ABES

Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Environmental sensitivity analysis of environments affected by the oil spill on the Brazilian coast

Análise da sensibilidade ambiental dos ambientes afetados pelo derramamento de óleo no litoral brasileiro

Carolina Mussi[1], Nalú Zago[1], Rosemeri Marenzi[1], Marcus Polette[1]

ABSTRACT

The crude oil spill that occurred in 2019 at the Northeast Brazilian Coast is considered one of the most severe disasters recorded in tropical coastal regions. In order to contribute to the understanding of the impact generated by the disaster, this work linked oil sightings by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) with the Coastal Sensitivity Index (CSI) of the Environmental Sensitivity to Oil Spills Maps (Carta SAO), generating an overview of the types of coastal environments affected by the oil. This crossing was carried out through the public vector bases in the Geographic Information System. The results show that intermediate beaches, mangroves and Salt Marshes, reefs and tidal flats recorded more than 50% of sightings with oil residues. At the end of this analysis, the environments that still had oil records were mangroves and Salt Marshes, and intermediate, dissipative and gravel beaches. The analysis allowed us to understand the main environments affected by the spill along the coast, also indicating the need to adopt mechanisms that integrate public data to assist in the structuring of oil combat mechanisms, with actions to combat oil arising from any spills on the Brazilian coast becoming more effective.

Keywords: marine oil spill; coastal sensitivity index (carta SAO); geografic information system; sensitivity oil spill maps.

RESUMO

O derramamento de óleo cru que ocorreu no litoral do Nordeste do Brasil em 2019 é considerado um dos desastres mais severos registrados em regiões costeiras tropicais. Para contribuir para a compreensão do impacto gerado pelo desastre, este trabalho relacionou as avistagens de óleo do Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) com o Índice de Sensibilidade do Litoral (ISL) das Cartas de Sensibilidade Ambiental a Derramamentos de Óleo (SAO), gerando um panorama dos tipos de ambientes costeiros atingidos pelo óleo. Este cruzamento foi realizado por meio da sobreposição de bases vetoriais públicas em sistema de informação geográfica. Os resultados demonstram que as praias intermediárias, manguezais e marismas, recifes e planícies de maré registraram mais de 50% de avistagens com resíduos de óleo. Ao fim desta análise, os ambientes que ainda apresentaram registros de óleo foram os manguezais e marismas e as praias intermediárias, dissipativas e de cascalho. A análise permitiu compreender os principais ambientes afetados pelo derramamento ao longo da costa, indicando também a necessidade de adotar mecanismos de integração dos dados públicos para auxiliar na estruturação de mecanismos de combate ao óleo, tornando mais eficazes as ações de combate em eventuais derramamentos na costa brasileira.

Palavras-chave: derramamento de óleo marinho; índice de sensibilidade ao derramamento de óleo; sistemas de informações geográficas; cartas de sensibilidade ambiental a derramamentos de óleo.

[1]Universidade do Vale do Itajaí – Itajaí (SC), Brazil.

Correspondence address: Carolina Mussi – Rua Uruguai, 458, Bloco D8, Sala 102 – Caixa postal 360 – Itajaí (SC), Brazil. E-mail: csmussi@gmail.com

Conflicts of interest: the authors declare no conflicts of interest.

Funding: none

Received on: 08/22/2022. Accepted on: 11/24/2022.

https://doi.org/10.5327/Z2176-94781441

Introduction

In 2019, a spill of about 6 tons of crude oil reached more than 3,000 km^2 of the Brazilian coastline, impacting the integrity of different natural environments and associated biological communities, as well as economic activities performed in the landscape (Lessa *et al.*, 2021). According to government agencies, the cause for this tragic, and also the biggest, oil spill event is tropical ocean waters still unknown (Lourenço et al., 2020).

The first record of oil at the coast occurred on August 30, 2019, at Praia Bela, Pitimbu, in Paraíba, and, over the months, the oil slicks were transported by the Guiana Current and the Brazil Current, reaching the states of Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, Sergipe, Espírito Santo and Rio de Janeiro. A total of 11 states, 129 municipalities and 14 federal conservation units were affected by the oil (Ibama, 2020). Handling crude oil waste is even more complex than common oil, because its high density does not allow it to be observed from the surface of the ocean, being identified only when it reaches the continent, including beaches, reefs, cliffs, mangroves (Soares et al., 2020). So, it is very difficult to estimate the volumes of oil that still remain submerged in Brazilian waters, and the real magnitude of the oil spill volume that was dispersed on the coast. Also, the effects of crude oil residues are long-lasting, and can be potentiated over the years through the process of magnification of toxins along the trophic chain. The measure of environmental, social and economic impact is not clear until now.

