Regional Studies in Marine Science 53 (2022) 102421

Contents lists available at ScienceDirect

Regional Studies in Marine Science

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

Standing stock and daily accumulation of beach litter in KwaZulu-Natal, South Africa

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ARTICLE INFO

Article history:
Received 23 July 2021
Received in revised form 29 April 2022
Accepted 30 April 2022
Available online 10 May 2022

Keywords:
Beach
Marine litter
Plastic
Daily accumulation
Standing stock
Durban
eThekwini
South Africa
KwaZulu-Natal

ABSTRACT

Beach litter accumulation studies are an important method to investigate litter flows to the marine environment. We detail a standing stock and daily accumulation study, conducted at two locations approximately 20 km north (uMhlanga) and south (Amanzimtoti) of the Port of Durban, South Africa. The materials collected were dominated in number by plastic, which constituted more than 90% of all items found during the surveys. Accumulation ranged from 134 to 719 items 100 m^{-1} d^{-1}, falling within the range of similar studies in South Africa. Accumulation weights (wet and uncleaned, WU) ranged from 0.10 to 2.49 kg per day. Between the two sites, standing stock per 100 m ranged between 921 to 1534 items, and between 1.06 to 4. 03 kg(WU). Overall, higher litter loads were observed at Amanzimtoti beach compared to uMhlanga beach. Our statistical modelling showed that litter numbers varied by beach, whether collection was above or below high tide and the amount of rainfall. At Amanzimtoti, more litter was found above the tide line throughout the study, but at uMhlanga, this was only true for the first part of the study. Analysis of the types of litter found between beaches, suggest different sources of litter that could be used to tailor waste management solutions in each local area. Greater numbers of cotton bud sticks found at uMhlanga, suggests sewage treatment outputs contribute to the litter loads in this area, while large amount of linoleum flooring fragments found at Amanzimtoti suggest construction could be the source.

1. Introduction

Marine litter is defined as 'any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment' (GESAMP, 2019) and is well recognised to be a global issue in all marine environments (Barnes et al., 2009). Marine litter is classified into several categories; nano (<50 µm), micro (50 µm–5 mm), meso (5 mm–2.5 cm), and macro litter (2.5 cm–1 m) (GESAMP, 2019) and poses serious environmental threats to marine life (Gall and Thompson, 2015). In addition to environmental impacts, marine litter presents anthropogenic threats, including risks to human health (Barboza et al., 2018; Smith et al., 2018; Campanale et al., 2020; Naidoo and Rajkaran, 2020) and economic impacts to sectors such as tourism and fisheries (Mouat et al., 2010; Newman et al., 2015; UN Environment, 2017; Arabi and Nahman, 2020). Plastic is the most abundant component of marine litter due to its wide-scale use, durability, lightweight and buoyant properties (Barnes et al., 2009; Thiel et al., 2013; Galgani et al., 2015). The increase in world population (Lutz et al., 2017) and the consequent increased demand for goods by markets worldwide has led to a substantial surge in plastic production (PlasticsEurope, 2019). This rise in the abundance of plastic items used and discarded, especially in the coastal areas where the population is increasing more quickly (Jambeck et al., 2015), is often not matched by adequate waste management systems (Wilson et al., 2015; AfDB, UNEP and GRID-Arendal, 2020). Without adequate systems, waste leaks out of the official disposal pathway and ends up in the environment, providing a major input of marine litter from land (Jambeck et al., 2015).

The issue of marine litter in South Africa is relatively well understood, due to availability of data spanning over 30 years (Ryan, 1987; Shaughnessy, 1980). The scope of previous studies is wide and includes the analysis of abundance and composition

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https://doi.org/10.1016/j.rsma.2022.102421
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of marine litter (Ryan and Moloney, 1990; Naidoo et al., 2015), its dispersion (Fazey and Ryan, 2016), the estimation of accumulation rates (Ryan et al., 2014), litter on the seafloor (Ryan et al., 2020b), microplastics dispersal rates (Nel et al., 2017; Collins and Hermes, 2019), effects on biota (Ryan, 1987; Cliff et al., 2002; Ryan et al., 2016a,b; Ross, 2017; Witteveen et al., 2017; Naidoo and Glassom, 2019a; Naidoo et al., 2020), as well as estuarine (Naidoo et al., 2015) and stormwater drain litter assessments (Armitage and Rooseboom, 2000; Weideman et al., 2020). Despite earlier studies suggesting that oceanic currents play an important role in marine litter levels in South Africa (Ryan and Moloney, 1990), recent findings suggest that proximity to urban centres increases the amount of plastic litter on beaches in South Africa (Ryan et al., 2009, 2018; Naidoo et al., 2015), highlighting large cities as areas of interest to study waste inputs leading to marine litter. More recently, five review papers were published to summarise the current knowledge and the outstanding research gaps on marine litter in South Africa including: land-based sources and pathways into the marine environment (Verster and Bouwman, 2020), transport and fate of plastics in the marine environment (Ryan et al., 2020a), impacts on biota and implications on human health (Naidoo et al., 2020), impacts on ecosystem services and the economy (Arabi and Nahman, 2020), as well as a detailed analysis on how to monitor marine litter, depending on the aim of the study (Ryan, 2020). A recurring conclusion of these studies is that significant knowledge exists in South Africa to take effective and immediate action on tackling marine litter.

Monitoring is used to understand the impact of mitigation strategies and further research studies are necessary to close the knowledge gaps. Beaches provide a useful deposition area to study marine litter and are commonly used in quantification and characterisation studies (Ryan et al., 2009). In South Africa, beach surveys have been conducted using several protocols and frequencies (Ryan et al., 2014), which have been shown to produce significantly different results for the same site (Ryan et al., 2009, 2014; Ribic et al., 2010, 2012). Infrequent analysis measures the 'standing stock' of marine litter on a beach and represents the amount of litter accumulating over a sustained period at the surveyed site. This snapshot masks the daily fluxes of litter from land and sea-based sources, as well as export of litter through factors such as wind and wave removal, burial, degradation and clean-ups (GESAMP, 2019). In contrast, when the same site is surveyed frequently, the removal rates are limited and, therefore, the accumulation rate more closely represents the loading rate (abundance of marine litter arriving at the site per unit time) (Smith and Markic, 2013; GESAMP, 2019; Ryan et al., 2020a). The majority of macro litter studies in South Africa have occurred along the western (Western Cape) and southern (Eastern Cape) coasts (Madzena and Lasiak, 1997; Ryan et al., 2018; Chitaka and von Blottnitz, 2019); beaches along the eastern coastline (KwaZulu-Natal) are included in two studies (Ryan et al., 2018, 2020a). This study was conducted to better understand both standing stock and daily litter fluxes around KwaZulu-Natal's largest population centres, in the coastal municipality of eThekwini.

