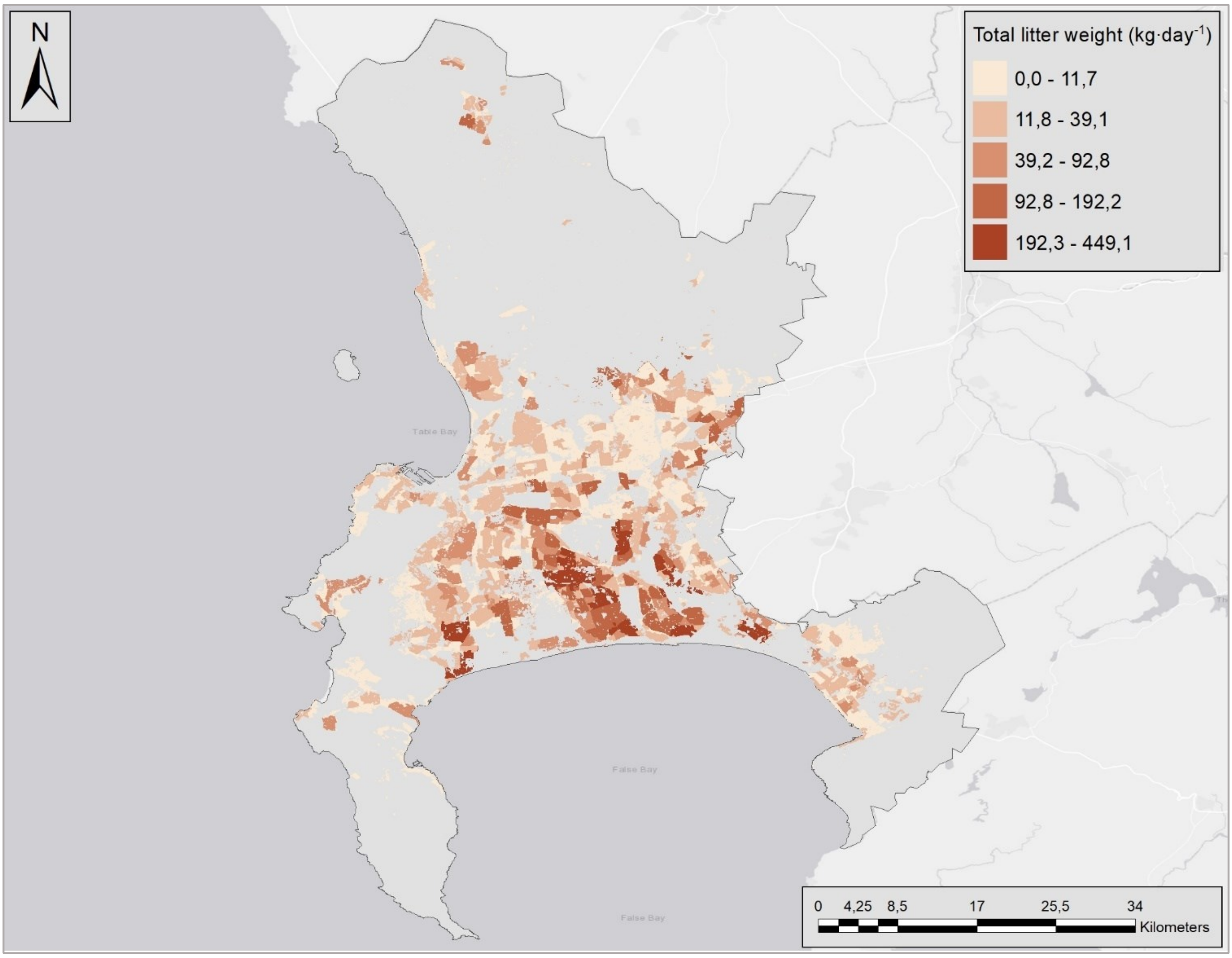

***Figure 4**. Daily average litter weight (kg·day^{-1}) produced across all residential and industrial areas in Cape Town.*

7.2 River network litter weights

Overall, the 31 diffuse coastal sub-catchments generate 1.8 (1.0–2.5) tonnes of litter·day–1 while the other 198 sub-catchments generate 24.2 (14.3–34.1) tonnes·day–1 (Appendix 1). Approximately 90% of this litter all falls within eight river networks and three diffuse coastal regions (False Bay, Atlantic Seaboard and West Coast sub-catchments) (Figure 5; Table 3) Plastic litter accounts for ~10.8 (5.3–16.3) tonnes·day–1 or 46% of the total weight of litter entering these networks.