One of the biggest oil spills in the word happened in April 2010 in the Gulf of Mexico. The Deepwater Horizon platform exploded, resulting in 11 deaths and 17 injuries, and, over the next 3 months, approximately 55,000 barrels of oil were spilled daily, reaching more than 1,500 km of the Gulf coast, resulting in the largest oil spill in US maritime history, causing financial losses and behavioral health problems (Buckingham-Howes et al., 2019). In Brazil, accidents with oil spills had already happened, but never in magnitudes as large as this event in 2019. In 1975, an Iraqi ship dropped more than 6,000 tons of oil in the Guanabara Bay, in Rio de Janeiro (Ribeiro et al., 2021); in 1994, almost 3 million liters of oil polluted 18 beaches on the north coast of São Paulo (Hoff et al., 2022).

In order to understand the impact of oil residues in the coastline landscape, it is important to understand that environments have different degrees of sensitivity to disturbance events, and local characteristics are essential to determine the impact as well (Pinheiro and Silva, 2021). Furthermore, the significance of the impact is verified not only by the volume of spilled oil, but also by the resilience of the different types of environments affected.

In this sense, environmental sensitivity mapping tools emerge to support the development of a response strategy for oil spill contingency plans in order to reduce the environmental and social consequences of possible oil disasters (Silva et al., 2019). The sensitivity mapping of the various types of environments and resources potentially exposed to oil spills enables the identification of the most sensitive sites, thus providing a basis for the definition of priorities for protection and clean-up, in order to plan the best-suited response strategy (IPIECA-IMO-OGP, 2012). Therefore, during response operations, sensitivity maps will be used by the decision makers to create effective contingency plans.

The environment ability to deal with any oil spills along the Brazilian coast was the assessment by the Sensitivity Maps for Oil Spill Response (Carta SAO) using the Costal Sensitivity Index (CSI) as a tool for the environmental sensitivity classification. Based on Law 9,966/2000 (Brasil, 2000) which provides for the prevention, control and inspection of oil pollution in waters under national jurisdiction, the Sensitivity Maps for Oil Spill Response were prepared for the entire Brazilian coastline through the Ministry of Environment (*Ministério do Meio Ambiente* — MMA). The sensitivity map evaluates the physical characteristics of the coastline and its ability to control oil deposition, persistence or longevity in the environment, as well as the extent of biological damage (Oliveira *et al.*, 2022). Based on abiotic descriptors, the index evaluates the geomorphological characteristics related to the exposure relative to wave and tidal energy, environmental gradient and granulometry, indicating from them ten classes of different intensities of oil sensitivity.

Assessing the sensitivity of different environments to oil spill collaborates for the creation of effective strategies to manage possible incidents, concentrating efforts in areas with more sensitive environments. But it is important to understand that different levels of response will be required depending on the scale of the oil spill, and this will determine the most appropriate types of maps (IPIECA-IMO-OGP, 2012). The Sensitivity Maps for Oil Spill Response (Carta SAO) have been structured in three levels of articulation, or scales of scope: Strategic Maps, of regional scale (1:600,000 and 1:800,000); Tactical Maps, for intermediary scale, covering the entire coastline of the basin (1:150,000); and Operational Maps, for local scale present in the Coastal Sensitivity Index (CSI) that describes environment sensitivity (1:10,000 to 1:50,000) (Soares *et al.*, 2019).

Even though the Sensitivity Maps for Oil Spill Response (Carta SAO) are a legal cartographic document for oil contingency planning, and a mandatory document of the National Contingency Plan for Oil Pollution Incidents (Decree 8157/2013), at the biggest oil spill event that happened in Brazilian coast they were not used in response operations.

