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Are mangroves hotspots of marine litter for surrounding beaches? Hydrodynamic modeling and quali-quantitative analyses of waste in southeastern Brazil

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ABSTRACT

The present study investigated the hypothesis that the marine litter found on the beaches of Santos, in Brazil, may have originated from the mangrove located in the adjacent estuary, acting as a hotspot. To this end, we performed quali-quantitative analyses of the waste found in the beach environments (beached and discarded litter) and the mangrove, as well as hydrodynamic modeling, to verify the influence of the tides on waste transport and the level of contamination according to the Clean Coast Index (CCI). The beached waste presented a similar composition to the items found in the mangrove, corroborated by multivariate analyses and Spearman's correlation. The hydrodynamic conditions revealed that tidal currents transport waste from the interior of the mangrove to the beaches through the Santos Channel, therefore indicating that the mangrove itself acts as a marine litter hotspot. This problem needs to be managed on a macro-scale by public management agencies, not just locally.

1. Introduction

Marine litter, a problem that has persisted for decades, has been the subject of several international studies, which focus on the global concern and the impacts caused on all sectors of society (UNEP, 2005). Marine litter encompasses all solid waste, manufactured or processed, disposed of in the environment that is found floating, submerged, or deposited in rivers, estuaries, and the coastal and oceanic regions (Cheshire et al., 2009) of densely populated (Pham et al., 2014) and remote areas (Ivar do Sul et al., 2009).

In aquatic environments, the presence of litter can cause esthetic damage, issues concerning public health and food safety, changes to natural habitats, entanglement and death of organisms, invasion of exotic species, and ghost fishing (PEMALM, 2021), in addition to the potential sorption of chemical contaminants, which may leach into the environment (Bridson et al., 2021; Chevalier et al., 2018; Lee et al., 2014; Novotny and Slaughter, 2014).

Estimates show that land-based sources are responsible for 80% of the input of marine litter (Jambeck et al., 2015), which originates from diffuse activities, such as recreation on beaches and coastal regions, waste discarded in urban areas, as well as industrial and port areas, irregular disposals, such as landfills and dumps, and introduction by accidental loss and extreme events (Galgani et al., 2015). Being products of inefficient solid waste management (Cheshire et al., 2009; UNEP, 2005), these residues can be transported to the sea by rivers and other industrial discharges and urban run-offs; the winds and other oceanographic and meteorological events can also influence such transport (Krelling and Turra, 2019; Rech et al., 2014; Sadri and Thompson, 2014).

Rivers and estuaries are the primary routes for the input of litter in the oceans. Studies involving these environments have increasingly explored the dynamics of waste transport (Lebreton et al., 2017; Mazarrasa et al., 2019; Tramoy et al., 2020). Estuaries, where mangroves are located, are situated at the land-ocean interface and are specific hydrosystems characterized by alternating flow patterns, presenting a mixture of fresh and saltwater that are subject to tidal dynamics (Perillo, 1995; Vermeiren

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et al., 2016). Furthermore, river discharges, winds, and interactions with bathymetry and morphology can influence the transport, deposit, and remobilization of solid waste (Browne et al., 2010; Fernandino et al., 2016; Krelling and Turra, 2019; Tramoy et al., 2020).

In light of these environmental conditions, estuaries are considered important sources (Mazarrasa et al., 2019), accumulation regions (Núñez et al., 2019), and sinks for marine litter in coastal areas (Tramoy et al., 2020; Vermeiren et al., 2016), retaining waste in the mangrove vegetation for months, years, or even decades (Gonçalves et al., 2020; Ivar Do Sul and Costa, 2014; Tramoy et al., 2020). In addition, estuaries often present population densifications and industrial and port activities that make these regions significant from an economic point of view; however, they are also environmentally vulnerable (Browne et al., 2010; Turra Alexander et al., 2014; Haddout et al., 2021; Mazarrasa et al., 2019). All of these associated environmental and anthropic factors make estuaries one of the most threatened environments by solid waste, which can have regional, social, and economic consequences in the short, medium, and long term (Mazarrasa et al., 2019). Their cleanliness, therefore, ensures the integrity of the river-estuary-ocean-beaches gradient and coastal preservation (Ivar Do Sul and Costa, 2014).

The contribution of river and estuarine discharges to marine litter contamination on beaches has been reported by several authors (Araújo and Costa, 2019; Ivar Do Sul and Costa, 2014; Haddout et al., 2021; Mugilarasan et al., 2021; Ryan and Perold, 2021). However, there is a lack of studies that relate hydrodynamic modeling and relative quali-quantitative analyses of solid waste origins and deposition sites on sandy beaches, a fact that highlights the complexity of litter transport in coastal areas and a scientific gap to be filled (Ryan and Perold, 2021).

In Brazil, particularly in the state of São Paulo (SP), studies assessing the presence and distribution of solid waste have been carried out on the beaches of the municipality of Santos (Barrella et al., 2021; Ribeiro et al., 2021) and in the Santos-São Vicente Estuarine System – SESS (Cordeiro and Costa, 2010; Fernandino et al., 2016). Nevertheless, none of them show the local contribution of waste discarded inside the estuary to the contamination of adjacent beaches, such as those located in Santos, only assumptions of the waste's allochthonous origin (Ribeiro et al., 2021) and the abundance of items transported by ebb tides from the estuary to the bay (Fernandino et al., 2016).

Therefore, we considered the hypothesis that part of the marine litter found on the Santos beaches comes from the mangrove located in the adjacent estuary. In this context, the objectives of the present study were to: (1) Determine the state of cleanliness of the mangrove and beaches based on a methodological indicator; (2) Quali-quantify the waste from these environments and, in the case of the beaches, distinguish between "Discarded" (out of reach from the tides, litter from local recreational activities) and "Beached" (deposited by the tides at different distances from the mouth of the estuary); and (3) Analyze the hydrodynamics of the system (estuary-beaches) under the hydrological conditions of different tides in order to relate the "Beached" waste found on the beaches with their supposed origin in the adjacent mangrove area.

2. Material and methods

2.1. Citizen science

In the fight against marine litter, non-governmental organizations (NGOs) play a crucial role in mobilizing campaigns aimed at civil society to combat and reduce waste accumulation, in addition to pressuring governments and companies for global changes and solutions (GIZ, 2018; Hulsken, 2014; Ribeiro et al., 2021). One of the strategies used to conduct studies on marine litter is Citizen Science (Ribeiro et al., 2021), which enables periodic surveys to be carried out in coastal areas and generates information on the temporal and spatial distribution of marine litter and its ecological impacts. Its pillars include the reliability of the collected data, the preparation of clear protocols, volunteer training, *in situ* supervision, and the review of samples and data by professional scientists (Hidalgo-Ruz and Thiel, 2015). In this context, we adopted this strategy together with the NGO *Ecofaxina* Institute, which has been working in the fight against marine litter for over a decade in the coastal region of southeastern Brazil by recruiting and training volunteers and performing waste collection.