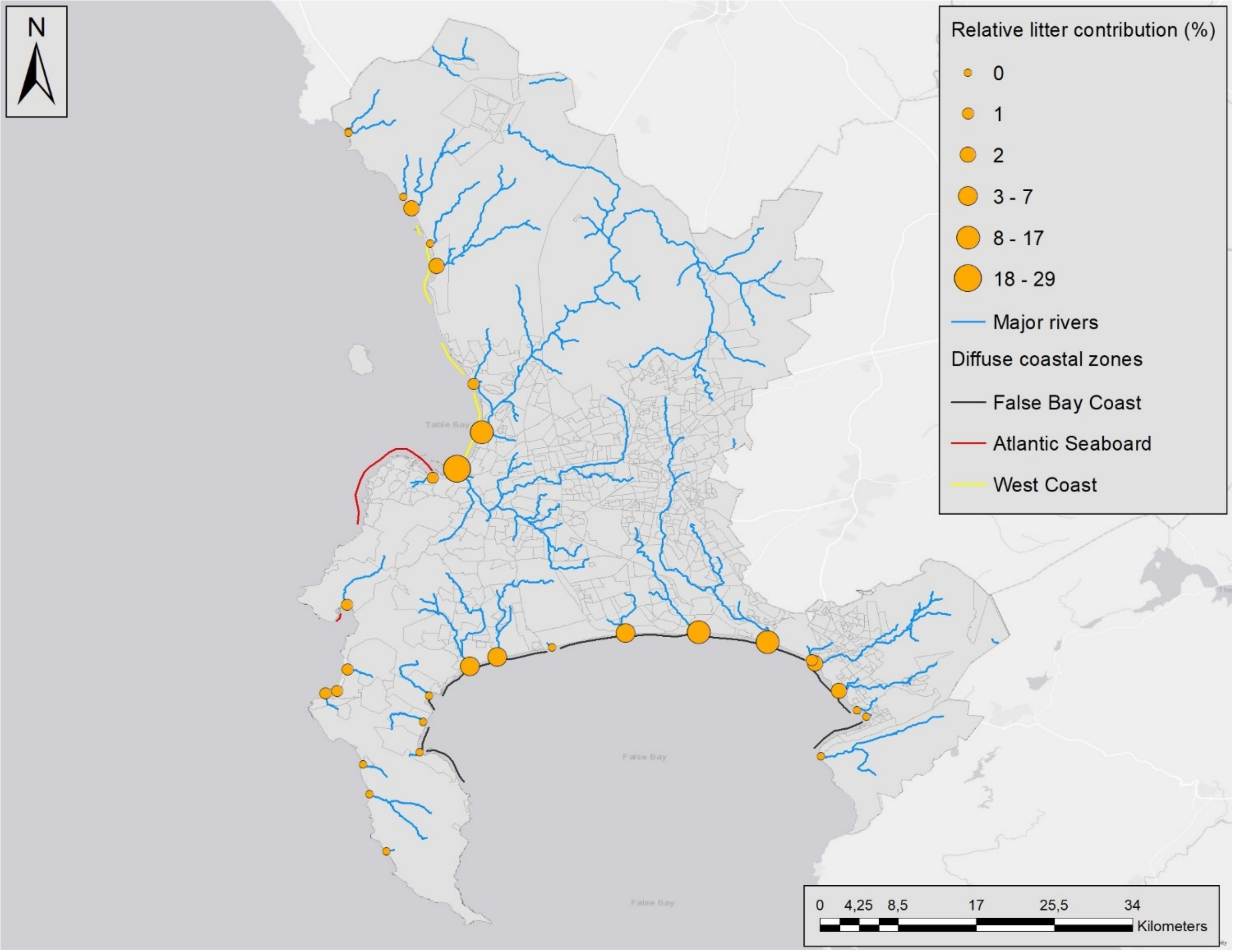

Figure 5. *Scaled river showing the river mouths' that contribute the largest percentage of the total litter weight produced in the city into the ocean. Diffuse coastal sub-catchments are grouped into False Bay coast, Atlantic Seaboard and West Coast.*

Table 3. *Major river networks total litter and plastic litter weight inputs in descending order.*

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

The three catchments with the highest litter loads; Salt/Black River, Eerste River and Diep River, receive 56% of the litter produced every day, 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 6; Table 3). The West Coast and Atlantic Seaboard diffuse coastal sub-subcatchments add 1.2 and 1.8 %, respectively, of the 26.0 (15.3–36.6) tonnes·day^{-1} of litter produced, directly into the ocean. While the False Bay sub-catchments contributed 3.7% of the total amount.