The lack of strategy and tactics over the months and the population's lack of preparation met a general appeal for volunteerism, which instigated thousands of unprotected fishermen, residents, students, traders, tourists and surfers to head to the beaches to help in the cleaning of oil residues (Pena et al., 2020). Many of them were not aware of the risks of exposure to the chemicals contained in oil, or how to deal with the environmental disaster, and did not protect themselves with proper safety equipment (Araújo et al., 2020).

Another important function of the Sensitivity Maps for Oil Spill Response (Carta SAO) is to assess the impact of oil on the different environments. Official government records on the sighting of oil on the coast, carried out by environmental government agency IBAMA, were not integrated with these sensitivity maps, and no report on affected habitats has been officially delivered. Aiming to contribute to this gap, this work identified the amount of habitats affected by the oil spill by crossing the Coastal Sensitivity Index (CSI) from Cartas SAO with the oil sighting records mapped *in situ* by IBAMA using the Geographic Information System (GIS).

Methodological procedures

In order to understand which were the main environments affected by the oil spill along the Brazilian coastline, the IBAMA oil sighting records were related, through the Geographic Information System (GIS), using the ArcGIS 10.2 software, to the CSI (the Coastal Sensitivity Index) of the Sensitivity Maps for Oil Spill Response (Carta SAO), available through the Ministry of Environment (MMA). The CSI describes the sensitivity of coastal environments regarding their ability to perform self-cleaning and to be less impacted by waste. The description of each environment by the CSI can be seen in Table 1.

The first stage of data processing consisted of spatializing, through the website http://www.ibama.gov.br/manchasdeoleo-localidades-atingidas, in a vector file, the records of sightings between August 30, 2019 and January 27, 2020. This spatialization was possible because the geographical coordinates of the sighting points were collected during field visits, as well as the characteristics of the oil residues spotted at the time. The observation of residues was classified into: Oil Slicks, Sparse Traces of Oil and Oil Not Observed. It should be noted that in the present analysis the number of sites affected by the oil was not evaluated, but rather the absolute number of types of sightings recorded over time by state and coastal environment.

To survey the number of sightings per environment, the IBAMA records, already spatialized as vector files, were related to the vector files of the CSI (the Coastal Sensitivity Index) of the operational Sensitivity Maps for Oil Spill Response (Carta SAO). For data crossing, a buffer of 2000 meters was created in the CSI line segments, and the number of sightings within this area was counted using the *Spatial Joint* tool. The type and number of sightings were identified through Selection by Attributes (SQL) (Table 1).

The methodology employed is similar to those used to quantify these types of environmental disasters, such as the accident in 2017 on the Indian coast. More than 196 tons of oil were dumped into the sea, and to measure the level of the accident the crossing of spatialized data with the Operational Modeling Environment of the National Oceanic and Atmospheric Administration (NOAA) was used (Prasad et al., 2018).

Results and Discussion

The disaster revealed that since the beginning of the first records of crude oil on the coast, there was a great institutional lack of preparation, with little effective actions in the fight against oil (Araújo et al., 2020; Brum et al., 2020; Soares et al., 2020). The Sensitivity Maps for Oil Spill Response (Carta SAO) were not officially mentioned as a strategy to combat oil by any government institution in the country, or even by the volunteers who participated in the process. This tool was developed in partnership with the Ministry of Environment (MMA) and several research institutions, and should have been the official guide for strategic actions to combat oil, indicating the places that should receive greater attention, especially for the most sensitive habitats.

The very organization of vector bases for using the Sensitivity Maps for Oil Spill Response (Carta SAO) in a GIS environment was not standardized for every coastline and for using the Coastal Sensitivity Index (CSI). Thus, it was necessary to standardize the language in the attribute tables of the vector files of the different sedimentary basins. Although the MMA created strict technical standards for structuring the CSI, there was no guidance to the different research groups that carried out the charts for harmonizing the metadata for later integration of the GIS data. Although the vector databases are available on the MMA website, the lack of integration of data between sedimentary basins makes it difficult for the community to access the data.

The geo-spatialization of field reports carried out by IBAMA shows that the first sightings occurred in Paraíba in August and, with the movement of oil by ocean currents, sightings were altered (Figure 1).

Table 1 – Description of coastal environments and CSI classes of the Sensitivity Maps for Oil Spill Response (Carta SAO).

