UNDERSTANDING THE ROLE OF RIP CURRENTS ON SOLID WASTE SETTLEMENT ON AN URBAN BEACH

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Resumo
Este estudo teve como objetivo determinar a influência de correntes de retorno fixas na contaminação de praias urbanas por resíduos sólidos. Quatro áreas ao longo da praia de Boa Viagem (Recife-PE) foram selecionadas com base na presença ou ausência de correntes de retorno. Adotou-se o critério de identificação de resíduos com tamanho superior a 3cm, independentemente da composição. O mecanismo de circulação costeira na Praia de Boa Viagem influenciou fortemente o padrão de distribuição de resíduos sólidos na área de estudo. Maiores quantidades de resíduos foram observadas ao norte das correntes de retorno. Os resultados indicam que as correntes longitudinais, juntamente com a intensidade e a direção do vento, influenciam fortemente os padrões de deposição de resíduos sólidos na Praia de Boa Viagem.

Palavras-Chave: correntes de retorno; resíduos plásticos; lixo marinho; dinâmica costeira.

Abstract
This study aims to determine the influence of fixed rip currents on the contamination of urban beaches with solid waste. Four areas along the Boa Viagem beach (Recife-PE) were selected based on the presence or absence of rip currents. A criterion for identifying waste larger than 3cm, regardless of composition, was adopted. The nearshore circulation mechanism at Boa Viagem Beach strongly influenced the pattern of solid waste distribution in the study area. Higher amounts of waste were observed north of the rip currents. The results indicate that longitudinal currents, together with wind strength and direction, strongly influence the solid waste deposition patterns on Boa Viagem Beach.

Keywords: rip currents; plastic waste; marine debris; coastal dynamics.

Introduction

The accumulation of solid waste on beaches has been reported in the literature since the 1980s, along with the origins, causes, and consequences of this contamination (Neves et al., 2011). With advances in research, it is now known that complex mechanisms of surface currents and winds are responsible for the distribution of this waste, resulting in accumulation zones in the open ocean and coastal areas. It is estimated that more than 250,000 tons of solid waste (marine debris) float on the surface of oceans, most of which is plastic waste easily distributed along coastal areas (Eriksen et al., 2014).

Within the circulation pattern, nearshore currents, represented by longitudinal and rip currents, play a leading role in water and material exchange, such as transporting sediments and marine debris along the areas over which they act (Gallop et al., 2018). Rip currents (often called "rips" or "rip tides") are strong narrow ocean currents driven by shore variations in the reef zone (Houser et al., 2017).

At Boa Viagem Beach on the south coast of Pernambuco, rip currents are formed by waves and depressions at the bottom (Maia et al., 2014). They are responsible for nearshore circulation close to the beach (Albuquerque et al., 2010). Thirteen rip currents have been identified at Boa Viagem Beach, with nine fixed and four mobile currents formed due to local morphodynamics (Maia et al., 2014). Although the spatiotemporal distribution pattern of solid waste on Boa Viagem beach is well-studied (Souza; Costa, 2004; Silva, 2006, 2008; Soares et al., 2007; Dias Filho et al., 2011; Silva-Cavalcanti et al., 2009, 2013; Araújo, 2018), there are no works that correlate the process of influence of the nearshore circulation mechanism, in particular, the rip currents on the solid waste contamination.

Some studies have suggested that the amount of solid waste deposited on beaches may be influenced by rip current activity (Santana Neto et al., 2014; Kataoka et al., 2013), which is a determinant for estimating the residence time of this waste in the water (Kataoka et al., 2015). Understanding how the circulation pattern of nearshore currents influences the solid waste accumulation pattern at Boa Viagem Beach is of fundamental importance for mapping the hotspots of this deposition. This study aimed to determine the influence of rip currents on the contamination of Boa Viagem Beach by solid waste.

MATERIALS AND METHODS

Study area

Boa Viagem Beach is an urban sandy beach (Ferreira et al., 2010), and is considered the oceanfront of Recife (Pernambuco, Brazil). It is located between latitudes 8°05'02''S and 8°08'06''S, with a length of 8 km, being the only marine environment immediately available to its inhabitants (Silva et al., 2006). This area constitutes a sedimentary environment of moderate energy, predominately fine sand (Gregório et al., 2004). The tides recorded in the Recife (PE) metropolitan region are semi-diurnal and classified as mesotidal in amplitude (Brazil, 2018).

Four beach areas were selected (Figure 1; Table 1). The areas were divided according to the morphodynamic characteristics reflected in the available sand strip and used by beachgoers (Gregório et al., 2004; Silva-Cavalcanti et al., 2009).