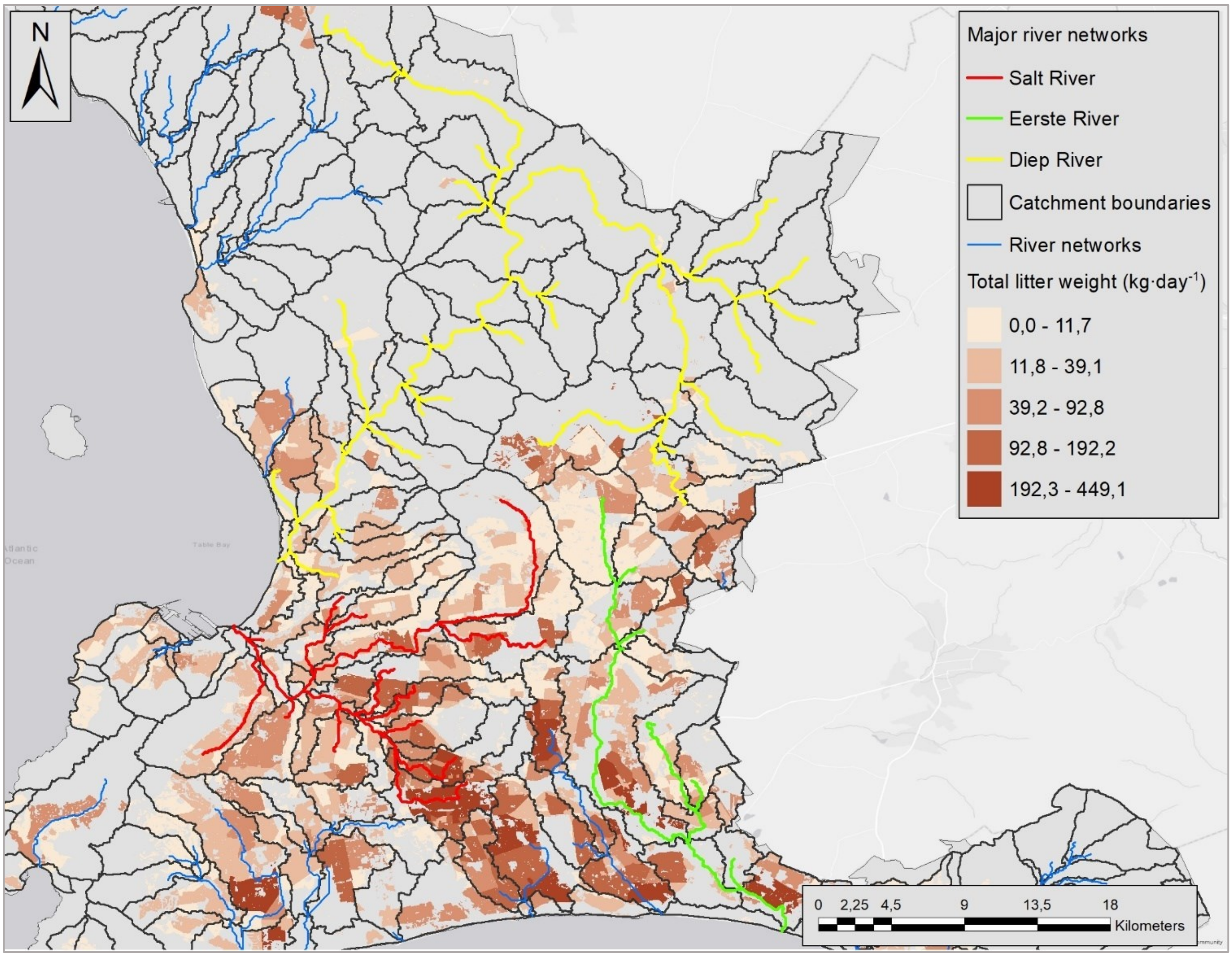

Figure 6. *Main three river networks which receive the greatest plastic litter weights (kg·day^{-1}) from their associated residential and industrial areas.*

The Salt/Black River catchment receives litter from 25 sub-catchments (25964 ha), of which 73% is residential and industrial areas (Figure 7). This catchment receives 29% or 7.51 (4.21–10.82) tonnes·day-1 of urban litter from its associated tributaries. The greatest litter contributing tributary transported 1.04 (0.65–1.43) tonnes of litter per day (Table 4) into the

Salt River and of the total area covered by this sub–catchment, 69% consists of built up area (residential and industrial area).