CSI 1	Impermeable substrates of high to medium gradient, exposed: Smooth rocky shores, Cliffs, Artificial Structures.
CSI 2	Impermeable substrates, sub-horizontal, exposed and with medium to low gradient, exposed: Smooth rocky shores, Terraces.
CSI 3	Semipermeable substrates with low oil penetration/burial: Medium to fine sand dissipative beaches, Escarpments/Slopes.
CSI 4	Medium permeability substrates; Moderate oil penetration/burial: Coarse sand beaches, Intermediate beaches with fine to medium sand, sheltered.
CSI 5	Medium to high permeability substrates, with high oil penetration/burial; or limestone rock structure: Mixed sand and gravel, or shells and coral fragments beaches; Terrace or fringe sandstone reefs.
CSI 6	High permeability substrates; high oil penetration/burial: Gravel beaches, limestone debris.
CSI 7	Sub-horizontal, permeable, exposed substrates: Exposed sandy tidal flat; Exposed Tidal Flats.
CSI 8	Impermeable to moderately permeable, sheltered substrates with abundant epifauna.
CSI 9	Semipermeable substrates, flat, sheltered, or reefs with bioconstructional concretions: Sandy/muddy tidal flat; unvegetated wetlands; Muddy low-water terrace; Sandstone reefs supporting coral colonies.
CSI 10	Swampy areas with above-water vegetation: Vegetated delta; Flood terraces, swamps, banks of rivers and lakes; Mangrove Salt Marshes.

Source: adapted from Brasil (2004).