2.2. Study areas

The SESS is located in the Baixada Santista Metropolitan Region, on the coast of the state of São Paulo (SP), Brazil. It comprises four main channels: the Santos and São Vicente Channels, located in the lower portion of the estuary and near the coast, and the Bertioga and Piaçaguera Channels, both located in the upper and inner regions of the SESS (Harari and Camargo, 1998). There are also stretches of rivers under the direct influence of the tidal regime and a mangrove ecosystem, considered a permanent preservation area (PPA), which is impacted by irregular occupation (Moschetto et al., 2021). In addition, there is also the presence of old municipal sanitary landfills and dumps, as well as the Port of Santos and the Industrial Pole of Cubatão. The tides are semi-diurnal, with diurnal inequalities, and their propagation within the estuary is conditioned by three factors: flood and ebb tides; mangrove areas that influence water flow, considered storage regions, with their own circulation; and the junction of the São Vicente and Santos estuaries (Parreira, 2012).

Sample collection was performed in two coastal environments: the beaches and the mangrove, all located in the municipality of Santos. The first sampling was carried out in the mangrove, near the junction of the São Vicente and Santos estuaries, adjacent to the Jardim São Manoel community (Fig. 1). This area, which covers approximately 11.6 hectares, is inhabited by more than 3 thousand people who live in stilt slums and are deprived of basic sanitation services (IBGE, 2017), thus characterizing it as one of the main polluting sources of the SESS as a result of the illegal disposal of solid waste and sanitary effluents that occurs daily in abundance in the ecosystem (Fernandino et al., 2016; Moschetto et al., 2021).

The second sample collection site was on the beaches of Santos, a highly urbanized city with more than 433 thousand inhabitants (IBGE, 2017), whose population density reaches 1494 inhab/km^2 (IBGE, 2017). The beaches total a 7 km stretch that is divided into José Menino Beach, Pompéia Beach, Gonzaga Beach, Boqueirão Beach, Embaré Beach, Aparecida Beach, and Ponta da Praia, which together form the Santos Bay.

Both samplings were carried out during the summer of 2019, when the municipality of Santos receives an estimated population of 1.5 million people, corresponding to more than three times the local population (Lescreck et al., 2016).

2.3. Sample collection

Waste collection in both ecosystems occurred simultaneously during low tide on December 9th, 2018. Both sampling procedures in the mangrove and on the beaches are detailed in the following sections.

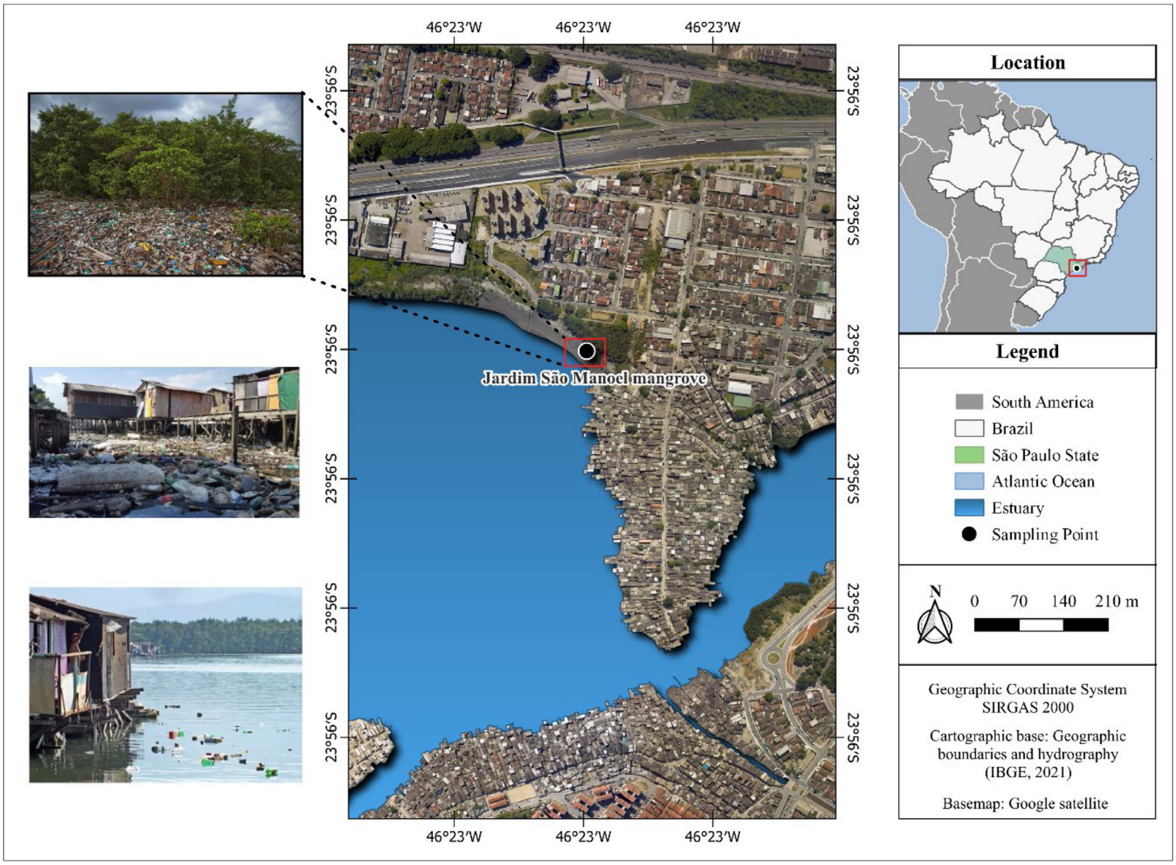

Fig. 1. Map of the Jardim São Manoel mangrove highlighting the sampling area (100 m^2) for the collection of solid waste, and some photographs (by William Rodriguez Scheppis) of the study area. This particular site was selected since it presented the highest levels of litter contamination when compared to the other mangroves in the region.

2.3.1. Mangrove

The collection site chosen for the mangrove constitutes a deposition region favorable to the accumulation of solid waste due to the characteristic low hydrodynamics of the SESS (Gimiliani et al. (2016); Parreira (2012)). A 100-m^2 plot was established in the Jardim São Manoel mangrove (Fig. 1) (23°55′55.97" S–46°22′51.78" W) for waste collection according to the methodology described by Schaeffer-Novelli et al. (2000).

2.3.2. Sandy beaches

The beach samplings followed the protocols described by Cheshire et al. (2009), in which each of the seven beaches was divided into 5 randomly determined areas (one of which was selected at random to define the transect). Seven transects were established during low tide along the beach strip, measuring 10 m in width and with lengths varying according to the distance between the seafront and the swash zone (intertidal), as shown in Table 1. The City Hall was advised to refrain from daily cleaning procedures the day before collection to avoid interfering with the amount and composition of solid waste in the transect regions. Fig. 2 shows a schematic map of the location of the study areas.