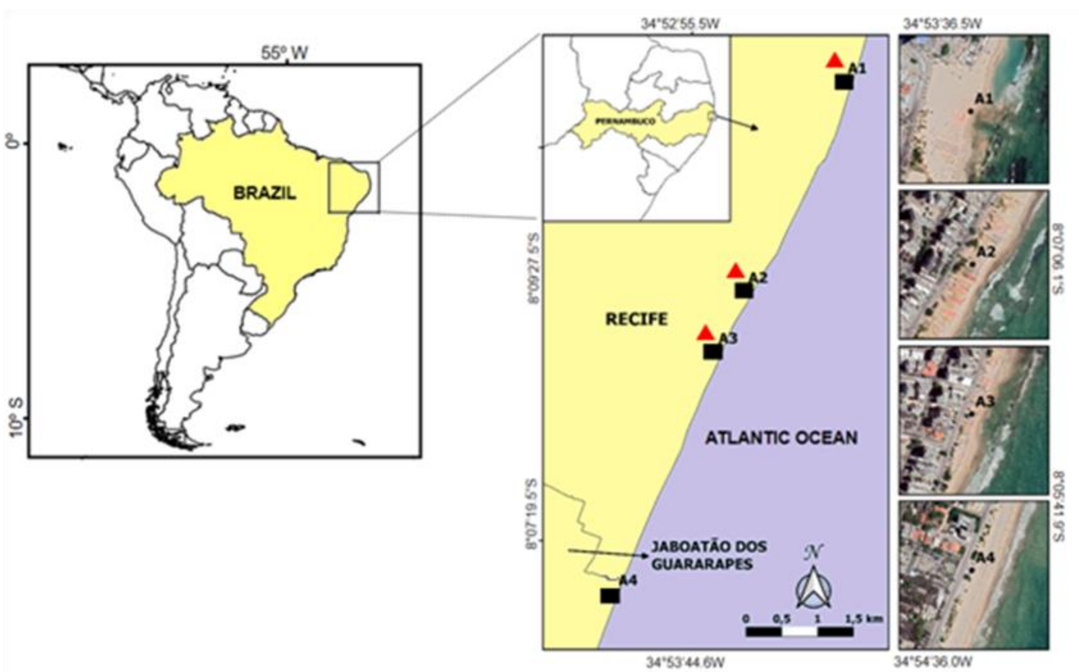

Figure 1 - Location of the study area (Boa Viagem beach) with the four delimited areas (A1, A2, A3 and A4; indicated by black rectangles) that were used to carry out the experiment. In the figure, the presence of rip currents is indicated by red triangles.

Table 1. Hydrodynamic characterization and occurrence of rip currents along the four parts of Boa Viagem beach.

Beach Area	Characteristics
A1	Presence of a fixed rip current, formed by the morphology of the reef structure. Sheltered beach. Net surface transport toward the north.
A2	Presence of fixed rip current. Open and dissipative beach. Net surface transport toward the south.
A3	Presence of a fixed rip current, formed by the morphology of the reef structure. Semi-sheltered beach. Net surface transport toward the north.
A4	Absence of rip current. Open beach. Net surface transport toward the north.

Source: Rollnic (2008); Maia et al. (2014) and Silva-Cavalcanti et al (2018).

Solid Waste Assessment

Transects were conducted on four parts of the beach 1x/month over an uninterrupted collection year (August 2020 to July 2021). The sampling period was divided into four seasons according to the historical average rainfall (Barletta et al. 2006): early dry period (September, October, and November), late dry period (December, January, and February), early rainy period (March, April, and May), and late rainy period (June, July, and August). Sampling was carried out during low tide in all periods owing to the smaller influence of the tide on the deposition of particulates at the study site.

In areas with rip currents (Areas 1, 2, and 3), the strandline was initially identified (considering a width of approximately 1m). Subsequently, the central part of the rips was marked with a flag. Twenty points were demarcated along 400 m of the rip current occurrence. Ten points were demarcated to the right and ten to the left of the central point of rip current occurrence (Figure 2). Other flags with colours different from those in the central part were used.

The interval between the flags was 20 m, totalling 400 m² in each area. In Area 4, which had no return current, a reference point was selected to be flagged, and then the twenty points on the sides were marked.

The total area sampled from the four areas (1,600 m^2) corresponded to 20 % of the entire beach length.

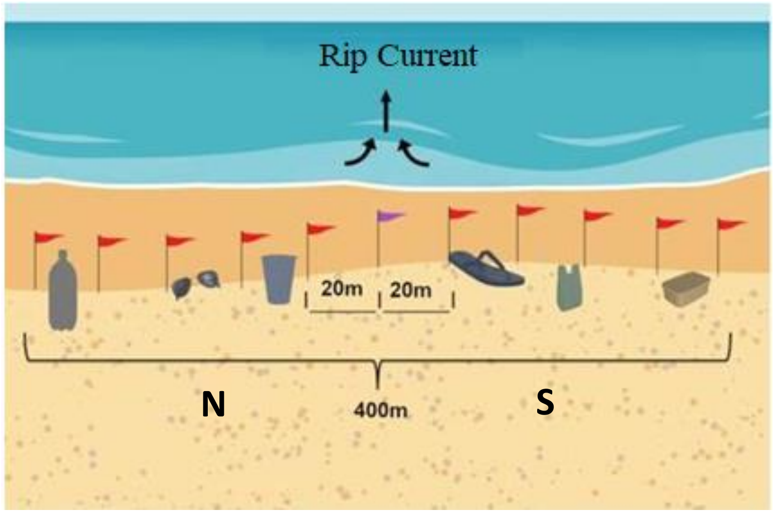

Figure 2 - Sampling scheme on the strandline

Each area was sampled once a month at low tide. All objects easily visible at the strandline (>3 cm) considering approximately 1m width (50 cm each side from the strandline) were counted, classified and registered. The sampling was performed in the morning, before the public cleaning service, which happens twice daily (Silva-Cavalcanti et al., 2009). All counted waste was categorised within one of the following categories: cigarette butts, plastic, paper, glass, wood, organic matter, steel, and aluminium (Araújo et al., 2018).