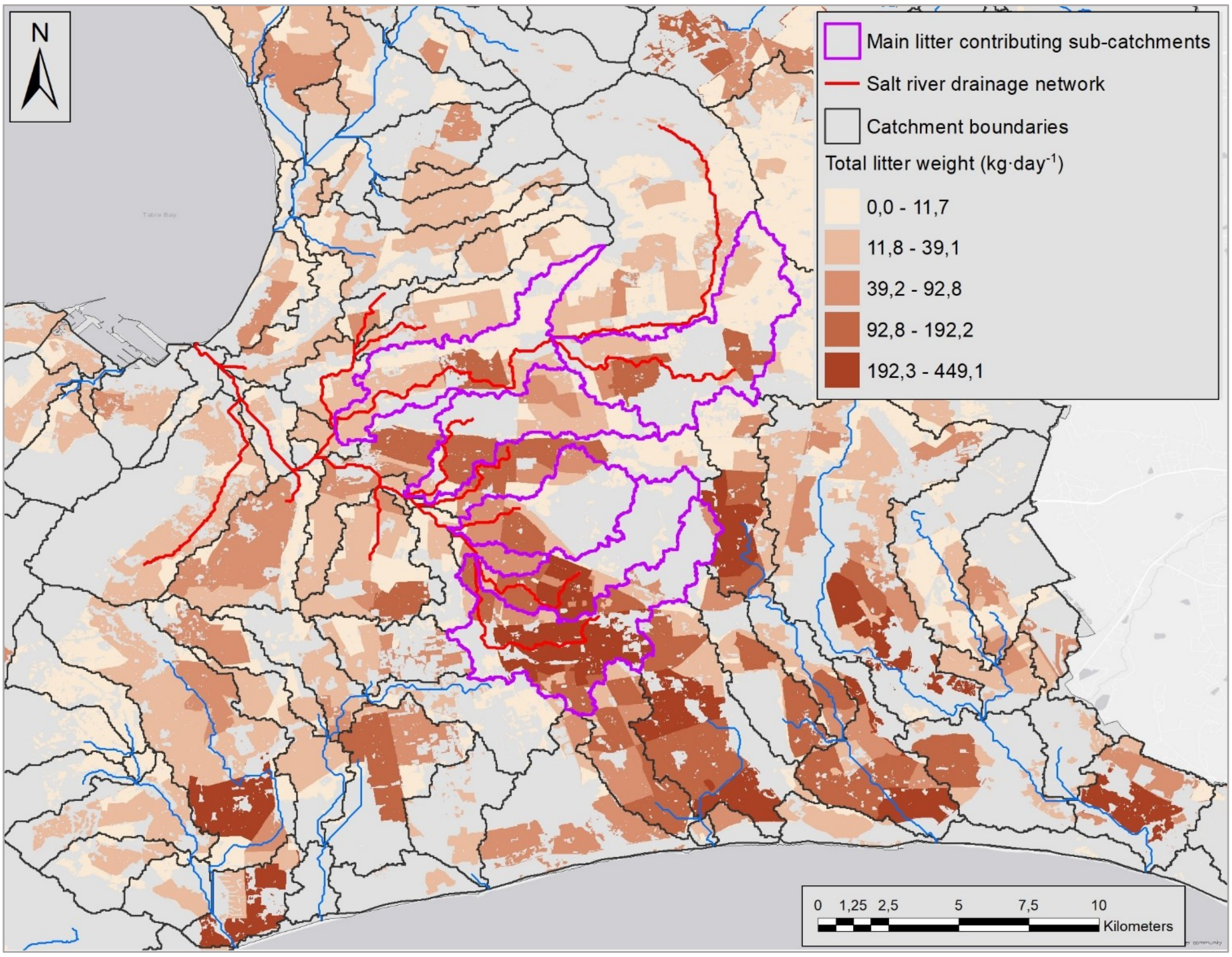

Figure 7. *Salt river catchment area and its contributing sub-catchments. Purple outlines represent the six sub-catchments that produced the greatest litter weights per day.*

***Table 4**. Major contributing sub-catchments total litter and plastic litter weight inputs in descending order of contribution.*

Rank	**Catchment area (ha)**	**Built up area (ha)**	**Litter weight (tonnes·day^{-1})**	**Plastic weight tonnes·day^{-1})**	**Percent total litter load (%)**	
					Catchment	Cumulative
1	2064	1433	1.04 (0.65–1.43)	0.50 (0.25–0.75)	13.8	13.8
2	1317	1228	0.73 (0.40–1.06)	0.33 (0.15–0.51)	9.7	23.5
3	2253	1925	0.72 (0.34–1.10)	0.30 (0.13–0.48)	9.6	33.1
4	1230	954	0.64 (0.34–0.94)	0.29 (0.13–0.45)	8.5	41.6
5	1207	1005	0.56 (0.29–0.84)	0.25 (0.11–0.39)	7.5	49.1
6	1588	1395	0.48 (0.25–0.70)	0.21 (0.10–0.32)	6.3	55.5

The total weight of litter produced per day is strongly correlated with the area of built up land in a catchment ($R^2 = 0.94$) and its sub-catchments ($R^2 = 0.73$). Figure 8 shows that larger and more built up catchments yield greater litter loads, particularly if they are low–income or industrial areas (Appendix 3). c