2.3.3. Collection and treatment of the solid waste

In all collection sites, waste larger than 2.5 cm found in the mangrove plot and the beach transects were collected on the surface and in the surface layer of the substrate up to 5 cm deep during low tide. The collected material was sorted, washed, and sieved (3 mm mesh) to remove sand and organic matter residues. Subsequently, the material was dried at room temperature and submitted to quali-quantification in the following classes: plastic, styrofoam, cigarette butts, paper, rubber, glass, metal, clothing, processed wood, and others, according to the methodology adapted from Cheshire et al. (2009) and Fernandino et al. (2016). In addition to categorization, the material collected at the beaches was classified according to the swash zone in which they were found, influenced by the low and high tide, as: discarded waste ("discarded" by local release — dry part) or waste beached by the ocean ("beached", originating from

Table 1
Location and detailing of the transects and sampling areas on the Santos beaches.

Beach	Code	Coordinates	Length (m)	Estimated sampling area (m^2)
José Menino	T1	23°58′9.75"S 46°20′52.66"W	249	2490
Pompeia	T2	23°58′10.93"S 46°20′31.84"W	293	2930
Gonzaga	T3	23°58′12.71"S 46°20′13.69"W	290	2900
Boqueirão	T4	23°58′23.05"S 46°19′32.43"W	242	2420
Embaré	T5	23°58′36.78"S 46°19′6.47"W	149	1490
Aparecida	T6	23°58′53.52"S 46°18′45.98"W	118	1180
Ponta da Praia	T7	23°59′5.17"S 46°18′34.54"W	131	1310

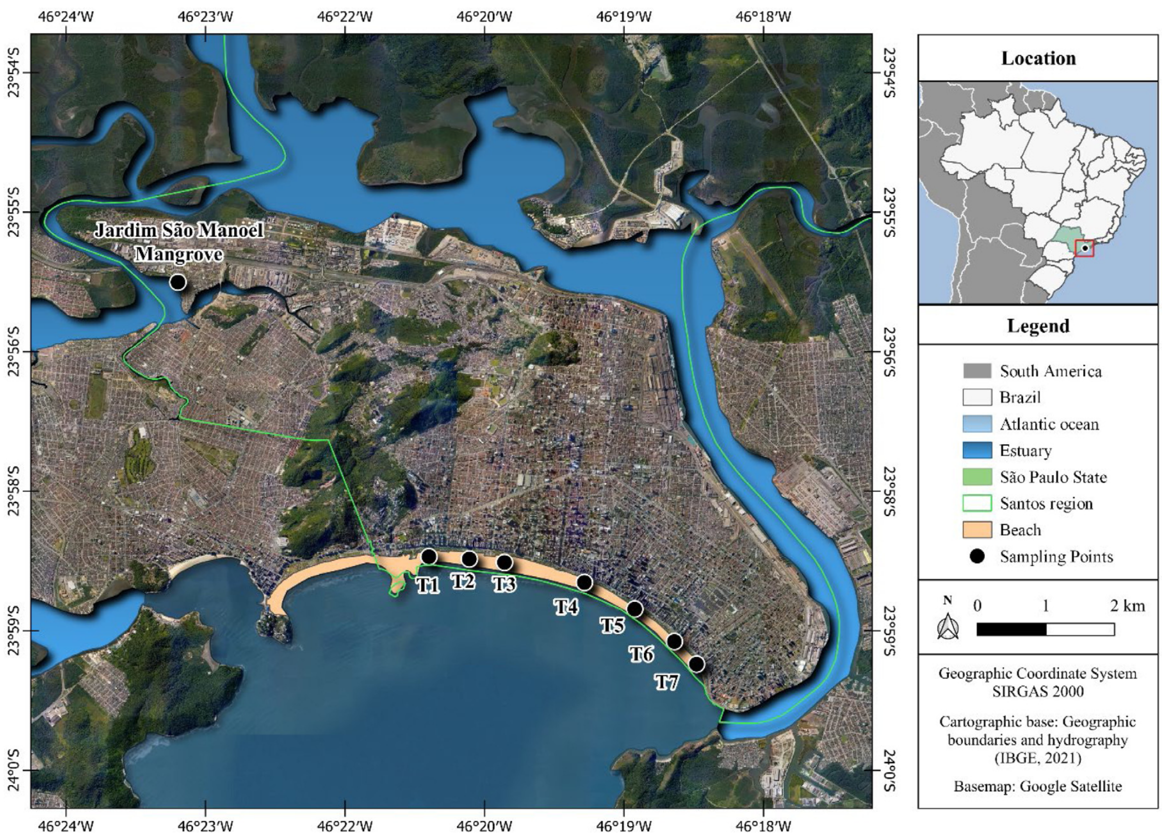

Fig. 2. Map of the Santos-São Vicente Estuarine System (SESS) and Santos Bay highlighting the sampling areas: mangrove plot (Jardim São Manoel) and beach transects.

adjacent regions, such as the regional estuarine system — wet part).

Data tabulation in spreadsheets was carried out using the Microsoft Excel® program, while the statistical analyses and sector graph construction were conducted in the R environment, version 4.0.4 (Ihaka and Gentleman, 1996). Using the information concerning the categories of the waste found in the "Mangrove", "Beached", and "Discarded", a similarity distance analysis was performed based on Euclidean distance, according to Kaufman and Rousseeuw (1990). The calculations were carried out using the FactoMineR package (Le et al., 2008), separating the first two dimensions into groups based on similarity. In addition, Spearman's correlation coefficients were determined between the sample collection points (Transects [T]) of the different regions (Mangrove [Mang], Beached [T.B], and Discarded [T.D]), using the number of different categories of waste found in each environment. The illustrative graphical display of this correlation matrix was generated using the ggplot2 package (Kassambara, 2022), as well as the statistical analysis of the Spearman correlation.

2.3.4. Clean coast index

In order to assess the level of solid waste contamination in the mangrove and on the Santos beaches, the Clean Coast Index (CCI) was used, which quantifies plastic and styrofoam residues as an indicator of ecosystem cleanliness (Alkalay et al., 2007). Data on the amount of plastic and styrofoam items collected were recorded based on the equation proposed by Alkalay et al. (2007), to obtain the CCI according to the numerical index of each sampled location, establishing the following levels of cleanliness: Very clean: from 0 to 2; Clean: from 2 to 5; Moderate: from 5 to 10; Dirty: from 10 to 20, and Extremely dirty: > 20.

2.4. Hydrodynamic modeling

Hydrodynamic modeling analyses were conducted using the MOHID Water Modeling System to verify the transport of internal currents from the SESS toward Santos Bay. The MOHID Water Model is a 3D finite volume model developed at MARETEC (IST – University of Lisbon) for Arakawa C staggered grids that solves 3D incompressible primitive equations (Leitão et al., 2005; Martins et al., 2001); it was built and developed using an object-oriented philosophy (Braunschweig et al., 2004). The analyses were carried out in a scenario of flood and ebb syzygy tides (strong tides) to assess their influence on the dispersion of solid waste within the estuary and their possible relationship with waste deposition on the beaches in the area.