Three people were selected for all data collection in the field; these people underwent training to standardise the data sampling criteria (Figure 3). A correction factor based on the standard deviation among samplers was applied.

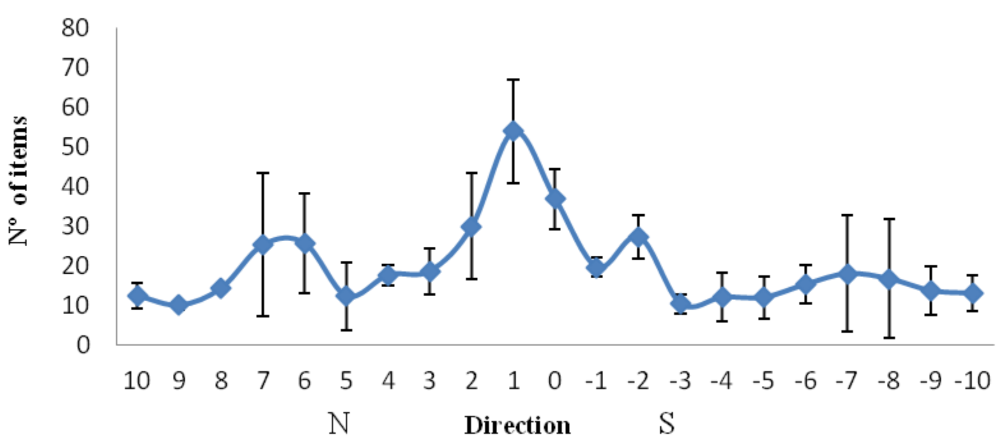

Figure 3 - Average solid waste counted by the three samplers over the course of the pilot sampling to serve as a calibration between the samplers and to determine the error.

Wind analysis

To analyse the role of wind in the transport of floating material and establish possible interactions with rip currents, the oceanic wind was studied along the same periods of samples. The wind data were extracted from a single point on an ERA5 reanalysis grid (Hersbach et al., 2020). This was the nearest point to the study area (8.2°S, 34.9°W) and was used in our analysis without interpolation. These data are part of the atmospheric hourly database on single levels from 1940 to the present and were freely obtained from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form.

For each beach sampling date, five days of hourly wind data were used (two days before, on the sampling day, and two days after). Three sample periods (15d) were used to present the seasonal evaluation, with the sampling day centred on the new moon of each month.

RESULTS

- Descriptive Analysis

Through quantifying the results, a decrease in the deposition of waste on a temporal scale occurred in both stretches (Figure 4). Area 1 had the highest amount of solid waste in all seasons, followed by Areas 2, 3 and 4, respectively. Collection in the early stage of the dry season presented the highest amount of waste (19,504), followed by the late dry season (10,866), early rainy season (5,530), and late rainy season (5,155).

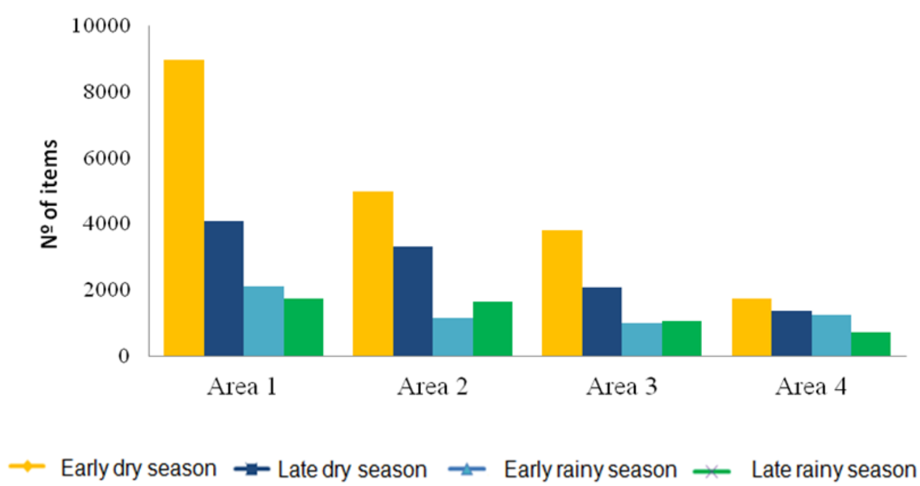

Figure 4 - Total amount of solid waste throughout the four areas during the four sampling periods, which were: early dry season (September, October and November), late dry season (December, January and February), early rainy season (March, April and May) and late rainy season (June, July and August).

To analyse the influence of the rip currents on solid waste deposition along the beach, the number of items per m² was quantified in all sampled areas (Table 2). During the early and late dry season, all areas with rip currents (Areas 1, 2, and 3) presented more solid waste than the control area (area 4). Only Area 1 showed a comparatively higher amount of items during the early rainy season, while the others (Areas 2 and 3) were quite homogeneous in relation to the control area (Area 4). During the late rainy season, all four areas showed similarly low amounts of items, especially the control area (Area 4).

Table 2 - Amount of solid waste per m² in the sampled areas over different rainfall periods.