2. Methods

Sampling locations

The eThekwini municipality has a population of over 3.7 million (STATS SA, 2018) and is the third most populous city in South Africa (Sawe, 2019). The Port of Durban falls within the eThekwini municipality and is the busiest port in Sub-Saharan Africa and an important area for tourism. Two beaches, Amanzimtoti and uMhlanga, about 25 km north and 25 km south of the Port of Durban were chosen for this study (Fig. 1). uMhlanga and Amanzimtoti are both urbanised areas with beaches that are heavily utilised for recreation year-round but with popularity increasing during the summer. To minimise the influence of beach users and municipal cleanings in this study, the two selected sites were intentionally far from the main swimming beaches. Exact GPS locations of the survey transects are included in Fig. 1. Relevant municipal authorities were approached to gather background information on cleaning, to request that the sites remained untouched during the study, to inform locals and to provide proof of permits to carry out this study. The authors noted no, or minimal interference of the study site through municipal cleaning. Members of the public were present throughout the study, but did not appear to interact with the marine litter or ongoing study. No signage was placed to further minimise public interference with the site.

Amanzimtoti covers an area of 9.19 km^2 and has a population of 13 813 (STATS SA, 2011). The beach is a sandy beach, stretching from the Amanzimtoti estuary in the south, to the eziMbokodweni estuary in the north. The beach is characterised by a gentle slope (estimated average slope of 30 degrees), with dune vegetation and housing developments behind the back of the beach. The average width during sampling was 70 m from the back of the beach to the low tide line. uMhlanga covers a greater area (16.75 km^2) and has a population of 24 238 (STATS SA, 2011). Similarly, uMhlanga beach is a sandy beach that stretches from the populated area around uMhlanga Rocks (and the main swimming beach) in the south, to the oHlanga estuary in the north (Forbes and Demetriades, 2008). The beach also has a gentle slope (estimated at around 20 degrees), with vegetation at the back of the beach that forms a wildlife reserve, eventually leading to housing developments. The average width during our sampling period was 40 m from the back of the beach to the low tide line. Both Amanzimtoti and uMhlanga are categorised as reflective beaches, characterised by coarse sand with a surf zone and one to two sandbars (Cooper, 1995; Nel et al., 2017). The sampling occurred during an increasing tidal range (see Supplementary Information for more detail).

Meteorology and Hydrography

The eThekwini municipality coastline has two dominant prevailing wind directions, from the north-east and from the south-west. The north-easterly (NE) wind is associated with settled weather, while the south-westerly (SW) is associated with more inclement weather and greater wave action (Tyson and Preston-Whyte, 2000). The prevailing Agulhas Current runs in a south-westerly direction along South Africa's eastern coastline. Closer inshore, due to a bathymetric feature to the north of Durban, termed the 'KZN Bight', the current moves offshore around 40–50 km and a north-wards flow is evident inshore of the main current off Durban (Schumann et al., 2019). Intermittently, the north- easterly flow is also observed to the south of Durban, a feature known as the 'Durban eddy', paired with northwards longshore drift (Guastella and Roberts, 2016; Roberts et al., 2016). Tidal heights and times (South African Hydrographic Office, 2019) wind direction, wind speed and rainfall data were obtained for the sampling period for Amanzimtoti (Durban South Athlone weather station) and uMhlanga (Virginia weather station) (South African Weather Service, 2021). Wind data were categorised into the two predominant wind directions for Durban and assigned daily, based on the dominant direction. The wind speed (knots) was averaged for each day of the study for inclusion in the model. Hourly rainfall data for Durban (South African Weather Service, 2021) were totalised to a value of mm/day.

Data collection

In September 2019, beach litter above 5 mm in size were collected, categorised and weighed in a standing stock and daily accumulation study along 100 m stretches at each site. The first two surveys at each site (10th and 21st September for uMhlanga,

Fig. 1. Survey locations for marine litter standing stock and accumulation study along the Kwa-Zulu Natal coastline (1:250,000). Transect locations (1:10,000): Amanzimtoti SOL: −30.04326, 30.89662 EOL: −30.04256, 30.89732 uMhlanga SOL: −29.70848, 31.09746 EOL: 29.70772, 31.098.

and 14th and 20th September for Amanzimtoti) were standing stock assessments of beach litter, which were followed by a 9 and 10-day stretch of daily surveys for Amanzimtoti and uMhlanga, respectively (variation in duration was due to field-working constraints). The categories of litter used were based on the OSPAR methodology (OSPAR Commission, 2010) to align with similar studies (OSPAR, 2017; Binetti et al., 2020), with modifications to allow for comparisons with pre-existing macro litter studies in South Africa undertaken in the WIOMSA region (Barnardo and Ribbink, 2020). The categories are designed to distinguish materials (e.g. plastic) but also litter usage (e.g. sanitary). The data were collected in two zones: from, and including on, the high tide line to the back of the beach; and from the high tide line to the water (Fig. 2). This allows for global comparison of data sets using the OSPAR methodology where litter is collected only from the high tide line to the back of the beach and with data collected in previous accumulation studies in the region (Ryan et al., 2014), this also aligns with the methodology now set out by Barnardo and Ribbink (2020). A 5 m buffer zone was designated either side of the 100 m stretch and cleared of all visible litter (>5 mm) on day 1 of the daily accumulation study to minimise the amount of wind-blown litter impinging on the study area throughout the study. GPS points were marked each day at 25 m intervals, along the back of the beach, the high tide line and the waterline, with measurements recorded between each point in Fig. 2, including beach width and area to examine tidal dynamics throughout the study. The surveys were carried out during an out-going tide and timed to be completed around low tide each day. Following the OPSAR protocol (OSPAR Commission, 2010), items were not cleaned nor dried prior to weighing. Scales for the standing stock were accurate to 5 g whereas, a change in the scales for daily accumulation, ensured the weights were accurate to 1 g.