The hydrodynamic modeling results were obtained from the early-warning system for storm surges of the Santos region (Ribeiro et al., 2019). This system uses the MOHID Water Model, with a set of four grids fitted using a methodology similar to Leitão et al. (2005). The first numerical grid (Level 1) is a 2D barotropic model, as are the three subsequent grids, in which the ocean boundary is forced upon by varying astronomical tides in space, calculated using the harmonic constants of the FES2012 global tidal model (Carrere et al., 2013). In the second numerical grid, the ocean boundary is forced upon with the conditions from the Level 1 grid (high frequency), added to the low-frequency conditions (sea level and currents) provided by the Copernicus Marine Service (CMS). The conditions generated by the Level 2 grid are imposed on the ocean boundary of the Level 3 grid, which, in turn, provides conditions at the ocean boundary for the last numerical grid, denominated Level 4, focused on the Santos Estuary, with a horizontal resolution of 50 m and 432 × 416 calculation points.

Being a free-surface boundary condition, the results obtained with the GFS atmospheric model provided by the National Oceanic and Atmospheric Administration (NOAA) were used to reproduce the atmospheric fields. Although GFS atmospheric data have low spatial resolution (~25 km), they show promising results in terms of forecasting and availability. Ruiz et al. (2021) also used atmospheric results from models with 20 to 50-km resolution and obtained good results regarding modeled hydrodynamic circulation in the studied region.

The entire model system is validated weekly, with sea-level data obtained by the São Paulo Pilots along the navigation channel of the Port of Santos, showing a high linear correlation with the measured data (>94%).

3. Results

3.1. Quali-quantification of the solid waste: mangrove and beaches

A total of 12,048 solid waste items were collected in the mangrove plot and beach transects. In the mangrove, 5209 items were found, with a prevalence of plastic waste, corresponding to 62.3% in relation to the total amount collected. Other materials were also recovered, including fragments of plastic film and hard plastic, lids, food packaging, plastic bags and microtubes, lid seals, cotton swabs, hygiene, cosmetic, and medication packaging, lollipop sticks, toys, PET bottles, straws, lighters, pens, sprays, tooth and hair brushes, hair clips, polyurethane foam, cleaning product packaging, school folders, DVD covers, and party articles.

Following the plastic items, styrofoam was the second predominant category, with styrofoam fragments and packaging corresponding to 30.49% of the total waste collected. Construction timber was the third category of most found items, corresponding to 2.61%. Flip-flops, party balloons, condoms, and tires comprised the rubber waste collected (1.52%); cosmetics bottles and packaging constituted the glass items category (0.79%), followed by aluminum food and spray cans (0.23%) and clothes/fabric (0.25%). Footwear, light bulbs, Tetra Pak packaging, candles (paraffin), electric wires, syringes, and pacifiers were categorized as Other (2.09%) since their composition included more than one material and because they did not fit into the rest of the categories mentioned above. With the exception of the plastic microtubes and syringes, the waste found was characterized as being of domestic origin, therefore following a decreasing order of prevalence: plastic (62.3%) > styrofoam (30.49%) > construction timber (2.61%) > other (2.09%) > rubber (1.52%) > glass (0.79%) > clothing (0.25%) > metal (0.23%).

On the beaches, the solid waste sampled in the transects totaled 7019 items, which were separated according to their mode of disposal, as 'beached by the tide' and 'discarded by beachgoers'. The quali-quantification of the discarded and beached waste followed a descending order of categories: plastic (45.25%) > cigarette butts (40.85%) > styrofoam (7.20%) > metal (2.71%) > timber (2.25%) > other (1.01%) > rubber (0.71%) > cellulose (0.26%) > clothing (0.046%) > glass (0.041%).

Among the beached waste, plastics were the predominant items found in the transects. Various plastic fragments, food packaging, lollipop sticks, cotton swabs, lids, straws, PET bottles, plastic bags and microtubes, foam, toys, tag pins, lighters, and toothbrushes were recovered. Meanwhile, the plastic items related to discarded waste corresponded to only 0.85 to 8.20% of the composition of plastic waste found in the beach transects, which mainly comprised disposable cutlery and cups. Cigarette butts were the predominant category in the discarded waste, equivalent to almost the total amount of litter dumped locally, ranging from 76.82 to 93.04% along the transects. Styrofoam fragments were also very common in the beach transects, corresponding to approximately 0.50 to 20% of the beached waste. Styrofoam food packaging ranged from 0.40 to 0.78% of the composition of the discarded items.

Metallic items, such as bottle caps and beer can seals, and wooden items, including toothpicks and barbecue, popsicle, and cotton candy sticks, were common among the discarded waste. Construction timber was found exclusively in the beached waste and in the mangrove.

Party balloons were the rubber items that were often found in the beached waste, as well as flip-flops, baby bottle nipples, condoms, and shoe soles. Paper from bar tabs and food and cigarette packaging was found among the discarded waste, while sandpaper sheets and packaging for cosmetics, medication, and hygiene products, clothes and cleaning cloths, as well as items that fell into the category of other waste (diapers, syringes, bandages, pacifiers, shoes, hair clips, brooms, electrical cords, Tetra Pak packages, remote controls, and candles/paraffin), were also found in this wet location. Fig. 3 shows the graphs referring to the proportion of waste discarded by beachgoers and those beached by the tide.

It can be noted that the proportion of discarded and beached waste was similar among transects T1, T2, T3, T4, and T5, a fact that did not occur in transects T6 and T7, in which there was a greater concentration of waste beached by the tide than discarded by beachgoers, namely in the region closest to the mouth of the estuary.

In summary, considering the portion of discarded waste, the three most abundant categories were found in the following order: cigarette butts (86.76%) > aluminum cans (5.50%) > plastic (4.68%). On the other hand, the portion of beached waste presented the following order of the three main categories: plastic (81.52%) > styrofoam (14.18%) > timber (2.02%), which was similar to the order of waste categories found in the mangrove plot, namely: plastic (63.78%) > styrofoam (30.12%) > timber (2.73%). The relative amounts recorded for the categories of solid waste found in these regions are shown in Fig. 4. The results indicate that there was a proportional relationship between the types of waste found in the mangrove and in the intertidal area of the beach (beached), especially floatable waste, such as plastic, styrofoam, and timber.

The results regarding the similarities of the transects in the different collection regions (solid waste from the mangrove and beaches [beached and discarded]) are shown in Fig. 5. The first two dimensions explained 74.6% of the variance of the obtained data. Corroborating the results observed in Fig. 4, the first dimension (58.24%) separated the transect from the mangrove (Mang) and the transects pertaining to the intertidal region (T.B: "Beached"). The floatable waste, such as styrofoam, plastic, and rubber, showed a positive correlation (0.92, 0.91, and 0.85, respectively) with the separation of the first dimension, whereas cigarette butts had a negative correlation (−0.94). These results reveal a substantial similarity between the waste found in the mangrove and the waste beached in the transects.