	Number of solid waste /m²			
	Early dry season	Late dry season	Early rainy season	Late rainy season
Area 1	90	41	22	18
Area 2	50	34	12	17
Area 3	38	21	10	11
Area 4	17	14	13	8
Total	195	110	56	54

It was observed that there is a very similar deposition of solid waste on the strandline in the three areas subjected to the action of the rip currents. Areas 1 and 3 presented the highest amounts of waste deposited in the transects in the northern direction of the current. Area 2, as shown in the graph, presented the largest quantities of solid waste in the transects located south of the return current. The control area presented a greater deposition of waste to the north (Figure 5).

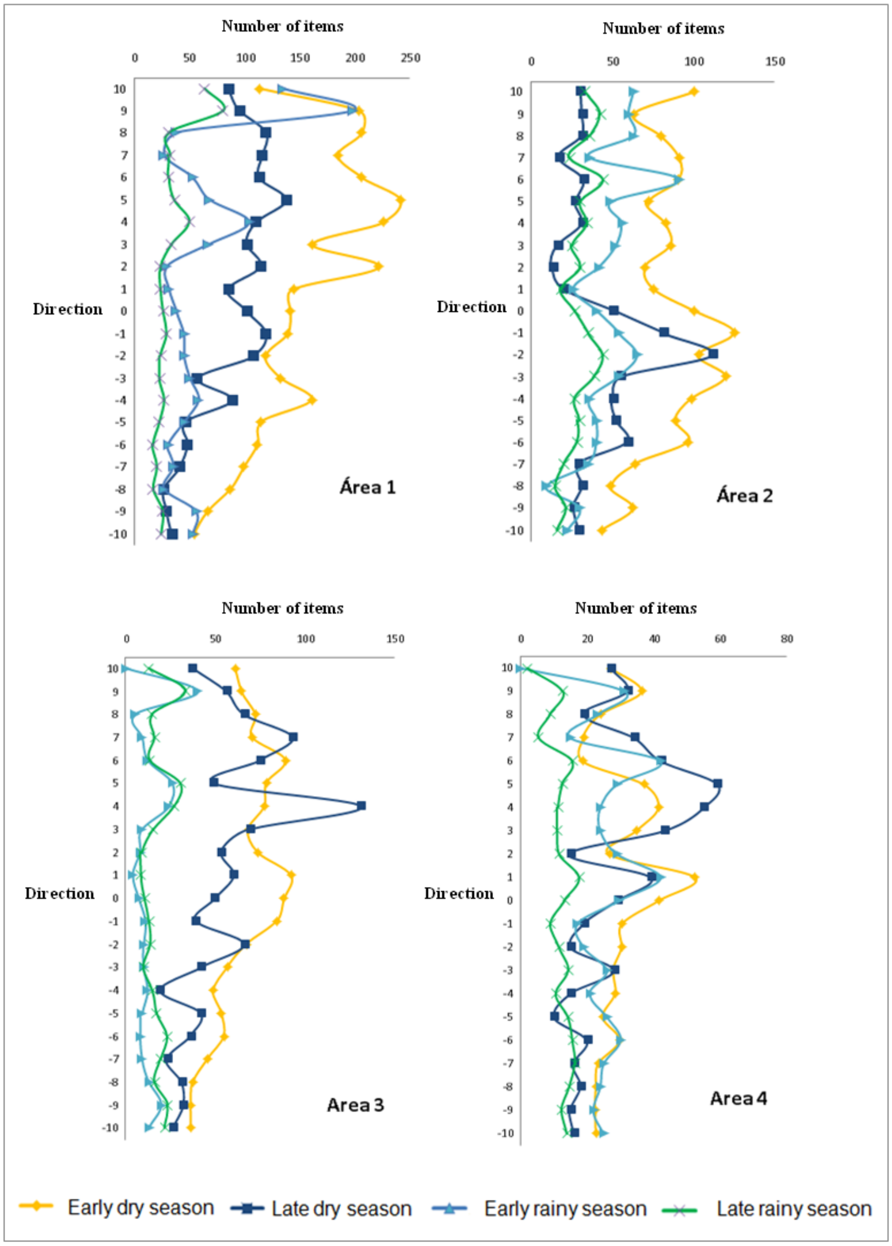

Figure 5 - Dispersion of solid waste on the strandline during the four sampled periods, which were: early of the dry season (September, October and November), late of the dry season (December, January and February), early of the rainy season (March, April and May) and late of the rainy season (June, July and August).

Considering the total amount of solid waste, the plastics category had the highest abundance in both areas throughout the sample periods, followed by cigarette butts. The other categories showed less relevance, such as wood, organic, paper and steel (Figure 6).