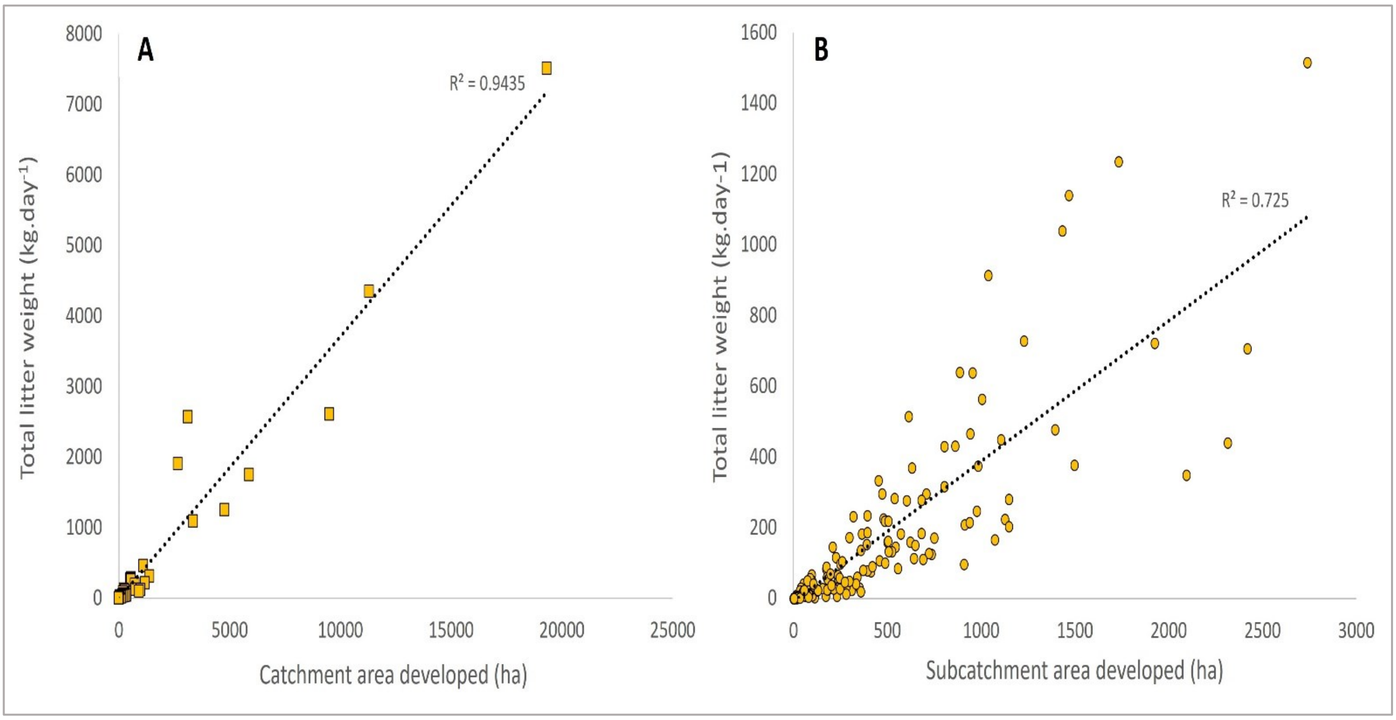

Figure 8. *Scatterplot showing the total litter weight (kg·day–1) versus the area of developed land in each (****A****) catchment (ha) and (****B****) sub–catchment (ha).*

7.3 Litter intervention devices

The spatial distribution of current litter traps in the city is poorly correlated ($R^2 = 0.28$) to the catchments receiving the largest total litter weight daily (Figure 9). The placement of intervention devices is spread across the city with certain rivers having far more installed traps compared to others (Figure 10).

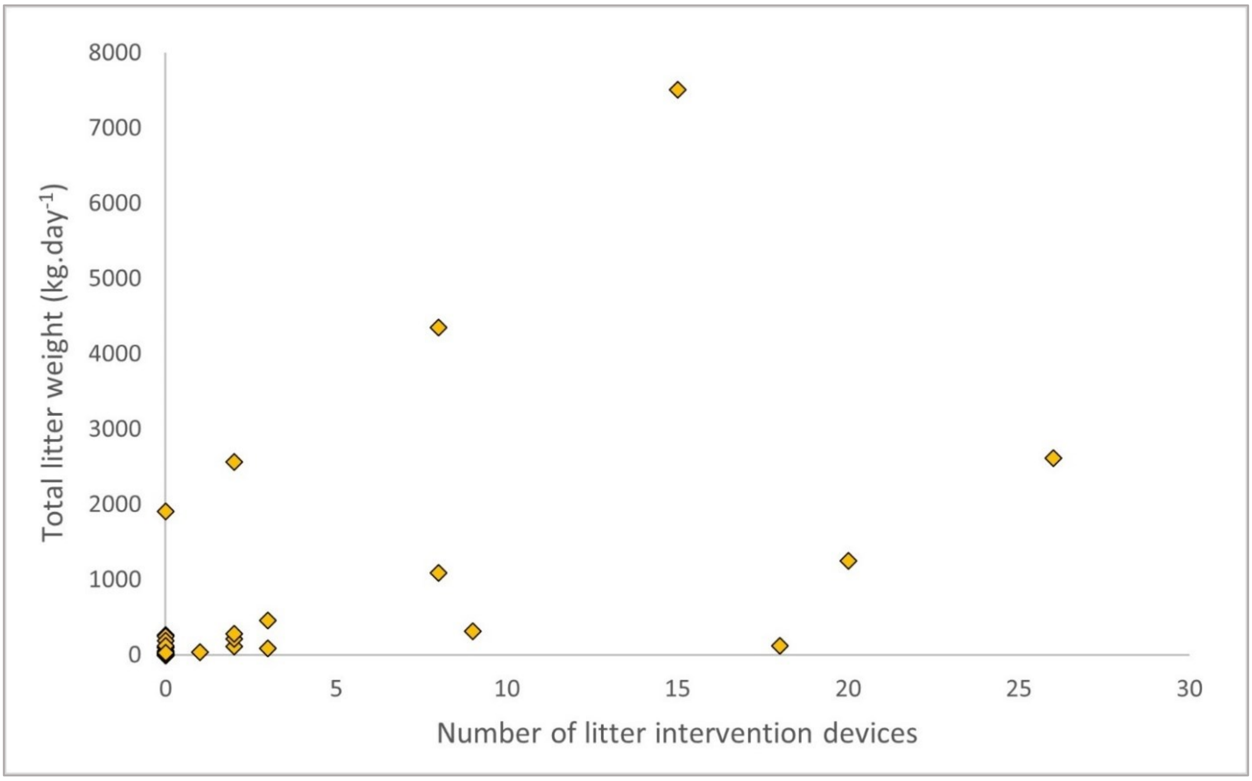

Figure 9. *Number of litter intervention devices versus the total litter weight produced in each major catchment (kg·day^{-1}). Each point represents a major river network i.e all the subcatchments contributing to that river across the city.*