Fig. 6 illustrates the Spearman correlation coefficients between the sample collection points (Transects [T]) of the different regions (mangrove [Mang], beached [T.B], and discarded [T.D]) using the number of different categories of waste found in each environment. Corroborating the similarity distance analysis presented above, the mangrove transect showed a positive and significant correlation ($p < 0.001$) associated with all beached transects (T1 = 0.64; T2 = 0.75; T3 = 0.74; T5 = 0.60; T6 = 0.57 and T7 = 0.63), while the discarded transects evidenced no positive correlation with the mangrove, only negative. Our results also indicate that there was no positive correlation between the beached and discarded transects, inferring that there was no association between these areas in terms of marine litter composition.

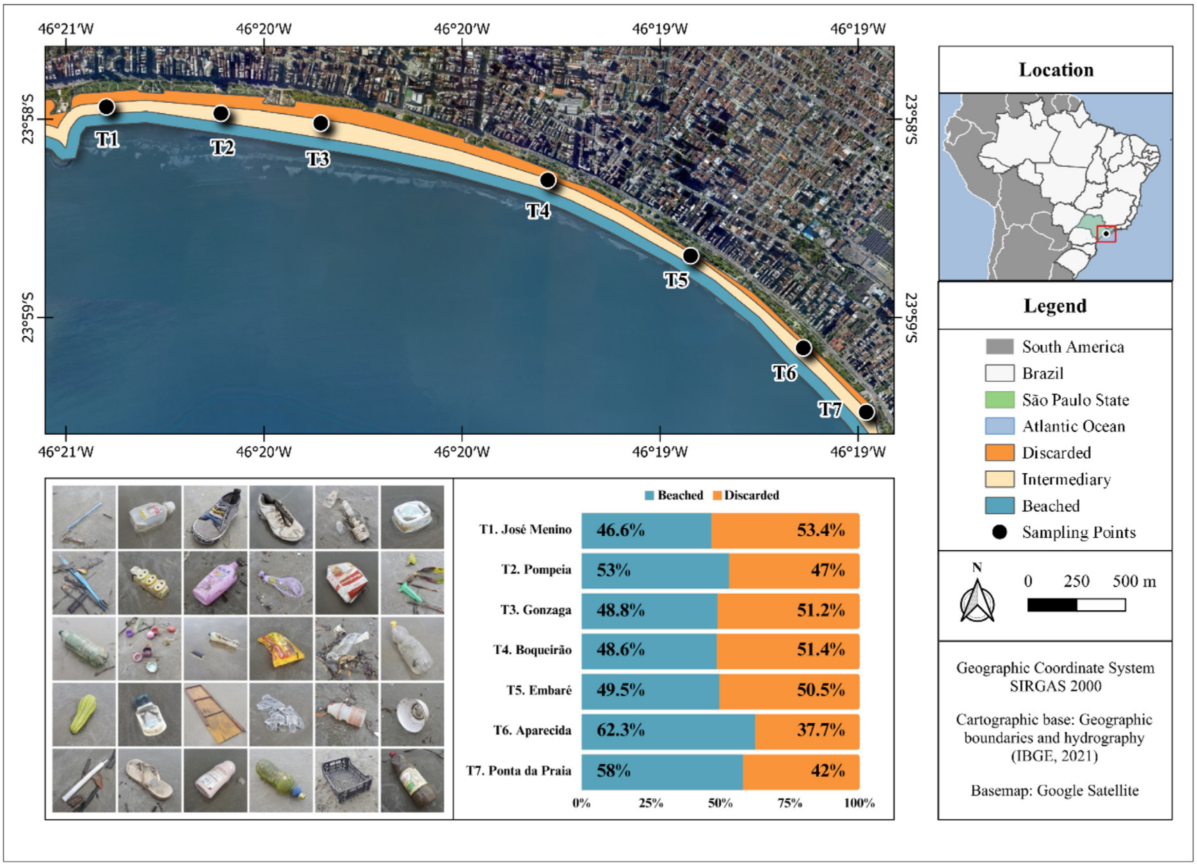

Fig. 3. Map of the beach transects (located in Santos Bay) highlighting the proportion of waste discarded by beachgoers ("Discarded": orange) and deposited by the tides ("Beached": blue). Some photographs (by William Rodriguez Scheppis) illustrating the variety of litter found in this region under the influence of the tide.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Marine litter items (n abundance (items/m^2) and the Clean Coast Index (CCI) recorded in the beach transects and the mangrove plot.

Region		Litter items (n)	Litter abundance (items/m^2)	CCI (items/m^2)
	T1	891	0.36	3.5 — Clean
	T2	953	0.33	3.49 — Clean
	T3	1047	0.36	3.52 — Clean
Beach	T4	919	0.38	3.74 — Clean
	T5	1158	0.78	7.64 — Moderate
	T6	1125	0.95	11.22 — Dirty
	T7	925	0.71	8.20 — Moderate
Mangrove		5209	52.09	965.6 — Extremely dirty

3.2. Clean coast index in the beaches and mangrove

Table 2 shows the number of items (n) collected, the abundance of marine litter, and the classification according to the CCI index. The mangrove was classified as extremely dirty, with a greater quantity of solid waste and a higher number of items collected. Among the beach transects, T5, T6, and T7 were characterized as moderate to dirty and showed a greater abundance of marine litter than the other transects, although lower than the mangrove. As for the more distant transects from the Santos Channel, T1, T2, T3, and T4 retained the lowest abundances, as well as fewer collected items and lower CCI indexes.

3.3. Hydrodynamic modeling

The results obtained in the hydrodynamic modeling analyses are shown in Figs. 7 and 8. Fig. 7A shows the flood tide in which the currents enter the Santos and São Vicente Channels and meet at the SESS junction, near the sampling area (Fig. 7B). In that region, the currents bifurcate, with one part entering the channel to the east and the other to the north.

On the other hand, the ebb tide currents migrate toward the Santos and São Vicente Channels, where the estuarine channel currents, in the vicinity of the Jardim São Manoel community, move toward the São Vicente Channel and, later, to Santos Bay, as can be observed in Fig. 8A.

The estimated velocity of the surface currents varied between 0.20 and 0.40 m s^{-1} in the Santos and São Vicente Channels. In the Santos Channel, in particular, the ebb currents present greater speed toward Santos Bay. Meanwhile, the velocity of the estuarine channels in the inner portion of the estuary was relatively low, especially near Jardim São Manoel, where it did not exceed 0.1 m s^{-1}, characterizing it as a region of low hydrodynamics. In Santos Bay, the currents can reach a speed of 0.2 m s^{-1} and present counterclockwise movement in the vicinity of the Santos and São Vicente Channels during the flood tide. As for the ebb tide, relatively higher-velocity currents, especially from the Santos Channel, reach transects T5, T6, and T7, while T1, T2, T3, and T4 are under the influence of lower-velocity currents. In short, the hydrological system favors the deposit of solid waste on the beaches (especially in transects T5, T6, and T7) originating from mangrove areas since the flood tide helps carry litter upstream from the São Vicente Channel, where it meets higher speeds in the ebb tide in the Santos Channel.