Statistical Modelling

For the modelling described below, total litter counts were analysed. However, due to the potential influence of both wind and tides, litter categories were sub-classified as ‘heavy’ (>5 g) or ‘light’ (≤5 g) based on the mean (wet and uncleaned, WU) weight of litter category items from the standing stock and accumulation surveys. The 5 g cut-off was chosen to represent the weight at which items collected did not register on the scales used in the field for the standing stock surveys. On this basis, 30 litter categories were classified as heavy, and 85 as light and density ranges were estimated retrospectively for each category (Table S1).

A linear model was used to determine the relationships between total litter (TL) counts and seven potential explanatory variables: *Rainfall* (R); *Wind direction* (WD) sub-divided into north -easterly (NE) and south-westerly (SW); *Wind speed* (WS); *Day of study* (D); *Beach* (B); Area surveyed (A); and *Tide* (T) classified as above or below the high tide line. Thus, when all explanatory variables are included, our linear models are of the form in Eq. (1):

$$TL = f\,(R, WD, WS, D, B, T, A) + error, \quad (1)$$

where the error is assumed to be normally distributed with mean 0 and constant variance, and f() denotes a linear function of the explanatory variables. For models that involved day of study (D), modelling was done using the Generalised Additive Modelling (GAM) function *gam* (Woods, 2017), where day of study was represented by a smoothing spline, with a maximum of four degrees of freedom.

All modelling was carried out in R (R Core Team, 2019). All combinations of the explanatory variables were fitted into the model and the Akaike’s Information Criterion (AIC) was used to judge the adequacy of the models (small values of AIC indicating

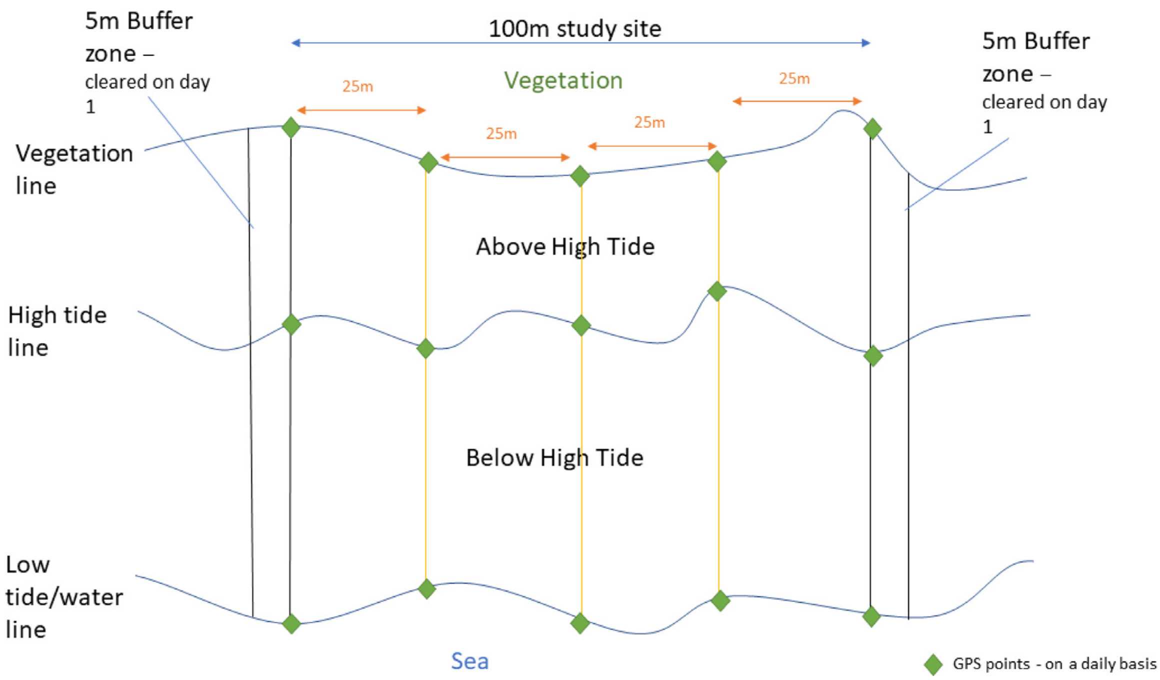

Fig. 2. Diagram showing sampling design for marine litter accumulation study, showing areas above and below high tide line and buffer zones used for clearing on day 1 of the accumulation study.

better models). Although the total litter variable is not continuous, the count values were sufficiently high (overall mean = 224 Items 100 m^{-1} d^{-1}) for them to be considered as a good approximation to continuous. Residuals from the model fitting were found to follow the Normality assumption closely.

3. Results

Standing stock

Two surveys were completed at each site to determine the standing stock of litter at each site, prior to the accumulation study. These surveys removed between 921 and 1534 items from the sites, with the total (WU) weight of litter items removed at individual surveys ranging between 1.06 and 4.03 kg (Table 1). The high total weight values were skewed by large single items, primarily in the wood category. A greater number of items were collected from Amanzimtoti than uMhlanga, with 1347 and 1534 items collected at each survey at Amanzimtoti, and 1005 and 921 items collected at uMhlanga. The most common material was plastics, which constituted over 90% of the items during each survey, followed by paper (1.3–4.5%) and sanitary (1.4–4.5%) waste categories.

The 'top ten' beach litter items were calculated from the standing stock surveys and reveal the common litter items found in these locations, along with the mean weight of an item in each category (Table 2). The most frequent item found at both sites were small pieces of plastic between 0.5–2.5 cm in length, representing meso litter, with an average weight of 2 g. Also commonly found at both locations were plastic fragments 5–50 cm with a total weight of 18 g. The 'other plastic' category was commonly found at both sites, but at Amanzimtoti, it was noted that this category was dominated by a large amount of linoleum flooring fragments. While the 'other plastic' category was commonly found at uMhlanga, linoleum was not observed at this location. While some litter categories were commonly found on both beaches, such as food packs and trays and burnt plastic, there were different categories found in each top ten litter items of the two sites. More cigarette butts were found at Amanzimtoti than uMhlanga, where they did not feature in the top ten litter items. Conversely, sweet packets were found in the top ten items for uMhlanga, but not for Amanzimtoti.