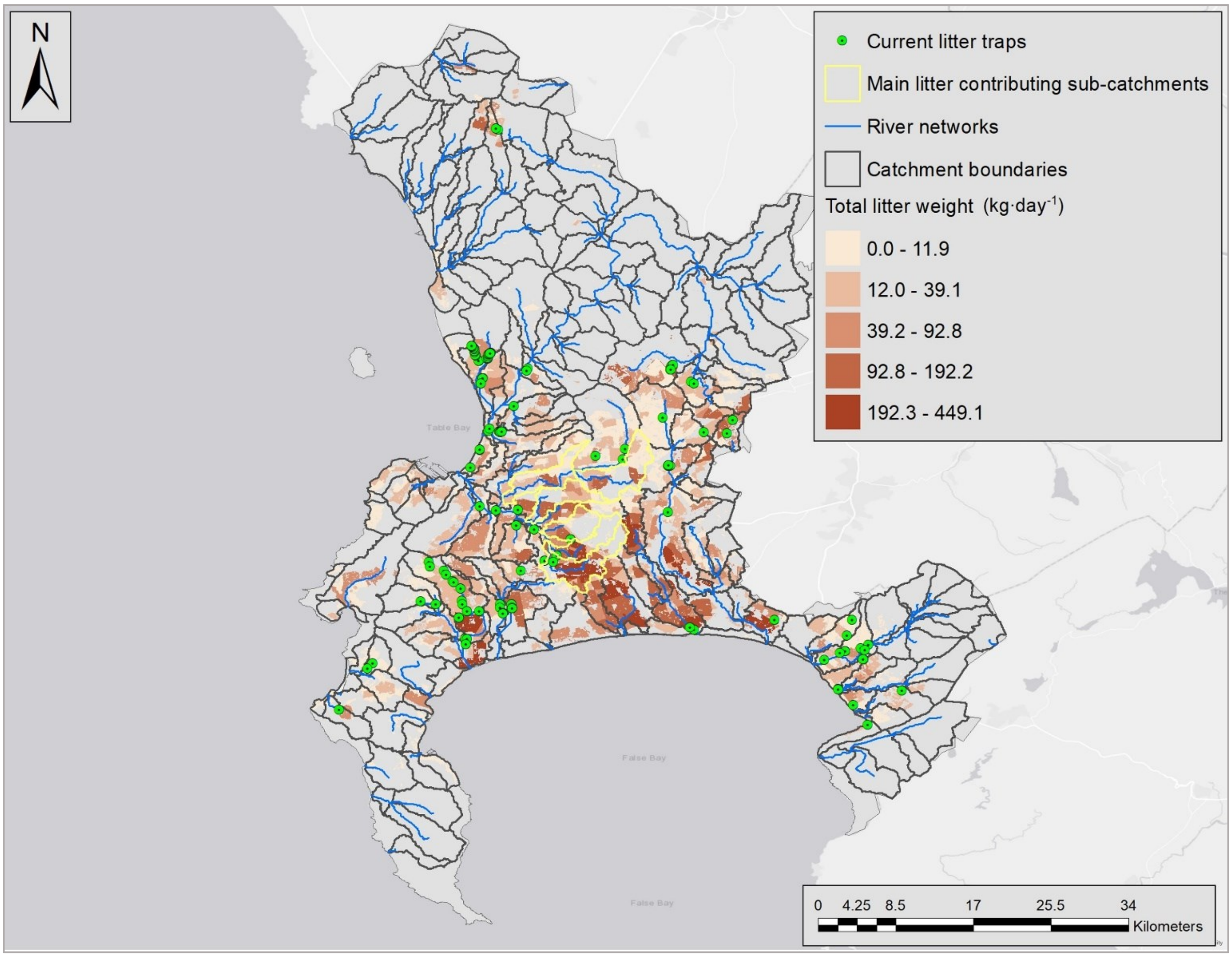

Figure 10. *Current litter trap intervention locations (green dots) in relation to the top plastic litter producing catchments (yellow polygons) in Cape Town.*

8 Discussion

The model predicted that ~ 26.0 (15.3–36.6) tonnes·day^{-1} of urban litter are produced in Cape Town, with 56% of this litter loaded into three main river networks; Salt/Black, Eerste and Diep Rivers. The placement of litter traps was poorly correlated with the catchments receiving the greatest litter loads per day, highlighting the need for data driven decision making.