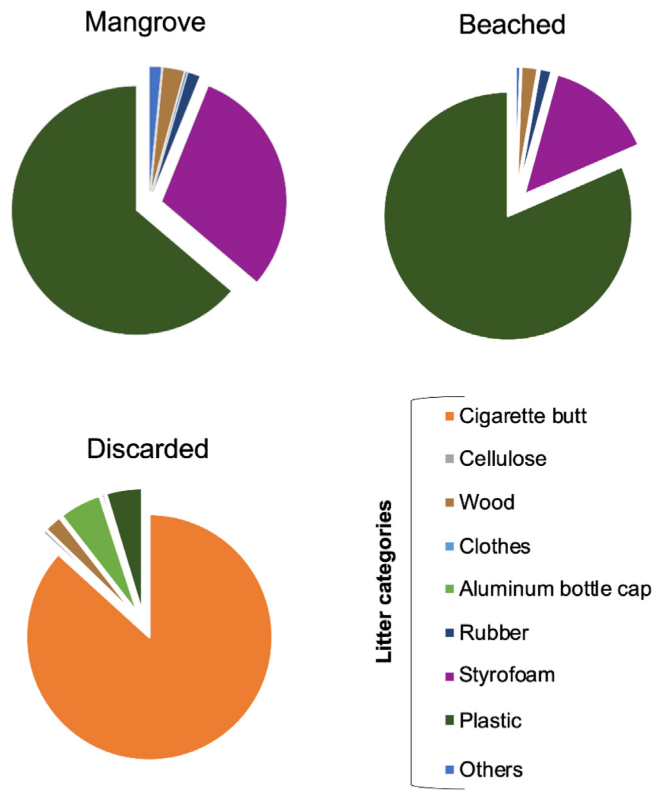

Fig. 4. Categories of solid waste in function of their relative quantities (%) sampled in the: (1) Mangrove; (2) Intertidal zone (beached), and (3) Post-beach region (discarded).

4. Discussion

4.1. Quali-quantification of the solid waste: mangrove and beaches

The present study revealed that plastic was the most frequent waste, both in the mangrove plot and the beach transects. Other authors have also shown that its prevalence in the composition of marine litter on the same beaches varied between 64 and 72% (Ribeiro et al., 2021) and around 89% in the SESS (Fernandino et al., 2016). Studies carried out in other coastal regions, including beaches and mangroves, have reported rates between 63 and 97% (Chiu et al., 2020; Consoli et al., 2018; Garcés-Ordóñez et al., 2019; Mallory et al., 2021; Mugilarasan et al., 2021; Santos et al., 2020).

Many plastic items found in mangroves are characteristic of household sources and personal use (*i.e.*, packaging for food, cleaning, hygiene, and cosmetic products and medication, cotton swabs, plastic bags, and toothbrushes), a classification also established by other authors for waste found in the analyzed region (Cordeiro and Costa, 2010; Fernandino et al., 2016). Since plastic waste predominantly exhibits a characteristic buoyancy in water bodies, it is subject to coastal hydrodynamic conditions and susceptible to tidal regimes, followed by constant deposition and/or remobilization processes in coastal regions (Tramoy et al., 2020), accumulating especially in areas with low hydrodynamics (Gimiliani et al., 2016). Plastic waste can remain accumulated for decades and, consequently, contribute to the characterization of these environments as "microplastic factories", resulting from the fragmentation of larger debris before reaching the ocean (Tramoy et al., 2020).

Construction timber items, foams, light bulbs, and electrical wires were also found in the mangrove and in the portion of beached litter, representing civil construction waste. Timber is a typical waste from favelas that is used in the construction of *palafitas* (stilted shacks suspended over the mangroves). These structures, which are built in clandestinely land-filled regions, need to be replaced, on average, every six months by their residents. Timber also comes from the tons of rubble discarded by trucks, which is used to fill in the mangrove areas to make way for the construction of irregular housing. This social and environmental scenario is frequent in the coastal region analyzed (Fernandino et al., 2016), a fact that explains the predominance of these items in the present study.

Another waste category, including plastic syringes and microtubes, both found in the mangrove and among the beached litter, may be associated with the region's social vulnerability. Syringes are usually used for illicit drug use; microtubes have been increasingly used in the transport and sale of cocaine and have been previously reported in other studies carried out in the same mangrove (Fernandino et al., 2016) and in the Santos beaches (Ribeiro et al., 2021).

The cigarette butts category was frequently found. These items were considered associated with leisure activities on the beaches, as they were collected only in the portion of discarded waste. The amount in which they were found on the beaches in our analyses was equivalent to almost all the waste discarded in the transects (76.82 to 93.04%). These results are in line with studies carried out in other regions, which reported that, according to beach cleaning actions around the world, cigarette butts are the predominant waste in urban beaches (Araújo and Costa, 2019; Chevalier et al., 2018; Novotny and Slaughter, 2014; Pon and Becherucci, 2012); their number tends to increase significantly during the summer, as verified by Ribeiro et al. (2021).

Styrofoam fragments were another prevalent item in the beached waste and the waste found in the mangrove. Due to the presence of fishing activities and marinas in the SESS, styrofoam is widely used as a buoy to keep fishing nets suspended, as well as for transporting fish. These residues, which originated from the fragmentation of larger products, tend to spread more quickly, becoming, according to some studies, a predominant item in the composition of waste in coastal regions (Heo et al., 2013; Rosevelt et al., 2013).

Items such as metal and glass found in the mangrove were not observed in the portion of beached waste. This was probably due to the low relative buoyancy of these materials. Floating litter is composed primarily of plastic (fragments, packaging, bottles, plastic bags, ropes, and fishing lines), styrofoam fragments, rubber (Galgani et al., 2015), and a small percentage of timber (González-Fernández and Hanke, 2018; Pogojeva et al., 2021). These were the categories most found in the beached waste in this study. Such residues are subject to hydrodynamic conditions (tides, winds, and wave activity), bidirectional flow and coastal structure, and the vegetation present in estuaries (Maclean et al., 2021). Items with greater buoyancy, therefore, tend to become stranded on the nearest beaches (Maclean et al., 2021). Their transport can be evidenced by the higher CCI indexes in the transects closest to the estuary mouth (T5, T6, and T7). The similarity distance analysis indicated a correlation between the floating waste found in the mangrove and the beached waste. Our results, therefore, favor a strong proportional association between the quantified waste in the two environments. This fact supports the hypothesis that the mangrove plays a relevant role as a source of contamination by solid waste for the adjacent beaches.