Daily accumulation

Accumulation rates observed during this study ranged from 134 to 719 items 100 m^{-1} day^{-1}, with the total (WU) weight of litter items removed at individual surveys ranging between 0.10 to 2.50 kg (Table 1). Similarly to the standing stock survey, a few large and/or heavy items, such as pieces of wet wood, skewed the recorded weights. The mean accumulation rates for the whole beach area were higher at Amanzimtoti (543 items 100 m^{-1} d^{-1}) than uMhlanga (340 items 100 m^{-1} d^{-1}). The number of litter items recorded on each accumulation study day was lower than the standing stock data for both sites, but fluctuated through the nine and ten-day period, with a higher variance at uMhlanga ($SD_{uMhlanga} = 170$; $SD_{Amanzimtoti} = 149$).

A higher number of litter items accumulated above the high tide line at Amanzimtoti ($Mean_{Amanzimtoti}$ = 350 items 100 m^{-1} d^{-1}, $Mean_{uMhlanga}$ = 216 items 100 m^{-1} d^{-1}) compared to below the high tide line ($Mean_{Amanzimtoti}$ = 193 items 100 m^{-1} d^{-1} $Mean_{uMhlanga}$ = 123 items 100 m^{-1} d^{-1}), as presented in Fig. 3.

The material composition of the items was dominated by plastic, which constituted 88%–97% for Amanzimtoti, and 87%–96% for uMhlanga (Table 1), followed by paper (1.5%-3.5% at Amanzimtoti and 0.7–5.9% at uMhlanga) and Sanitary items (0.7–6.6% at Amanzimtoti and 1.0%-4.0% at uMhlanga). Plastic pieces (0–2.5 cm) were commonly observed items on both beaches during the accumulation study (Table 2). However, notable differences between the two sites over the daily accumulation study was the presence of cotton bud sticks in uMhlanga's top items (ranked fifth), with their absence from Amanzimtoti's top 10 items (Table 2). An additional point of interest is that caps/lids from soda drinks appear higher on the daily accumulation rate top 10 (ranked 6) in uMhlanga compared to Amanzimtoti (Ranked 10) (Table 2).

Fig. 4a and 4b show the similarity in the pattern of accumulation throughout the study between the two sites, suggesting that some external factors, such as weather, affect both sites

Table 1
Percentage contribution of material category using the OSPAR Methodology (OSPAR Commission, 2010) by number of marine litter surveys by date (grey cells indicate surveys used for standing stock estimation) at Amanzimtoti and uMhlanga per 100 m survey with total number of litter items collected and total weight (kg). An asterisk (*) indicates when a large anomalous weight was excluded and the corresponding category.

		Percentage Contribution of Material Category by Number										Total Number of Items	Total Weight (kg)
	Survey Number	Plastic	Rubber	Textile	Paper	Wood	Metal	Glass	Sanitary	Medical	Other		
Amanzimtoti	14/09	93.0	0.2	0.3	4.5	0.2	0.2	0.0	1.4	0.0	0.1	1347	1.54
	20/09	92.4	0.1	0.5	2.2	0.2	0.3	0.1	3.7	0.1	0.4	1534	1.68
	21/09	91.0	0.2	0.0	3.5	0.9	0.5	0.2	2.8	0.2	0.5	423	0.87
	22/09	94.3	0.4	0.0	2.1	0.4	0.7	0.4	1.8	0.0	0.0	281	0.19
	23/09	89.4	0.0	0.2	3.2	0.2	0.0	0.0	6.6	0.2	0.0	407	0.47
	24/09	92.4	0.3	0.1	2.2	0.1	0.9	0.6	2.6	0.4	0.3	687	2.50
	25/09	95.6	0.5	0.2	1.6	0.2	0.2	0.0	1.4	0.0	0.2	431	0.31
	26/09	94.5	0.2	0.4	2.1	0.2	0.2	0.0	1.9	0.0	0.5	568	1.42
	27/09	96.6	0.0	0.1	1.8	0.6	0.0	0.0	0.7	0.0	0.1	669	0.56
	28/09	88.4	0.3	0.3	3.2	1.5	0.2	0.0	2.1	0.2	3.8	585	0.98
	29/09	93.8	0.0	0.0	1.5	1.2	0.0	0.2	2.4	0.3	0.6	664	0.58
	30/09	93.2	0.0	0.1	1.7	0.6	0.7	0.1	2.9	0.0	0.7	719	0.46
uMhlanga	10/09	91.7	0.4	0.3	1.3	0.9	0.4	0.4	4.5	0.1	0.0	1005	4.03
	21/09	90.2	1.0	0.0	3.7	0.9	0.4	0.0	3.0	0.7	0.1	921	1.06
	22/09	90.0	0.0	0.0	5.9	0.5	0.5	0.0	2.3	0.9	0.0	221	0.60
	23/09	90.9	0.6	1.0	3.6	0.6	0.6	0.0	1.0	1.0	0.6	309	0.84
	24/09	91.2	0.6	0.0	2.8	0.4	0.1	0.1	4.0	0.3	0.4	707	1.51
	25/09	89.8	1.1	0.0	3.6	0.0	0.7	0.0	3.3	0.7	0.7	274	0.48
	26/09	89.3	0.9	0.0	3.2	0.4*	0.4	0.0	3.6	0.2	1.9	468	0.32*
	27/09	95.4	0.7	0.0	0.7	0.3	0.0	0.0	2.3	0.3	0.3	305	0.22
	28/09	87.3	3.0	0.0	4.5	0.0	0.7	0.0	3.0	0.7	0.7	134	0.10
	29/09	89.6	0.0	0.0	5.7	0.4	0.9	0.0	3.0	0.0	0.4	230	0.31
	30/09	90.3	0.5	0.0	4.6	0.5	0.2	0.0	2.7	0.7	0.5	413	0.37

Table 2
Top ten litter items classified from standing stock surveys with number of items and rank in brackets from each day of the daily accumulation study and mean weight of each item in these categories.