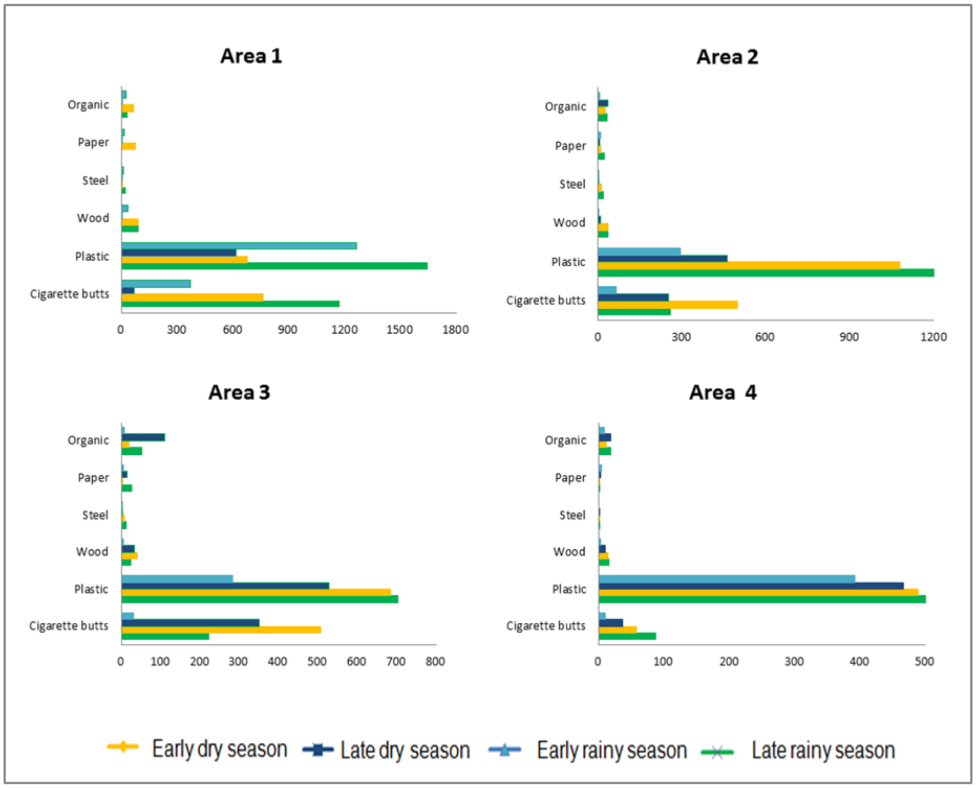

Figure 6 - Amount of solid waste by category during the four sampling periods, which were: early of the dry season (September, October and November), late of the dry season (December, January and February), early of the rainy season (March, April and May) and late of the rainy season (June, July and August).

Within the category of plastics, some items appeared more frequently than others. The same pattern was observed in the four areas, where the most representative item is the fragments, followed by cellophane, bags, straws, and lids, throughout the four seasons (early dry season, late dry season, early rainy season and late rainy season) (Figure 7).

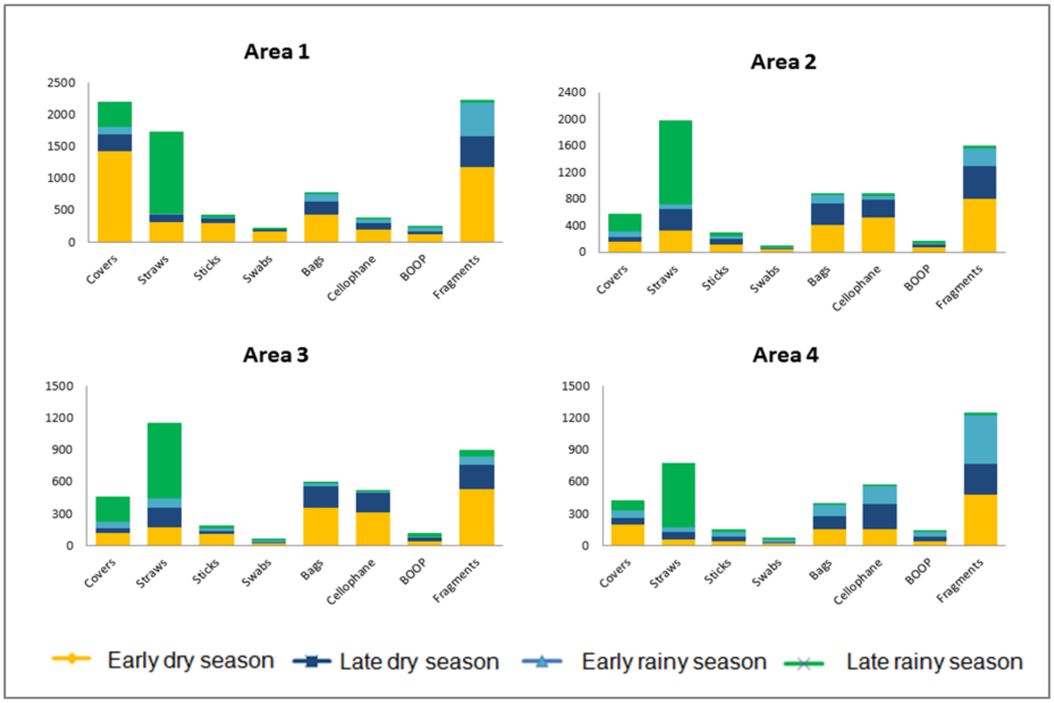

Figure 7 - Variations within the plastic category during the four sampled periods, which were: early of the dry season (September, October and November), late of the dry season (December, January and February), early of the rainy season (March, April and May) and late of the rainy season (June, July and August).

Statistical analyses

When we performed an Analysis of Variance (ANOVA), the factors showed significant differences ($p<0.001$). The factor that contributed the most to significant differences in the data was the amount of waste in each sampled area. The area presented significant differences ($p<0.003$ and $F=4.59$), as did the transects ($p<0.001$ and $F=77.19$). Analysis of the junction of the area and transects also showed a significant difference ($p<0.001$, $F=14.72$) (Table 3).