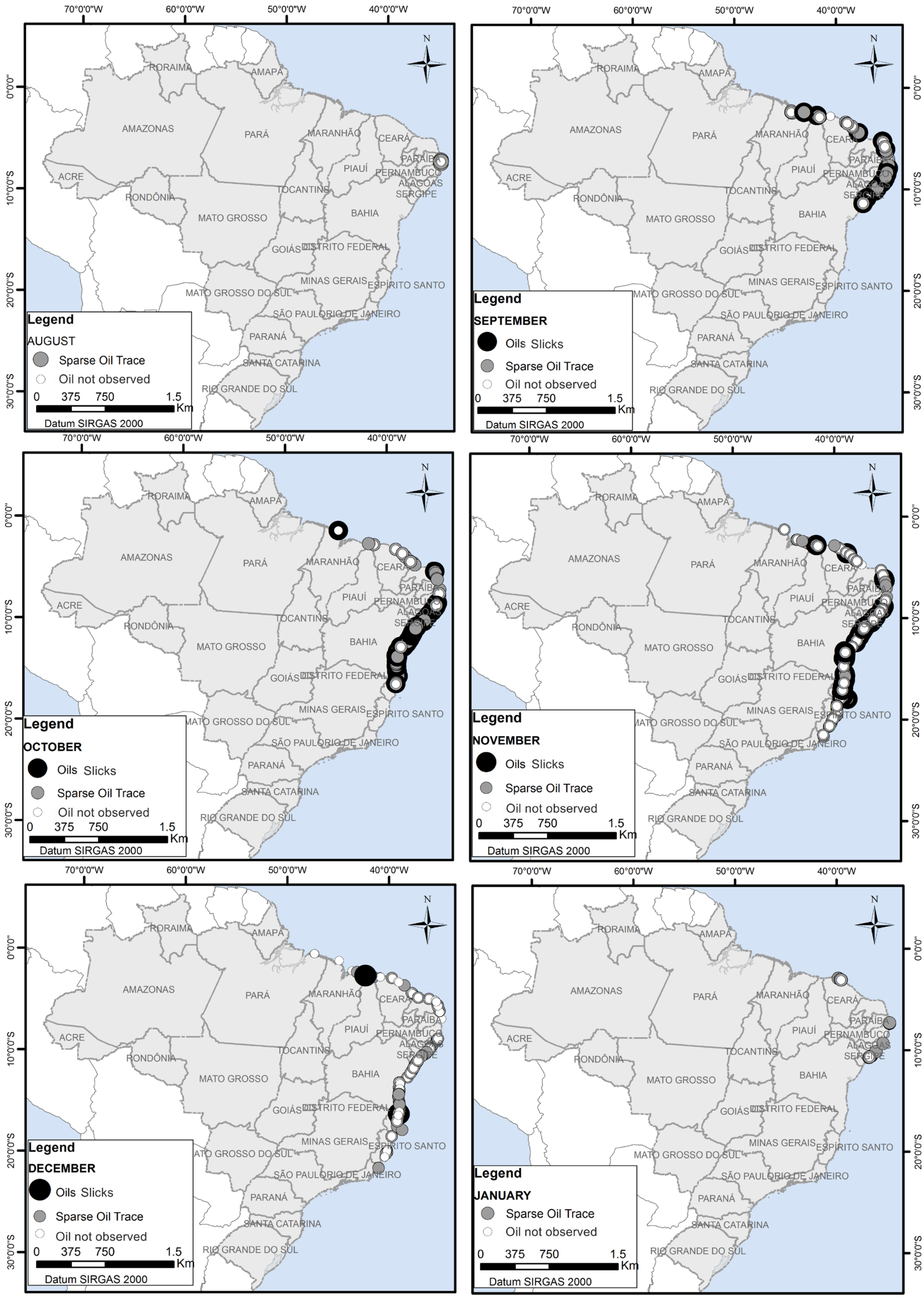

Figure 1 – Distribution of oil residues along the Brazilian coastline, August 2019 to January 2020.

In September, oil residues were already in the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Sergipe, Pernambuco, Alagoas and Bahia. In October, the waste reached Espírito Santo and in December, Rio de Janeiro. The sightings carried out by IBAMA also increased in the months with the highest amount of oil on the coast. That is, over the months there was a differentiated sampling effort, which became more intense in the months with the highest amount of crude oil on the coast. This sampling effort per state can be seen in Table 2. With regard to oil slicks, which are the most intense residues, the month of October had the highest number of records, followed by November and September. In December and January the sightings of oil slicks reduced a lot, and in January there were no oil slicks.

Observing the chronology of waste dispersion (Figure 1 and Table 3), it is observed that the coast of Bahia had the highest record of oil slicks, mainly in October and November. In October, in addition to the coast of Bahia, slicks also appear in Alagoas, Sergipe, Pernambuco, Maranhão and Rio Grande do Norte. And in November, the slicks spread along the coast reaching seven different states. The coast of Bahia continued to be the most affected, followed by Sergipe, Alagoas, Ceará, Rio Grande do Norte, Piauí and Pernambuco. In December, only Bahia and Maranhão had records of oil slicks.

The sparse traces of oil, on the other hand, had the highest volume of sightings in the month of November, distributed along the coast of 11 states, even reaching Rio de Janeiro. In December there was a reduction to 9 states: Bahia, Alagoas, Maranhão, Sergipe, Espírito Santo, Piauí, Rio Grande do Norte, Ceará and Rio de Janeiro. And, finally, in January, the sparse traces reduced considerably, appearing only in Sergipe, Ceará, Paraíba and Alagoas.

As for the habitats affected by the oil spill, it can be seen that 50% of the sampling effort was carried out on Intermediate Beaches (CSI 4), followed by Dissipative Beaches (CSI 3) with 14%, Mangroves and Salt Marshes (CSI 10) with 13%, Gravel Beaches (CSI 6) with 9%, Mixed Beaches (CSI 5) with 4%, Exposed Tidal Flats (CSI 7) with 3%, Reefs/Tide Flats, even as High and Medium Rocky Shores Slope (CSI 9, CSI 2 and CSI 1), with 2%, and Impermeable substrate with abundant epifauna (CSI 8) with 1%. Thus, according to the sensitivity classification of the Sensitivity Oil Spill Maps, it can be said that 68% of the sampling effort was concentrated in habitats of low sensitivity (CSI 1 to 4), 17% of medium sensitivity (CSI 5 to 8) and 14% of high sensitivity (CSI 9 to 10).

However, when we observe which environments presented oil slicks (Figure 2), it is clear that 23.7% of all impermeable substrates with abundant epifauna (CSI 8) were covered by residues.

Table 2 – Chronology of the sampling effort carried out with sightings of oil.