4.2. The estuary as a marine litter contamination hotspot on beaches

Complementary to what was described in the previous topic, the hydrodynamic modeling results showed how the currents

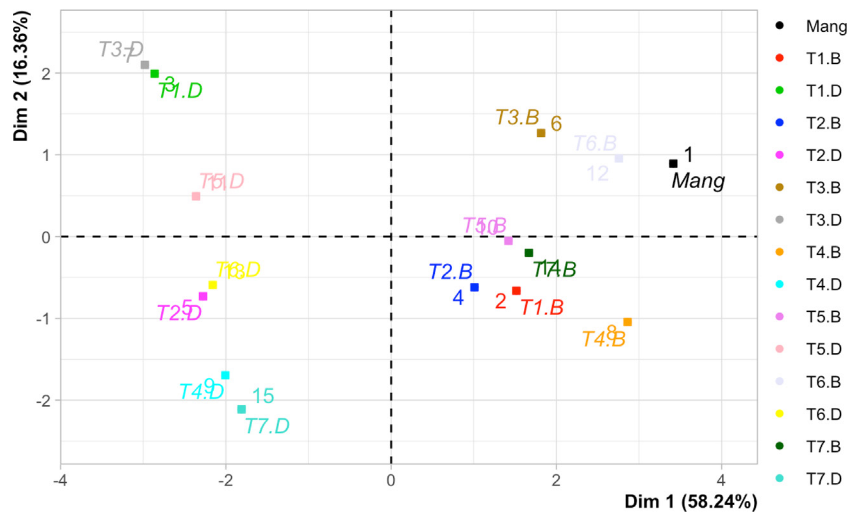

Fig. 5. Analysis of the similarity distances based on the Euclidian distance of the sample collection points (Transects [T]) of the different regions (Mangrove [Mang], Beached [T.B], and Discarded [T.D]) using the number of different categories of waste found in each environment.

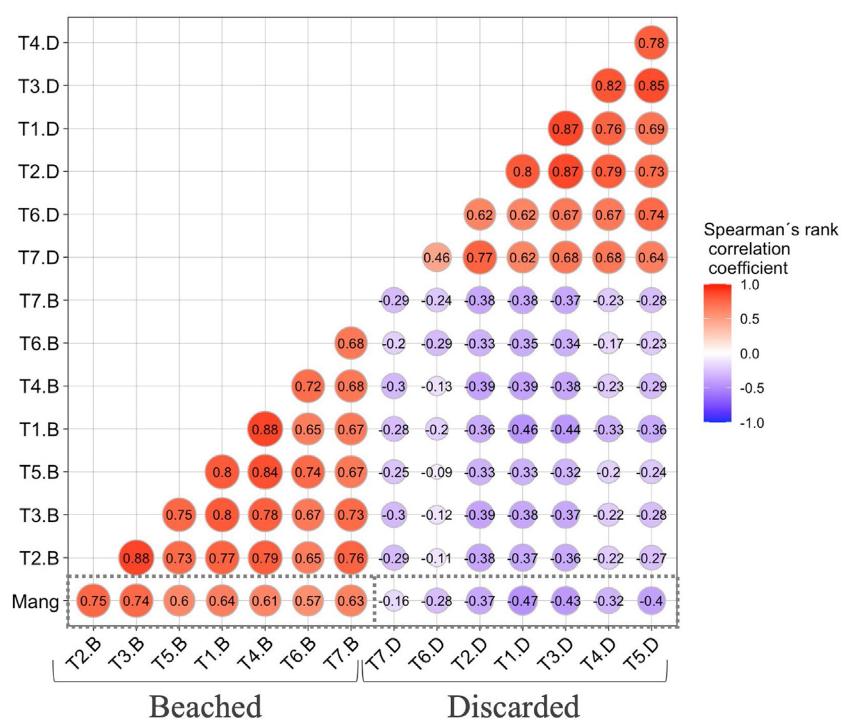

Fig. 6. Spearman's rank correlation coefficients ($N = 45$) between the sample collection points (Transects [T]) of the different regions (Mangrove [Mang], Beached [T.B], and Discarded [T.D]) using the number of different categories of waste found in each environment. The dotted rectangles indicate the correlations between the beach transects and the mangrove.

under the conditions of ebb and flow syzygy tides can act in the dispersion of floating solid waste between the SESS and Santos Bay through the Santos Channel. The sampled mangrove region is influenced by currents during the flood tide, and part of them flows northward into the estuarine system and, later, the Santos Channel. These hydrodynamics can favor the remobilization of waste stranded in the sampled mangrove, redirecting them to the closest part of the Santos Channel. The presence of semi-diurnal tides with diurnal inequalities, typical characteristics of the SESS (Harari and Camargo, 1998), during lower tidal variations, may not be enough to transport waste toward Santos Bay. Therefore, part of the debris may remain contained within the estuary until there are syzygy tides, which should be able to transport the waste out of the estuary toward adjacent beaches (Fernandino et al., 2016).

On the other hand, during the ebb tide, currents can transport such waste through the Santos Channel toward Santos Bay, as well as remobilize waste present in the mangrove to the São Vicente Channel, thus indicating two routes of transport of waste to Santos Bay. The intensity of the ebb currents, especially in

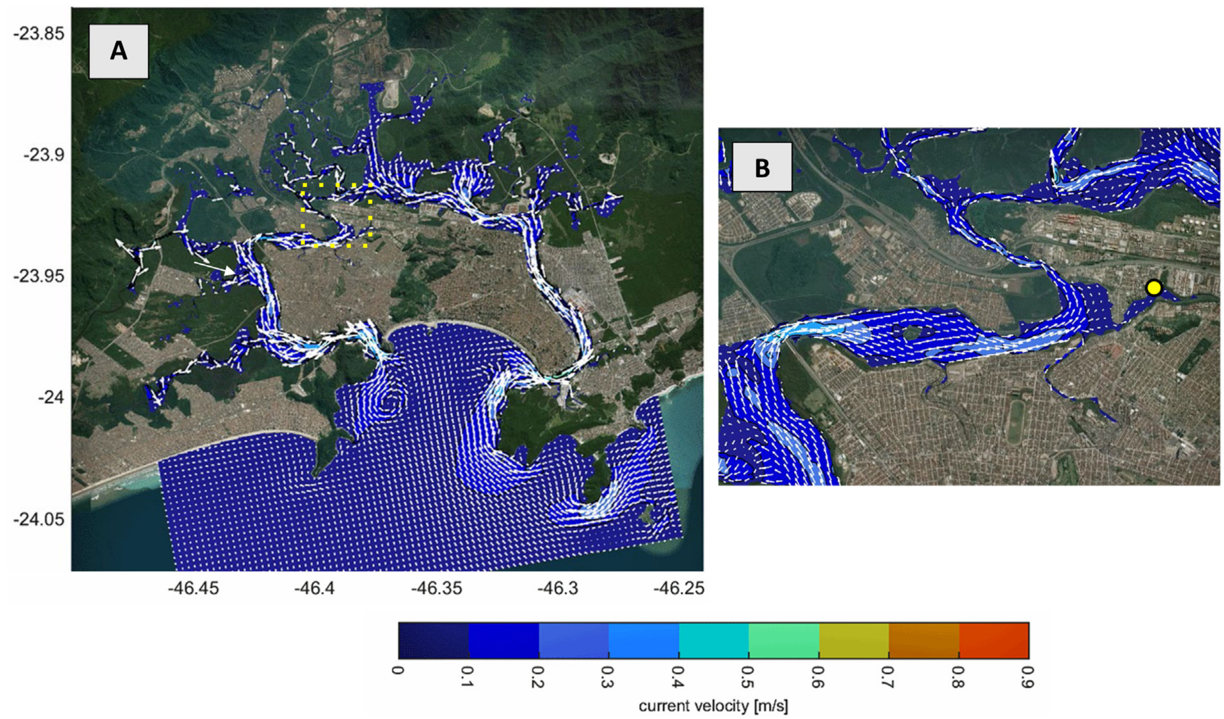

Fig. 7. Hydrodynamic modeling at the moment of intense tidal swell in the SESS and Santos Bay (A) and near the Jardim São Manoel mangrove (B).