Table 3: Summary of Analysis of variance (ANOVA) with the four areas and the north and south transects during the sampling periods, being: A1 (Area 1), A2 (Area 2), A3 (Area 3) and A4 (Area 4). F (f value), Df (degree of freedom), P (p value), * (when significant) and NS (not significant) were presented.

Variables	F	Df	P (value)	Post hoc
Intercept	42.76	1	<0.001	NS
Area X Solid waste quantity	4.594	3	<0.003	* A1 A2 A3 A4
Transect X Solid waste quantity	77.19	7	<0.001	* North South
Area X Transect X Solid waste quantity	14.72	21	<0.001	NS

Significant differences can be confirmed using the *post hoc* test. All areas showed significant differences (p<0.001). When analysed in pairs, Area 1 differs significantly from Areas 2, 3 and 4 (p<0.001). Area 2 differed significantly from Area 3 and Area 4 (p<0.001). Area 3 differed significantly from Area 4 (p<0.01).

Comparisons were made between the northern (N) and southern (S) transects during the four sampling seasons: early dry (ED), late dry (LD), early rainy (ER), and late rainy (LR) (Figure 8).

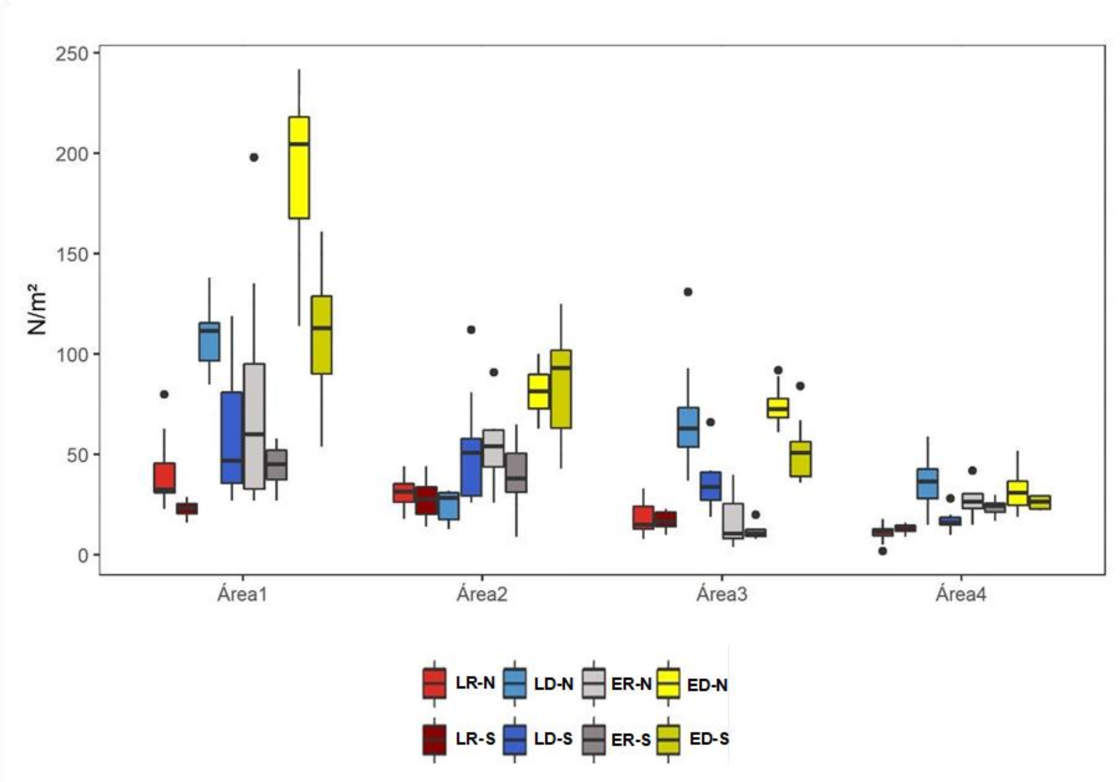

Figure 8: Boxplot of the dispersion of solid waste on the strandline within the transects (N: northern and S: southern) during four sampling seasons: early dry (ED); late dry (LD), early rainy (ER); late rainy (LR)

Considering the predominance of objects in the samples (straws and fragments – Figure 7) and their composition (plastic - Figure 6), an analysis of the wind as physical forcing is presented in Figure 9 to extend the analysis to one of the main factors that control the drift of surface floating materials. Winds during the dry season were predominantly from the southeast (Figure 9). During the early dry season (BDS), the most frequent winds were also the strongest (reaching $7m.s^{-1}$), with the east component acting significantly. At the late of the dry season (EDS), the east components were less active, and the maximum wind reached $6m.s^{-1}$ from the SE direction. In both seasons, a northeast component wind acted with low frequency at intensities between 2–$4m.s^{-1}$(Figure 9 upper panels). In the rainy season (Figure 9 lower panels), the winds were also predominantly from the southeast. At the early of the rainy season (BRS), the maximum winds reached $7m.s^{-1}$; at the late of the rainy season (ERS), they reached a maximum of ~$6m.s^{-1}$. A clear transition of predominance of winds with east components to south components can be observed between the dry and rainy seasons.