Chronology	Total Sightings	Oil Slicks (%)	Sparse Traces (%)	Oil not observed (%)
August	75		12	88
September	1995	1.50	27.90	70.50
October	2857	6.40	51.50	41.10
November	3457	3.40	57.62	39
December	517	1	36.40	63
January	43		65.12	34.90

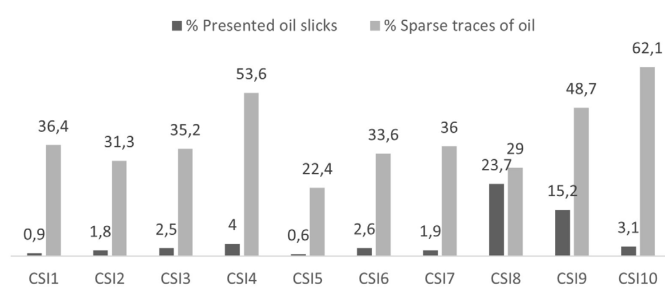

Figure 2 – Percentage of environments affected by oil residues,August 2019 to January 2020.

Table 3 – Chronology of waste dispersion by state, where type S is Oil slicks and type T is Sparse traces of oil.

States	August		September		October		November		December		January	
	S	T	S	T	S	T	S	T	S	T	S	T
AL				83	52	344	9	196		38		3
BA					104	690	87	826	1	89		
CE				24		30	4	37		4		8
ES								350		7		
MA				12	2	2		36	4	24		
PA		9		3		7		7				5
PE				1,288	6	149	1	45				
PI				14		6	2	29		7		
RJ								3		2		
RN				210	1	54	3	70		6		
SE				84	20	194	14	415		14		12

Next is Tidal Reefs/Plains (CSI 9) where 15.2% of its extension was covered by oil slicks. In smaller extensions, oil slicks covered 4% of Intermediate Beaches (CSI 4), 3.1% of Mangroves and Salt Marshes (CSI 10), 2.6% of Gravel Beaches (CSI 6), 2.5% of Dissipative Beaches (CSI 3), 1.9% of Exposed Tidal Flats (CSI 7), 1.8% of Rocky Shores of Medium Slope (CSI 2), 0.9% of Rocky Shores of High Slope (CSI 1) and 0.6% of Mixed Beaches (CSI 5).

Considering the sparse traces of oil, it is noted that 62% of the Mangroves and Salt Marshes (CSI 10) presented this type of residue, whereas it was present in 53.6% of the Intermediate Beaches (CSI 4), 48% of the Reefs/Tide Plains (CSI 9), 36.4% of High Slope Rocky Shores (CSI 1), 36% of Exposed Tidal Flats (CSI 7), 35.2% of Dissipative Beaches (CSI 3), 33.6% of Gravel Beaches (CSI 6), 31.2% of Rocky Shores of Medium Slope (CSI 2), 29% of Impermeable substrate with abundant epifauna (CSI 8), and 22.4% of Mixed Beaches (CSI 5).

Figure 3 chronologically shows the different types of waste sighting sorted by environment. In August, the habitats affected were Intermediate Beaches (CSI 4), with 7 sightings, and Dissipative Beaches (CSI 3), with 4 sightings. In September oil slicks were found on the coast of Intermediate Beaches (CSI 4) totaling 11 sightings, Dissipative Beaches (CSI 3) with 9 sightings, Gravel Beaches (CSI 6) with 6 sightings, Mangroves/Salt Marshes (CSI 10) with 2 sightings and Rocky Shores (CSI 1) with 1. In this same period, sparse traces of oil were recorded in much higher quantities than slicks. Intermediate Beaches (CSI 4) had 229 sightings, while there were 115 on Gravel Beaches (CSI 6), 81 on Dissipative Beaches (CSI 3), 38 on Mixed Beaches (CSI 5), 35 on Reefs/Tide Flat (CSI 9), 28 on Mangroves/Marismas (CSI 10), 12 on Exposed Tidal Flats (CSI 7), and 10 sightings on Rocky Shores (CSI 1 and CSI 2).