8.1 Where will it all go?

Since the development and constant improvement of urbanised centres, urban litter loads have become more of an issue, driven largely by socio-economic change (Madhani, 2009). Increased levels of impervious surfaces in urban centres, coupled with the urban drainage network i.e stormwater drains, has created an efficient means through which urban litter is transported directly into rivers and the environment (Madhani, 2009). In Cape Town, increased levels of built up urban area has resulted in greater urban litter loads being produced and ultimately transported into rivers and the ocean (Figure 8). Marine litter is made up of 60 -80% plastic with a large percentage of that litter originating from land based sources (Winterstetter et al. 2021). Cape Town is covered by ~ 36 river networks which enter relatively quickly into the ocean given their length. The proximity of the urban areas to the coast line, coupled with the diffuse coastal zones that drain directly into the ocean, makes it easy for urban litter, particularly plastic, to enter the marine ecosystem (Figure 5).

Modelling processes, such as urban litter movement into rivers are built on the large, simple pipeline assumption that litter disposed of in the streets is washed directly into the river system (Figure 4). This however is not the case, whereby there are a myriad of factors influencing the movement of urban street litter. One of the biggest issues is that urban litter which enters the environment will remain there until it is eventually broken down. In certain instances it may take anywhere from several weeks to a hundred years for various litter items to become completely decomposed (Karimi & Faghri, 2021). Retention time of urban litter is highly variable and changes substantially as litter moves from the urban environment to urban rivers and ultimately the sea. A study by Tramoy et al. (2020) demonstrated that microplastic litter items may remain in the estuarine environment for several decades before being removed from the system or washed out to sea. Despite not being able to determine exact total litter load amounts that enter each river drainage network, key catchment areas were identified (Figure 6; Figure 7) where the greatest litter loads are mostly likely to be loaded into the river system.

8.2 Littering culture

Developing countries, such as South Africa, often have rapidly growing populations, large amounts of urban expansion and inadequate waste removal strategies. This leads to littering and dumping of urban waste in the environment, often due to the lack of accommodating infrastructure and poor service delivery (Franz & Freitas, 2012). South Africa’s diverse socio-economic population results in varied attitudes towards littering and further exacerbates the problem. A study by Ryan et al. (2020b) on the effects of Covid19 on littering made clear that human behaviour was the root cause of littering, mainly due to inappropriate waste disposal practises. Littering behaviour ultimately comes down to how people perceive nature and their personal value systems. This represents a systemic problem, whereby people do not care about their environmental impact but rather for their own self-interest. If we are to truly understand and ultimately curb the current urban litter crisis, greater insights into the littering culture of South Africans in required.

8.3 Litter traps

Litter trap intervention devices represent a short-term solution to the increasing urban litter crisis and as such needs to be as effective as possible, particularly in a country with poor service delivery and waste management plans. The city of Cape Town uses several intervention devices, however there is a substantial mismatch between where these interventions are placed in relation to urban litter loads (Figure 9; Figure 10) 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 urban litter weights into rivers (Ryan & Perold, 2021). Understanding the magnitude of urban litter loads in certain key areas will help provide the data needed to underpin more efficient management plans.

8.4 Caveats and improvements

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 i.e commercial areas were mixed with residential areas. 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.

8.5 Conclusions

This study further highlighted the flawed waste management system in Cape Town and indicates the lack of understanding around the culture of littering and perceived litter loads.

The model quantified urban litter loads across the various catchment areas in the city. These data will help better inform local waste management plans and maximise effectiveness of limited resources in employing stop gap litter interventions. Finally, the model has the capability of being applied to other cities to better understand hotspot litter generation areas and identify key intervention areas.

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10 Appendices

Appendix 1. Total litter and plastic litter weights for each of the 36 river networks in descending order of contribution.

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 (0.52–1.73)	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)	6.8	79.8
7	Atlantic Seaboard	–	3903	1740	0.46 (0.24–0.69)	0.20 (0.09–0.31)	4.8	84.6
8	West Coast	–	4064	1161	0.32 (0.17–0.47)	0.14 (0.06–0.21)	4.2	88.8
9	Zandvlei	28	8826	4766	1.25 (0.79–1.72)	0.58 (0.30–0.87)	1.8	90.6
10	Zeekoevlei Canal	20	6006	3361	1.09 (0.67–1.51)	0.51 (0.26–0.76)	1.2	91.8
11	Gordons Bay River	15	4133	1107	0.46 (0.28–0.63)	0.22 (0.11–0.32)	1.1	92.9
11	Lourens River	33	9699	1392	0.31 (0.18–0.44)	0.14 (0.07–0.21)	1.1	92.9
12	Stellenbosch River	1	777	538	0.28 (0.19–0.38)	0.14 (0.07–0.21)	1.0	93.9
13	Sout River	31	11116	520	0.27 (0.16–0.37)	0.13 (0.06–0.19)	1.0	94.9
14	Malmesbury River	21	4813	545	0.25 (0.11–0.39)	0.10 (0.04–0.17)	0.8	95.7
15	Somerset River	5	2343	1184	0.21 (0.12–0.31)	0.09 (0.04–0.14)	0.7	96.4
16	Foreshore River	4	1681	716	0.19 (0.12–0.27)	0.09 (0.04–0.13)	0.5	96.9
17	Milnerton River	7	2608	735	0.13 (0.08–0.17)	0.05 (0.03–0.08)	0.5	97.4
18	Mamre River	12	5136	216	0.12 (0.08–0.16)	0.06 (0.03–0.09)	0.4	97.8