Rank	uMhlanga	Mean weight[a] (g)	21/09	22/09	23/09	24/09	25/09	26/09	27/09	28/09	29/09	30/09
1	Plastic pieces 0–2.5 cm	2		65 (1)	77 (1)	254 (1)	79 (1)	78 (1)	20 (1)	12 (1)	19 (1)	31 (1)
2	Plastic pieces 2.5–50 cm	18		7 (8)	18 (5)	37 (4)	28 (2)	19 (2)	5 (4)	2 (13)	2 (12)	3 (10)
3	Foam sponge Food packs and trays 2.5–50 cm	7		21 (3)	25 (2)	45 (3)	14 (3)	15 (3)	4 (6)	6 (2)	12 (2)	11 (2)
4	Burnt plastic	17		24 (2)	20 (3)	53 (2)	8 (6)	5 (10)	1 (20)	0 (106)	1 (17)	4 (7)
5	Cotton bud sticks	5		4 (13)	1 (33)	25 (5)	6 (10)	6 (8)	1 (20)	2 (13)	0 (105)	1 (23)
6	Caps/lids (soda drinks)	10		7 (8)	14 (7)	17 (9)	1 (36)	4 (14)	1 (20)	0 (106)	2 (12)	0 (110)
7	Other plastic	7		8 (6)	2 (22)	18 (7)	3 (19)	4 (14)	2 (11)	4 (4)	0 (105)	2 (13)
8	Foam sponge Food packs and trays 0–2.5 cm	1		15 (4)	20 (3)	18 (7)	10 (4)	8 (4)	12 (2)	6 (2)	8 (3)	7 (4)
9	Caps/lids (other)	20		8 (6)	7 (11)	23 (6)	6 (10)	8 (4)	1 (20)	2 (13)	1 (17)	1 (23)
10	Sweet packets	8		2 (19)	5 (14)	12 (14)	6 (10)	3 (19)	2 (11)	0 (106)	1 (17)	1 (23)
	Amanzimtoti											
1	Plastic pieces 0–2.5 cm	2	98 (1)	65 (1)	100 (1)	226 (1)	144 (1)	137 (1)	108 (1)	137 (1)	135 (1)	142 (1)
2	Other plastic	7	51 (2)	32 (3)	43 (2)	83 (2)	70 (2)	71 (2)	60 (2)	52 (2)	54 (2)	87 (2)
3	Plastic pieces 2.5–50 cm	18	15 (5)	42 (2)	21 (3)	31 (4)	10 (4)	11 (4)	0 (107)	7 (9)	9 (6)	25 (4)
4	Burnt plastic	17	18 (4)	14 (5)	12 (6)	40 (3)	21 (3)	18 (3)	18 (4)	26 (4)	24 (4)	15 (6)
5	Foam sponge Food packs and trays 0–2.5 cm	1	30 (3)	23 (4)	17 (4)	17 (5)	5 (10)	9 (6)	36 (3)	44 (3)	47 (3)	42 (3)
6	Caps/lids (other)	20	3 (19)	3 (12)	11 (7)	11 (10)	2 (18)	2 (16)	1 (22)	4 (13)	2 (21)	8 (11)
7	Plastic bottle labels	5	6 (11)	3 (12)	9 (9)	8 (13)	6 (8)	3 (13)	0 (107)	2 (20)	3 (14)	6 (15)
8	Cap rings (Plastic)	4	4 (16)	3 (12)	4 (16)	16 (6)	10 (4)	7 (8)	2 (14)	1 (31)	3 (14)	7 (13)
9	Cigarette butts	4	11 (7)	1 (20)	7 (11)	13 (8)	5 (10)	6 (9)	3 (9)	9 (5)	4 (11)	8 (11)
10	Caps/lids (soda drinks)	10	2 (24)	4 (8)	7 (11)	0 (117)	8 (6)	11 (4)	11 (5)	9 (5)	9 (6)	12 (7)

[a]Mean weight of litter categories calculated from all surveys.

simultaneously. The peak in litter items in the above high tide area is seen on 24th September on both beaches, as well as the subsequent drop in litter items the following day. From this day onwards accumulation rates drop in the above high tide line area at uMhlanga, but not at Amanzimtoti (Fig. 3a). The area below the tide line shows similar patterns in accumulation between beaches (Fig. 3b)

Meteorology

The weather during this study was mild. A south-westerly wind was dominant, apart from the period between 26th–29th September when the wind came from the north-east (Table 3). The wind speed was generally less than 5 m/s but peaked up to 19 m/s in Amanzimtoti. Wind speeds were generally higher at Amanzimtoti, than uMhlanga. Light rain was experienced during the study on days 22nd, 24th, 25th and 30th September, with a maximum of 7 mm rain recorded in a day (Table 3).

Statistical modelling

Table 4 gives a summary of the AIC values for a succession of linear models fitted with total litter as the dependent variable. Model 1 uses all seven explanatory variables. Models 2 and 3 successively drop the explanatory variables *Wind Direction and Windspeed*. These models all result in higher AIC values than model 1, indicating that neither of these variables are important explainers of *Total litter*. However, dropping *Rainfall* in Model 4