In October oil slicks were sighted in much larger numbers, and in the following coastal environments: Intermediate Beaches (CSI 4) with 99 sightings of oil slicks, Gravel Beaches (CSI 6) with 13, Dissipative Beaches (CSI 3) with 5, Exposed Tidal Flats (CSI 7) with 5, Rocky Shores (CSI 1 and CSI 2) with 2, and Mixed Beaches (CSI 5) with 1 sighting. The sparse traces of oil had an even more expressive increase in the month of October. Intermediate Beaches (CSI 4) had the highest number of sightings, totaling 942, followed by Mangroves and Salt Marshes (CSI 10) with 281, Gravel Beaches (CSI 6) with 78, Dissipative Beaches (ISCL3) with 71, Reefs/Tidal Plains (CSI 9) with 32, Exposed Tidal Flats (CSI 7) with 19, High Slope Rocky Shores (CSI 1) with 14, Medium Slope Rocky Shores (CSI 2) with 10, and Impermeable substrate with epifauna abundant (CSI 8) with 6.

In November oil slicks reduced a little, but the sparse traces of oil increased even more. The environments identified with oil slicks were: Intermediate Beaches (CSI 4) with 70 sightings, Reefs/Tide Flats (CSI 9) with 26, Dissipative Beaches (CSI 3) with 14, Mangroves and Salt Marshes (CSI 10) with 7 and Gravel Beaches (CSI 6) with 1 sighting. The environments affected by sparse oil traces in November were: Intermediate Beaches (CSI 4) with 1121 sightings, Mangroves and Salt Marshes (CSI 10) with 345, Dissipative Beaches (ISCL3) with 258, High Slope Rocky Shores (CSI 1) with 61, Gravel Beaches (CSI 6) with 59, Terraces at low tide (CSI 7) with 52, Impermeable substrate with abundant epifauna (CSI 8) with 32, Rocky Shores with Medium Slopes (CSI 2) with 28, Reefs/Tide Flats (CSI 9) with 19, and Mixed Beaches (CSI 5) with 17 sightings.

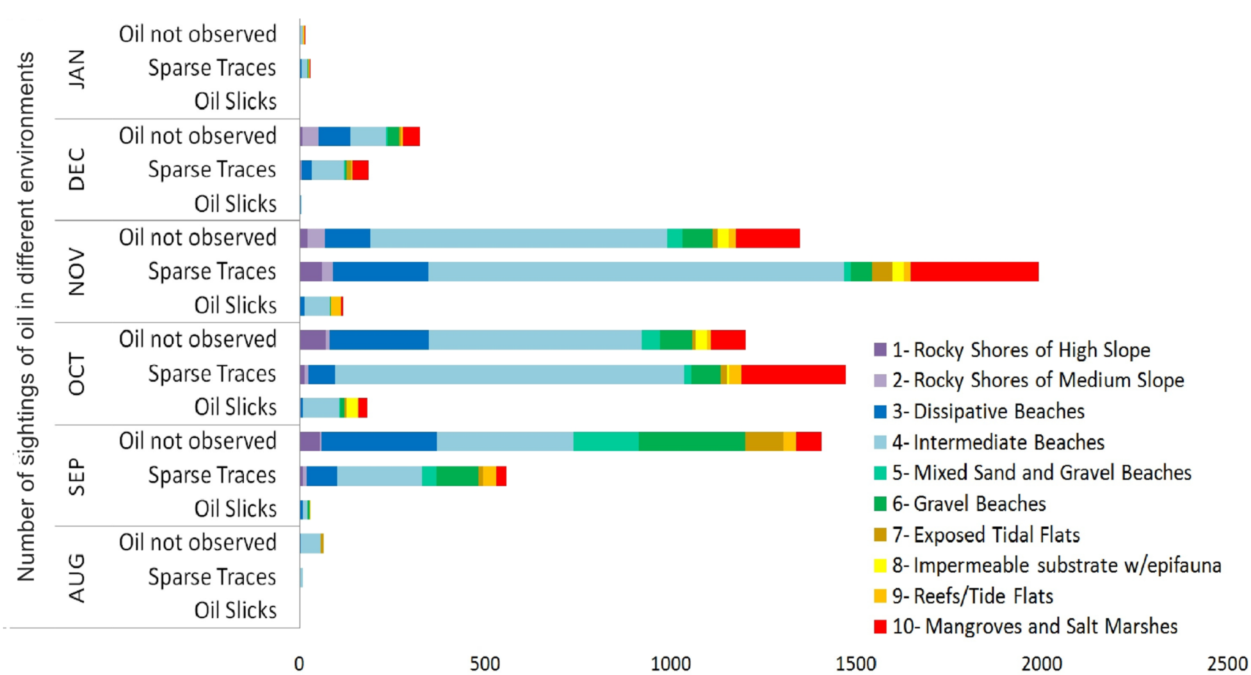

Figure 3 – Number of sightings of oil in different environments from August 2019 to January 2020.