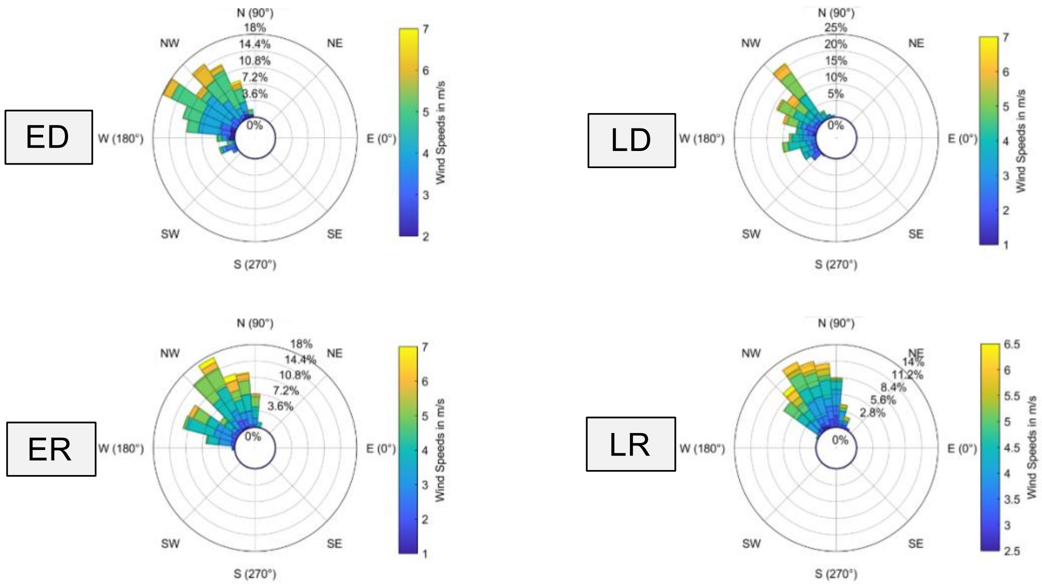

Figure 9. Wind speed (colors) and direction during sample seasons: early dry (ED); late dry (LD), early rainy (ER); late rainy (LR)

DISCUSSION

The nearshore circulation mechanism at Boa Viagem Beach strongly influenced the pattern of solid waste distribution in the study area. The distinct morphology along its eight kilometres, with the presence of reefs, the Jaboatão River plume, and longitudinal currents, which favour the formation of rip currents, were determinants of this deposition. The morphology of the coastline and its interaction with hydrodynamics affect the transport of solid waste (Kataoka et al., 2015; Kataoka et al., 2018; Van Sebille et al., 2020) and which can be perceived at Boa Viagem Beach.

Owing to the predominance of southeasterly winds, the plume is displaced from the Jaboatão River estuary to the north of Boa Viagem Beach (Rollnic, 2008). This displacement borders the reefs along their protected stretches. This influence was indicated by the higher amount of waste in the northern part of the area. Only at point A2, a pattern contrary to that found in other areas was observed. This is justified because in this stretch of beach, the local circulation mechanism (Kataoka et al., 2015), a semi-sheltered beach, favours net transport to the south of the area.

The pattern of deposition of solid waste north of the rip currents may also be related to net surface transport toward the north, which occurs during the summer and winter months (Rollnic; Medeiros, 2006). Northward currents are predominant during ebb tides, indicating that wind forcing prevails over astronomical forcing (Rollnic, 2011). Rip currents are stronger at low tide than at high tide (Brander; Short, 2001; Macmahan et al., 2005; Aagaard; Vinther, 2008; Scott et al., 2008; Bruneau et al., 2009; Castelle et al., 2009; Leatherman; Fletemeyer, 2011; Austin et al.,2014; Scott et al., 2014). The northern part of Boa Viagem Beach (A1) has an expressive reef bank that contributes to two fixed rip currents in its depressions (Maia et al., 2014), intensifying their activities in the area. In addition, during the dry season, the plume from the Pina Basin reaches Pina and Boa Viagem beaches until the mediation of Area 2 (Rollnic; Medeiros, 2006). This favors a greater accumulation of solid waste in the early dry and late dry seasons in Areas 1 to 3, regardless of the season.

As the period studied used spring tides, it is believed that the action of rip currents in the area was at its maximum, suggesting a strong relationship between the amount of solid waste found on the strandline in areas subject to the action of these fixed return currents. However, it is worth noting that the results suggest that wind direction is the controlling variable of this deposition, as the control area showed results similar to those of Areas 1 and 3.

It is important to keep in mind that rip currents throw water from the surf zone to the inner shelf and form an important channel for the maritime transport of plastic waste from the coast to deep waters (Maia et al., 2014; Van Sebile et al., 2020) and are determinants of shoreline morphology (Serrão, 2019). Within the anatomy of the rip current itself, it is worth noting that surf zone circulation systems can retain floating material as their currents move items toward the centre of the vortex (MacMahan et al. 2010, Fujimura et al. 2014). The waste can also be carried behind the sweep zone ("swash zone") and subsequently transported to other locations (Santos et al., 2004). Therefore, the waste's path depends on the return current's intensity, determining whether the waste will be deposited on the beach, carried offshore, or backwashed (Kataoka et al., 2015; Meyerjurgens et al., 2019). Unfortunately, estimating the percentage of items transported offshore was impossible. However, data from the same area suggest that more than 40% of the solid waste in the study area is carried offshore (Araújo et al., 2021).