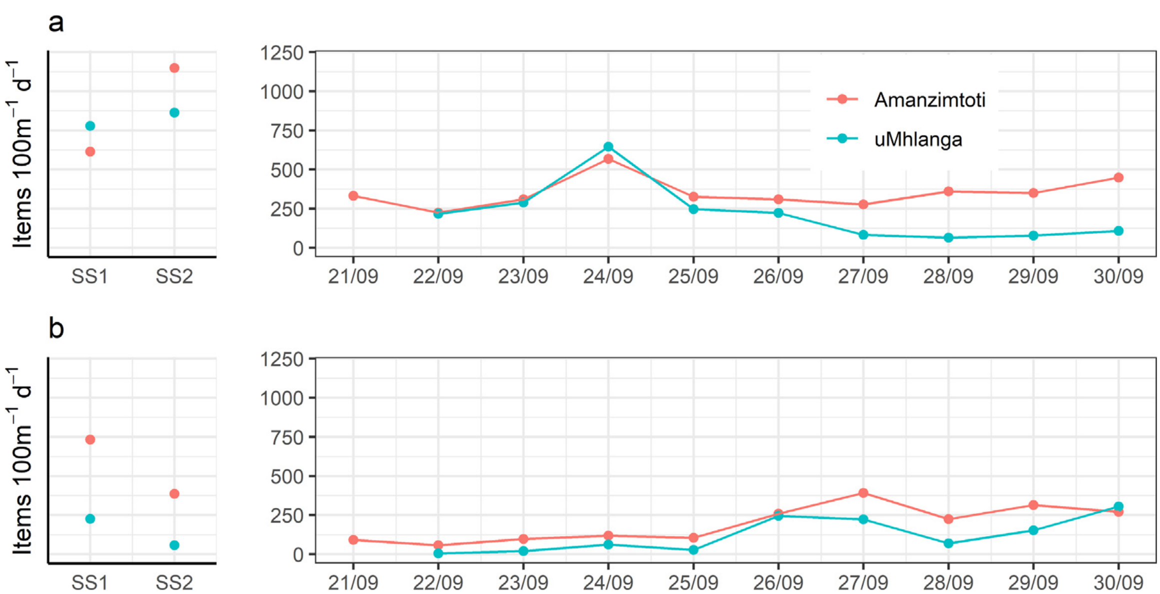

Fig. 3. Accumulation rates of marine litter at two sites on the KwaZulu-Natal Coast: a. Accumulation rates of litter items from the high-tide line to the back of the beach b. Accumulation rates of litter items from the high-tide line to the water line.

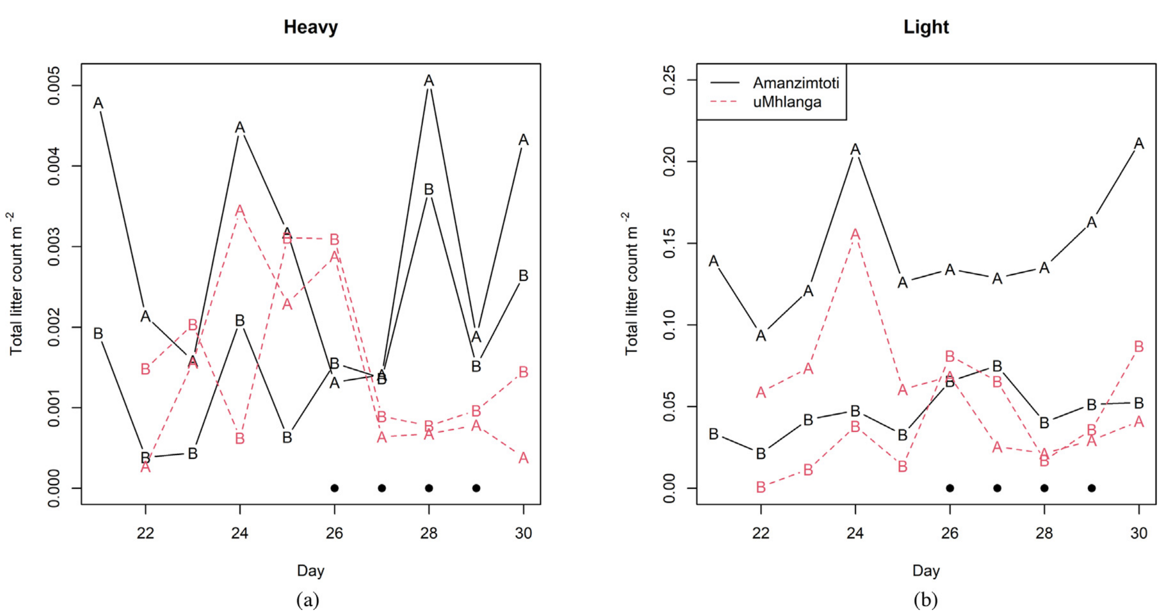

Fig. 4. (a) Mean total heavy (>0.005 kg) and (b) Mean total light ($\leq$0.005 kg) litter Items recorded during daily accumulation study in September 2019 at two sites; uMhlanga and Amanzimtoti. Means are per m^2 of survey area. Large black dots represent days when the wind was from the north east.

results in a small increase in AIC compared to Model 3, suggesting that *Rainfall* is a marginally important explainer of variations in *Total Litter* (more rainfall implies more litter). The AIC for Model 5 shows that *Day* is unimportant. Models 6 to 8, however, show that *Area* (area of the beach calculated from GPS points), Beach (Amanzimtoti or uMhlanga) and Tide (whether the litter was collected from the water line to the high tide line or from the high tide line to the back of the beach) are important, as models without these variables show an increase in AIC compared to Model 5. Models 9 and 10 show that both the *Beach* × *Tide* interaction and the *Area* × *Tide* interaction are important. The model with the lowest AIC value is model 10 and includes both interaction terms. Further investigation of the *Area* × *Tide* interaction suggested that there is a relationship between *Area* and *Total Litter* in the area from the water line to the high tide line, but not from the high tide line to the back of the beach.

The plots of means for the heavy (>5 g) and light ($\leq$5 g) items are shown in Fig. 4. The heavy items mean shows more variability in accumulation rates, reflecting the fact that there are more light items (8273) than heavy items (222) (overall mean of 0.983 items per m^{-2} compared to the heavy items mean of 0.026 items per m^{-2}). Heavy items constituted materials such as wet wood and high-density plastics (Table S1). The plot of the light items shows similar patterns between the two beaches and is almost identical to the total litter items in Fig. 3. A modelling analysis on the light items produced very similar results as for total litter items. The heavy items, however, (Fig. 4) show a different pattern to total litter items; from 26th September, the litter load of heavy items

Table 3
Meteorological data for the period of the study (South African Weather Service, 2021).