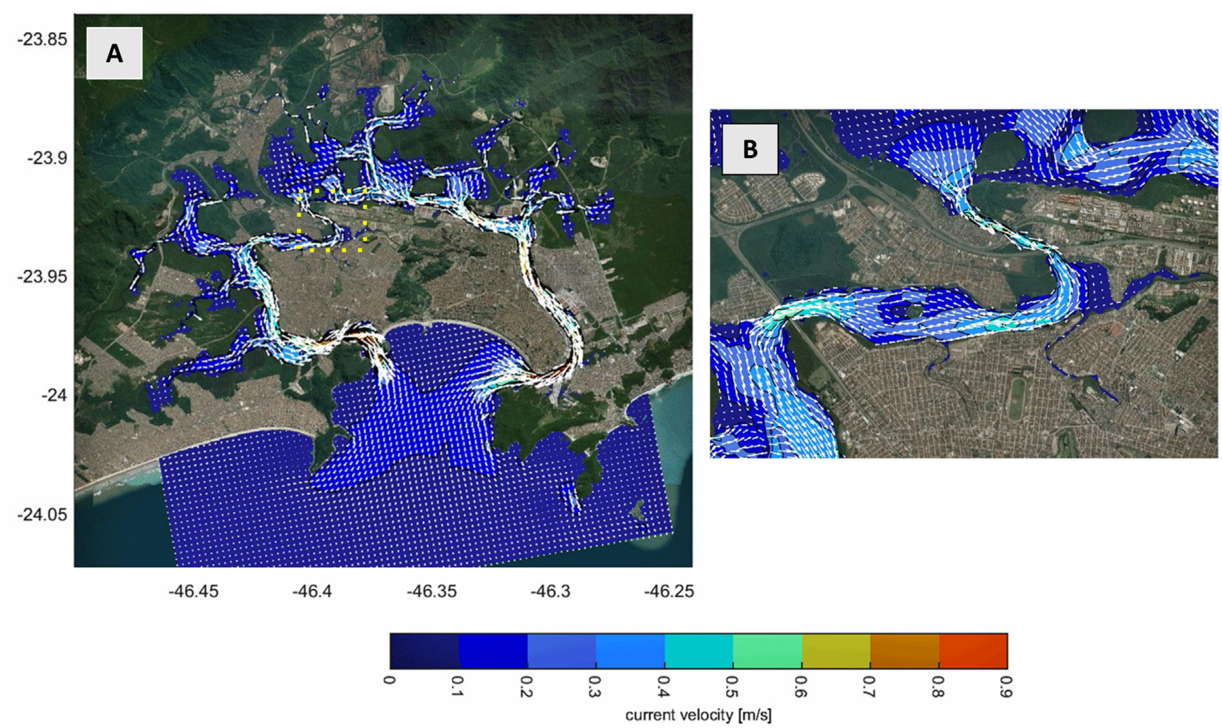

Fig. 8. Hydrodynamic modeling at the moment of intense syzygy tidal ebb in the SESS and Santos Bay (A) and near the Jardim São Manoel mangrove (B).

the Santos Channel, is greater than the flood currents during the syzygy periods (Harari and Camargo, 1998), providing greater transport of waste from the interior of the estuary to Santos Bay.

In addition, the Santos Channel presents greater intensity currents, indicating a more intense transport of waste when compared to the currents of the São Vicente Channel, where convergence and divergence in flood and ebb currents occur in opposite directions, rendering them relatively weak (Harari and Camargo, 1998). Thus, the larger proportion of waste beached in transects T6 and T7 can be explained by the proximity with the ebb currents of the Santos Channel. Barrella et al. (2021) also found a greater number of floating debris near these transects.

It is expected that the waste present in Santos Bay will also be transported to the interior of the SESS due to the influence of flood currents in the west-northwest direction during the syzygy period (Harari and Camargo, 1998). Therefore, there may be an influence on marine litter originating from diffuse sources toward the Santos beaches and the SESS. In the winter, storm surges produce strong currents (Balthazar-Silva et al., 2020; Barrella et al., 2021; Pieper et al., 2021), which can lead to the accumulation of beached waste from sea currents.

The results obtained from the quali-quantitative analysis of the solid waste found in the different regions (''Mangrove'', ''Discarded'', and ''Beached'') and the hydrodynamic modeling corroborate how the influence of the waste generated inside the estuary affects the beaches of the municipality of Santos. The distribution and abundance of marine litter are related not only to environmental conditions (tides, winds, and currents) (Maclean et al., 2021) but also to the conditions of basic sanitation services, population density, human activities, waste management, economic development, and the level of education of the populations in each region (Chiu et al., 2020; Hidalgo-Ruz and Thiel, 2015). Finally, the information generated in this study indicates that the problem of marine litter contamination needs to be managed on a macro-scale by public management agencies and not only locally, since the intrinsic hydrodynamic processes of each region contribute to the destination of part of the regionally produced aquatic waste.

5. Conclusion

The hydrodynamic conditions revealed that the tidal currents act in the transport of floating waste from the interior of the SESS to the Santos beaches (beached) through the Santos Channel, which was confirmed by the similarity and predominance analyses regarding the proportions of the same floating items (plastic, styrofoam, and construction timber) also found in the mangrove, which was classified as extremely dirty. Furthermore, the quali-quantitative analysis of the waste found in these environments also showed an association between the beached area and the mangrove, revealing a different waste composition compared to the discarded area. This corroborates the hypothesis that the adjacent mangrove is one of the primary sources and a hotspot of litter contamination on the Santos beaches.

The beaches closest to the Santos Channel were relatively more polluted, ranging from moderate to dirty. Meanwhile, the more distant ones were classified as clean.

The waste discarded by beachgoers resulting from recreational activities on the beaches was predominantly composed of cigarette butts, aluminum cans, and plastics.

The present study highlights the importance of the influence of the intrinsic hydrodynamic processes of each region on the destination of marine litter. The problem regarding its disposal on beaches needs to be managed on a macro-scale by public management agencies, not just locally.

CRediT authorship contribution statement

Luis Felipe de Almeida Duarte: Conceptualization, Writing, Statistical analyses, Graphical performed, Writing – review & editing. **Renan Braga Ribeiro:** Hydrodynamic modeling analysis. **Tierry Val de Medeiros:** Writing – review & editing. **William Rodriguez Scheppis:** Conceptualization, Investigation, Methodology. **Giovana Teixeira Gimiliani:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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