Rip currents can exhibit different behaviours: longitudinal drift, escape behaviour from the surf zone, predominantly cell circulation behaviour, cell circulation with escape, and return to the beach (Mocellin, 2006; Galvão, 2018). These patterns are determined by the wind direction and wave breaking (Galvão, 2018). The results of this study suggest that the rip currents at Boa Viagem Beach exhibit northward longitudinal drift behaviour due to the wind direction, except at point A2, where the data suggest cell circulation behaviour. However, it is worth pointing out the need for further studies using georeferenced floats so that the patterns of the dynamics and behaviour of the return current for Boa Viagem Beach can be better understood.

Longitudinal variations in bathymetry play key roles in the formation and maintenance of rip currents (Serrão, 2019). The dynamics of tidal currents and seasonal variations reflect the amount and composition of waste deposited on beaches (Neto; Fonseca, 2011). Quantification of the amount of waste per metre ² in all sampled areas showed that the values found during the early (195) and late (110) dry periods were higher than those in the early (56) and late (54) rainy periods. The average rainfall on the sampling days was 8.5 mm, with a peak of 6.7 mm during the dry season and 25 mm during the rainy season. Although waste accumulation is often higher during rainy periods (Moore et al., 2011), the results of this study did not follow this pattern, with the highest values observed during the dry period. Between 1961 and 2016, the average annual rainfall recorded in Recife (PE) was 2292.9 mm, with a standard deviation of 482.5 mm (Wanderley et al., 2017). Thus, it was observed that rainfall during subsequent years, including the collection period (2017 to 2021), was lower (1874.2 mm, with a standard deviation of 413.3 mm) than in previous years, thus influencing the dynamics of liquid transport. Despite the precipitation anomaly, the analysis of the winds during the sample periods revealed that in the dry season, there was a preponderant easterly component that directed the floating materials towards the coastline (westward). During the rainy season, the wind is mainly from the south, contributing to the longitudinal current in a northerly direction. Interestingly, even during the season in which the highest leaching flow provides greater availability of waste, the action of wind, especially on surface-floating waste, proved to be a significant factor for deposition along the strand line.

Plastics stood out among all other solid wastes, presenting the highest representation in both areas throughout the sampling period. Carminatto et al. (2017), Neto et al. (2016), and Sousa et al. (2019), during their work on Brazilian beaches, also verified the presence of plastic as the main category; thus, plastic presents itself as a key waste source. The wide dispersion of this category in all water bodies makes it an important tool for monitoring coastal contamination. Its resistance and durability favour its carriage through marine currents.

Most solid waste drifting in oceans has slow degradation rates and high buoyancy, especially plastics, which are generally less dense than seawater and must float (Geyer et al., 2017). Many plastic items also contain trapped air (e.g., expanded polystyrene, bottles, and buoys), further increasing their buoyancy and aiding their dispersal (Van Sebille et al., 2020).

The information generated in this work can be directed and deepened for coastal management and the systematisation of beach cleaning services. Public managers should closely examine areas subject to the action of these currents, as this study suggests a strong relationship between the amount of solid waste found in areas with protected beaches and the presence of fixed rip currents. However, it is important to emphasise the need for further studies to measure the behavioural pattern of currents in these areas, as wind forcing is a determinant of this distribution.

CONCLUSIONS

A large sampling effort was carried out over a year to investigate the relationship between rip currents and the dynamics of solid waste deposition on Boa Viagem Beach. Monthly sampling was conducted during the period of lower tidal influence to investigate the power of rip currents flowing over waste settlements with the least possible interference from external factors. Spatially, four areas were investigated concerning solid waste deposition on the strandline: three in the presence of fixed rip currents and one in the absence of this process (control area). Four periods that differed in terms of rainfall regimes were compared.

Regarding the depositional pattern of solid waste along the strandline, it was verified that there was a depositional maximum interspersed by a minimum zone (rip-current action zone). The maximum deposition peak was almost always displaced northward following the interaction flow with longitudinal currents. An exception was found in Area 2, where the flow resulting from coastal recirculation was predominantly to the south. Plastic items and cigarette butts were predominant among the deposited materials. Among these materials, fragments and straws were found in greater numbers, and worth mentioning that most materials presented high buoyancy.

The early dry season had the highest deposition number, followed by the late dry, early rainy, and late rainy seasons. This unexpected pattern is mainly attributed to wind direction; the easterly winds had a stronger effect during the early dry season, acting as an amplifier factor for the migration of floating waste toward the coastline.

This study demonstrates that rip currents play an important role in the depositional patterns of solid waste along beaches. It is worth mentioning that even in places with fixed rip currents (this study), the final deposition patterns will always be a composition resulting from the interaction of several factors, such as the interaction with the longitudinal current, strength and direction of the winds, and tidal flows.

This work suggests that future studies with the application of numerical modelling, where coastal circulation can be reproduced at high resolution and with all possible forcings, should be employed to understand the transport of solid waste whenever possible. This is because they can provide relevant information for identifying depositional zones and the retention times of floating objects in coastal zones.

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