	Amanzimtoti (Durban South Athlone Park weather station)				Umhlanga (Virginia weather station)			
	Rainfall (mm)	Windspeed daily average (m/s)	Max daily wind speed (m/s)	Approximated predominant wind direction	Rainfall (mm)	Wind speed daily average (m/s)	Max daily wind speed	Approximated predominant wind direction
10/09/2021					0	2.5	9.6	NE
14/09/2021	0	2.6	7.1	SW				
2009/2021	0	3.8	13.3	NE				
2109/2021	0	3.4	12.8	SW	0	2.3	10	SW
2209/2021	0.2	6.1	15.8	SW	0	3.6	13.4	SW
2309/2021	0	6.7	19.3	SW	0	4.1	16.1	SW
2409/2021	3.4	4.8	19.9	SW	6	3.1	15.1	SW
2509/2021	6.8	6	19.6	SW	4.8	4.2	14.2	SW
2609/2021	0	4	10.7	NE	0	3.5	10.8	NE
2709/2021	0	4	11.9	NE	0	3.6	12.3	NE
2809/2021	0	3.8	10.8	NE	0	3.1	9.6	NE
2909/2021	0	4	20	NE	0	3.2	15	NE
3009/2021	1.8	7.1	21.5	SW	2.2	3.9	17.4	SW

Table 4
Outputs of modelling, using different variables to explore effects on total litter. AIC (Akaike Information Criterion) estimates error in the fit of the model. A further column gives the change in AIC relative to model 1.

Model	Explanatory variables in model	AIC	Model term being evaluated	Reduction in AIC (reference model in brackets)
1	Windspeed+ Wind direction + Day + Beach + Tide + Rainfall + Area	477.0		
2	Windspeed+ Day + Beach + Tide + Rainfall + Area	475.6	Wind direction	+1.4 (1)
3	Day + Beach + Tide + Rainfall + Area	474.2	Windspeed	+1.4 (2)
4	Day + Beach + Tide + Area	475.7	Rainfall	−1.5 (3)
5	Beach + Tide + Area + Rainfall	472.3	Day	+3.4 (4)
6	Beach + Tide + Rainfall	481.7	Area	−9.4 (5)
7	Tide + Area + Rainfall	478.4	Beach	−6.1 (5)
8	Beach + Area + Rainfall	486.7	Tide	−14.4 (5)
9	Beach + Tide + Area + Rainfall + Beach.Tide	461.7	Beach.Tide	−10.6 (5)
10	Beach + Tide + Area + Rainfall + Beach.Tide + Area.Tide	458.8	Area.Tide	−2.9 (9)
11	Beach + Tide + Area + Beach.Tide + Area.Tide + Area. Beach	460.5	Area. Beach	+1.7 (10)

at Amanzimtoti are virtually identical above and below the tide line.

4. Discussion

Accumulation studies provide a useful indication of the daily load arriving at a particular location (Smith and Markic, 2013; Kershaw et al. 2019; Ryan et al., 2020a). Higher litter loads were consistently recorded above the high tide line during this study, with our model showing area of beach surveyed was an important factor to explain litter loads. This has several possible explanations. The first possibility is that most of the litter in this area originates from beach users. The study recorded a large number of litter item types that may have originated directly from beach users, such as sweet wrappers and cigarette butts, especially between the high tide line and the back of the beach. Future awareness campaigns could target the common items found on each beach to enlighten beach users to minimise these effects (Silva et al., 2016; Wilson and Verlis, 2017; Araújo et al., 2018). The correlation between the accumulation patterns of the two sites is stronger for the area from the high tide line to water, suggesting that the area between the high tide line and the back of the beach is influenced by factors that are site-specific. One factor is human interactions such as beach users dropping and/or removing litter items; however, no data on human presence were collected as part of this study. The recent South African marine litter monitoring guide (Barnardo and Ribbink, 2020), as well as Ryan et al. (2020a), suggest asking the public to stay out of the monitoring area. Our results confirm this to be an important aspect for future studies, although compliance is difficult to monitor or enforce. The second hypothesis to explain greater differences between the two sites above the high tide line is that the litter washed ashore is transported above the high tide line by the wind. This possibility in our study is evidenced by the differences between heavy and light items, and the pattern in which they accumulated between the two beaches. In an attempt to understand the natural movement of marine litter using the model, no effort was made to clean items of sand or natural material before weighing consequently some items recorded as heavy might be much lighter in their original state, but not in the environment where they have been deposited at the time of collection. Examples include plastic bags and bottles, which are originally very light and will be easily affected by wind and waves. Once these items are partially buried in the sand, especially if they are also wet, their turnover rate is likely to be affected. Dense litter items are underrepresented on South African beaches due to their properties and are likely to deposit elsewhere, for instance on the seafloor (Ryan, 2020). A further explanation to why more litter items were consistently found above the high tide line, is that a large amount of litter is present buried in this area and footfall caused by beach goers, or sand movement by wind caused this litter to become exposed throughout the study. While this is possible, observations during the survey period did not record either significant footfall or high wind speeds to deem this option likely.

Variables such as wind speed and direction, temperature and rainfall, help to understand environmental effects on litter loads (Eriksen et al., 2014). Consideration of wind direction is particularly important during a daily accumulation study as wind stress and the resulting localised wave heights and patterns can affect litter pathways. Wind direction was averaged for inclusion in the model where a single value was required for each day, which might have overlooked some fine scale changes in direction during the study. Despite variations in windspeed between sites, no effect was seen by the windspeed variable in the model on litter loads. The length of this study makes picking up meteorological effects of litter deposition difficult to detect as periods of sustained winds, rather than day-to-day fluctuations, are important in litter accumulation (Schumann et al., 2019). Detecting correlations in litter loads during an interval with mixed wind directions (e.g. both offshore and onshore) was not found to be possible in previous studies (Turrel, 2018). There were low precipitation amounts seen during the peaks of litter (22nd, 24th, 25th and 30th) of the daily accumulation day study (Fig. 1). The statistical modelling carried out found rainfall to be an explanatory variable to explain litter loads, however rainfall was light during this study with minimal effect was seen on the beaches, unlike the episodic flooding experienced in summer months in KwaZulu-Natal, resulting in large volumes of litter on beaches (Naidoo and Glassom, 2019b).

Plastic was the dominant litter type collected in this study and is consistent with other studies in South Africa (Ryan et al., 2018; Chitaka and von Blottnitz, 2019) as well as globally (Coe and Rogers, 1997; Wilson et al., 2015). The large quantity of small plastic items (0–2.5 cm) found in this study poses a particular threat to the environment. Their removal is more challenging than that of larger items as their size makes them more likely to get buried in the sand (Turra et al., 2014). Their sizes also make estimating changes in abundance more difficult as they are likely to be missed in surveys (Ryan et al., 2009). The sources of these large quantities of small plastics is not easy to determine, although distinctions between litter categories in the two beaches in this study suggest different drivers of small plastic items. Examples of this include the large amounts of laminate flooring fragments found at Amanzimtoti suggests illegal dumping of construction waste nearby and the greater amount of cotton buds at Umhlanga could suggest insufficient local water treatment.