19	De Goede River	3	2285	966	0.12 (0.07–0.16)	0.05 (0.03–0.07)	0.4	98.2
20	De Goede River	0	879	258	0.10 (0.07–0.14)	0.05 (0.03–0.07)	0.4	98.6
21	Hout Bay River	8	3785	909	0.10 (0.06–0.13)	0.04 (0.02–0.06)	0.3	99.0
22	Bokram River	3	955	175	0.09 (0.06–0.12)	0.04 (0.02–0.06)	0.2	99.2
23	Strandfontein River	1	886	182	0.05 (0.03–0.08)	0.02 (0.01–0.04)	0.2	99.3
24	Koeberg river	11	3323	140	0.04 (0.01–0.08)	0.01 (0.00–0.03)	0.2	99.5
25	Gordons Bay River	3	1227	333	0.04 (0.02–0.06)	0.02 (0.01–0.03)	0.1	99.6
26	Sir Lowry's River	1	698	280	0.03 (0.02–0.05)	0.01 (0.01–0.02)	0.1	99.7
27	Atlantis River	4	1343	42	0.03 (0.02–0.04)	0.01 (0.01–0.02)	0.1	99.8
28	Else River	6	1776	178	0.02 (0.02–0.03)	0.01 (0.01–0.02)	0.1	99.9
29	Simonstown River	1	746	47	0.02 (0.00–0.03)	0.01 (0.00–0.01)	0.1	99.9
30	Shusters River	3	1578	84	0.02 (0.01–0.02)	0.01 (0.00–0.01)	0	100
31	Silvermine River	7	2072	97	0.02 (0.01–0.02)	0.01 (0.00–0.01)	0	100
32	Steenbras River	20	6556	5	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100
33	Good Hope River	13	4142	8	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100
34	Peninsula River	1	676	0	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100
35	Malmesbury River	5	988	0	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100
36	Silver Stream	6	1920	7	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100
37	Buffels River	6	2795	2	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0	100

Appendix 2. *All associated litter weights and contributions for the sub–catchment areas in the Salt River river network.*

Rank	Catchment area (ha)	Built up area (ha)	Litter weight (tonnes·day^{-1})	Plastic weight tonnes·day^{-1})	Percent total litter load (%)	
					Catchment	Cumulative
1	2064	1433	1.04 (0.65–1.43)	0.50 (0.25–0.75)	13.8	13.8
2	1317	1228	0.73 (0.40–1.06)	0.33 (0.15–0.51)	9.7	23.5
3	2253	1925	0.72 (0.34–1.10)	0.30 (0.13–0.48)	9.6	33.1
4	1230	954	0.64 (0.34–0.94)	0.29 (0.13–0.45)	8.5	41.6
5	1207	1005	0.56 (0.29–0.84)	0.25 (0.11–0.39)	7.5	49.1
6	1588	1395	0.48 (0.25–0.70)	0.21 (0.10–0.32)	6.3	55.5
7	1090	942	0.47 (0.27–0.66)	0.21 (0.10–0.32)	6.2	61.7
8	1179	1106	0.45 (0.27–0.63)	0.21 (0.10–0.31)	6.0	67.7
9	3987	2314	0.44 (0.27–0.61)	0.20 (0.10–0.29)	5.9	73.5
10	1076	861	0.43 (0.29–0.58)	0.21 (0.11–0.31)	5.7	79.3
11	1124	939	0.22 (0.13–0.30)	0.10 (0.05–0.14)	2.9	82.2
12	1330	1148	0.20 (0.13–0.28)	0.09 (0.05–0.13)	2.7	84.9
13	2637	1073	0.17 (0.10–0.23)	0.07 (0.04–0.11)	2.2	87.1
14	866	623	0.16 (0.09–0.23)	0.07 (0.03–0.11)	2.1	89.2
15	211	208	0.15 (0.10–0.19)	0.07 (0.04–0.11)	1.9	91.1
16	698	543	0.14 (0.07–0.22)	0.06 (0.02–0.09)	1.9	93.1
17	469	359	0.14 (0.07–0.20)	0.06 (0.03–0.09)	1.8	94.9

18	497	458	0.11 (0.04–0.18)	0.04 (0.01–0.07)	1.4	96.3
19	335	248	0.10 (0.02–0.18)	0.03 (0.01–0.06)	1.3	97.6
20	378	236	0.07 (0.03–0.10)	0.03 (0.01–0.04)	0.9	98.5
21	72	52	0.04 (0.03–0.05)	0.02 (0.01–0.03)	0.5	99.0
22	174	154	0.03 (0.02–0.04)	0.01 (0.01–0.02)	0.4	99.4
23	69	47	0.02 (0.00–0.03)	0.01 (0.00–0.01)	0.2	99.6
24	99	47	0.02 (0.01–0.02)	0.01 (0.00–0.01)	0.2	99.9
25	16	14	0.01 (0.01–0.01)	0.00 (0.00–0.01)	0.1	100

***Appendix 3**. Total litter weight (kg·day–1) versus the proportion of developed land in each (A) catchment (ha) and (B) sub–catchment (ha) as well as the overall (C) catchment area and (D) sub–catchment area.*