This study recorded higher accumulations of litter at Amanzimtoti beach than at uMhlanga beach, with our model results showing beach surveyed had an important effect on litter load. This finding aligns with the classification by Forbes and Demetriades (2008), where the Amanzimtoti and eziMbokodweni estuaries that surround Amanzimtoti beach were both classified as being at high risk of litter, whereas the same assessment classified the Ohlanga estuary, adjacent to uMhlanga beach as 'low' risk of litter. Although oceanic sources of litter that have travelled great distances do form part of the litter loads of beaches, the Agulhas Current known to carry plastics towards the Western Cape (Ryan, 1987; Schumann et al., 2019), runs offshore by Durban (Guastella and Roberts, 2016) and it is likely that these loads are secondary to the loads originating from the KwaZulu-Natal coastline through riverine inputs and direct beach littering (Ryan et al., 2009, 2018; Naidoo et al., 2015). Near-shore water movement off the KwaZulu-Natal coastline varies with a northward easterly current to the north of the port of Durban (Guastella and Roberts, 2016), and predominantly southerly off Amanzimtoti (Naidoo and Glassom, 2019b), meaning that any effects from the Port of Durban is likely to be complex and difficult to draw any conclusions on effects on litter loads.

Though Ryan et al. (2021), shows that foreign bottles contribute to marine litter found on South African shores through both illegal dumping from ships, as well as, long-distance drift from southeast Asia. The primary source of marine litter near South African urban areas has been identified as nearby urban centres (Naidoo et al., 2015; Ryan et al., 2018) so it is important to examine information about the study site's locality. Census records show that the population densities at uMhlanga (1447 people/km^2) and Amanzimtoti (1503 people/km^2) (STATS SA, 2011) are similar, with uMhlanga having a higher overall total population (13 813 and 24 238 for Amanzimtoti and uMhlanga respectively), suggesting that higher litter loads at Amanzimtoti are not due to greater influence from higher population numbers. Other factors that could influence land driven litter loads between sites, but that are not fully explored in this study are proximity to industrial sites, as well as proportion of the population living in informal settlements with insufficient waste collection and water treatment facilities. It is acknowledged that insufficient service delivery to informal settlements is a source of marine litter (Verster and Bouwman, 2020) and some evidence from this study might relate to the socio-economic position of nearby communities. uMhlanga has items such as cotton bud sticks, commonly found items more utilised by more communities of a more affluent group, whereas these items are either absent or found less frequently at Amanzimtoti.

Limitations of this study design must be noted, including the short timespan between the two 'standing stock' surveys. The fact that the period between surveys differed between sites must also be noted. Despite this, the consistent result of higher loads experienced at Amanzimtoti still allows us to draw conclusions. Another major limitation that must be noted that the scales available for part of the study did not provide readings below 5 g, although this was rectified for the accumulation surveys. This means that the analysis of standing stock focuses mostly on litter items, rather than weight. As this study used the OSPAR methodology to categorise the litter collection, there was no quantification of meso-litter. Future studies need to be aware of the importance of excluding the meso litter during collection, rather following protocols such as those set out in Barnardo and Ribbink (2020), and may need to consider additional methodologies to monitor the smaller size fractions (mesolitter), such as using quadrats.

Our methodology used average (WU) weights of litter items, which allows consideration of factors in the natural environment but does mean that weights presented here may be heavier than some studies. Under our methodology, all items that fit into the top 10 items are classified as "light" in weight (S1, Table S1), but have approximate densities both above and below the density of seawater (1.02 g/cm^3) (S1, Table S1). Looking at the approximate averaged densities in relation to seawater (S1, Table S1), the weight classification of "heavy" categories makes up a greater share of the items denser than seawater (33% for >seawater density with 24% <seawater density) (S1, Table S2). However, when density is considered, some "heavy" litter items would have the same characterisation as those classified as "light" (such as Plastic Food containers [0.015 g/cm^3] or ice cream packer [0.905 g/cm^3] that have similar densities to "light" items), as well as items that would have dried to a lighter weight (e.g., cardboard [0.69 g/cm^3]). With these reclassifications taken into account, the share of "heavy" items are changed substantially, especially in items with a density lower than seawater, adjusting to 27% for >seawater density and 9% for <seawater density (S1, Table S3). Using this approach, we found that 11% of our categories would shift (marked in SI Table S1). These categories do not make up the top 10 litter categories found on either beach so, the model is run with the original weights rather than a theoretical changed weight based on density. Therefore, the results in the model are accurate to wet and dirty items, but not for dry nor clean items. If items are dried and cleaned, the authors note that density does not need to be considered and we recommend cleaning of items before weighing for all future surveys (Ryan et al., 2020a).

Conclusion

Standing stock and daily accumulation studies provide a method to assess litter inputs into beaches. However, they still provide only a small snapshot of the situation and do not account for seasonal variations. Higher litter loads by number of items and mass were recorded consistently at one site, where issues such as waste from industry and informal settlements with insufficient waste collection and water treatment systems may be a contributing factor. The accumulation rates recorded in this study are consistent with those previously reported for other areas such as Cape Town (Chitaka and von Blottnitz, 2019). Future studies looking at accumulation in the area surrounding the Port of Durban should consider trying to capture seasonal variation. The heterogeneous qualities of marine litter loads make it difficult to detect trends (Schultz et al., 2013), however longer-term studies would better explore the effects of meteorological and hydrological patterns on litter accumulation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research presented in this paper was funded through the Commonwealth Litter Programme (CLiP) in collaboration with the University of KwaZulu-Natal. The Commonwealth Litter Programme (CLiP) was funded by the UK Government's Official Development Assistance (ODA) with research permit RES2019/100. The authors gratefully acknowledge the contributions of Kellie-Kirsty Hennessy who helped with fieldwork sampling at Amanzimtoti beach and Clement Garcia who helped with the production of the figures.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2022.102421.

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