In December oil slicks reduced significantly, being observed only in two classes of CSI, Intermediate Beaches (CSI 4) with 4 and Dissipative Beaches (CSI 3) with 1 record. Sparse traces of oil were also reduced, and the environments where this type of residue was found were: Intermediate Beaches (CSI 4) with 86 sightings, Mangroves and Salt Marshes (CSI 10) with 45, Dissipative Beaches (ISCL3) with 28, Terraces low tide (CSI 7) with 12, Reefs/Tide Flats (CSI 9) and Gravel Beaches (CSI 6) with 4, Mixed Beaches (CSI 5), and High and Medium Slope Rocky Shores (CSI 1 and CSI 2) with 3 sighting records.

In January, there were only records of sightings of sparse traces of oil, and the affected environments were: Intermediate Beaches (CSI 4) with 17 sightings, Dissipative Beaches (CSI 3) with 5, Reefs/Tide Plains (CSI 9) with 3, Beaches of Gravel (CSI 6) with 2, and Mangroves and Salt Marshes (CSI 10) with 1.

The environments considered by the Sensitivity Maps for Oil Spill Response (Carta SAO) as the most sensitive to oil spills are Mangroves/Salt Marshes (CSI 10) and Reefs/Tide Flats (CSI 9). Oil residues were present in 65.1% of the Mangroves/Salt Marshes, and in 63.2% of the Reefs/Tide Flats. Both environments at the end of this analysis in January still had oil residues, indicating that the oil spill may have compromised their integrity.

Mangroves and Salt Marshes (CSI 10) are extremely important environments precisely because they act as a nursery for marine life, having high levels of biodiversity (Brasil, 2004) and high productivity (Menghine, 2008). However, the difficulty of restoring mangroves is highlighted, given the failure in the use of techniques or the small worldwide representation of areas that are commonly recovered (Rovai, 2012). Interferences in these environments directly affect the tidal flats, since they comprise part of the same estuarine system (Godefroid et al., 2003), as well as Salt Marshes. In vegetation, oil forms a kind of wrap around the roots, adversely influencing the absorption of nutrients and water (Franco et al., 2016). In addition, toxicity causes reduced transpiration and carbon fixation, which may result in the death of plants (Rosa, 2006).

The ability of mangrove roots to purify oil residues in sediments and water (Franco et al., 2016; Silva et al., 2016) can help in the process of self-cleaning of oil residues visible to the naked eye in the vast majority of mangroves. On the other hand, the soft substrate and the difficulty of access make cleaning impractical; the effort in this sense tends to introduce the oil into the deeper layers and aggravate the damage (Brasil, 2004). In January, 2.3% of the sightings in Mangroves and Salt Marshes (CSI 10) still showed scattered traces of oil.

The restoration of coral reefs is not even considered, but their relocation is necessary to the detriment of the impacts of human activities on the places of natural occurrence (Kimura et al., 2008; Tun et al., 2008), since reversing damage to these habitats is impossible. Large-scale persistent ecological effects included impacts to deep ocean corals, failed recruitment of oysters over multiple years and damage to coastal wetlands (Barron et al., 2020). Therefore, significant interference in these habitats, mangroves/Salt Marshes and reefs/tidal flats, also compromise the ecosystem services provided by them, with these services highlighted among other coastal ecosystems (Menghine, 2008).

Although Reefs/Tide Plains (CSI 9) are less expressive in area extension than the mangroves, representing only 2% of the analyzed coastline, a large part of these environments was affected by oil residues and did not show a decline in oil records as pronounced as the mangroves. At the end of the evaluated period, 7% of the samples taken in these environments still showed sparse traces of oil. This occurs precisely because the natural removal of oil in these environments is extremely slow, and the soft substrate and the difficulty of access make cleaning this environment almost impossible, where any effort tends to introduce oil into the deeper layers. In the case of biological reefs, cleaning is impracticable, and any response actions may exacerbate the damage (Brasil, 2004).

In environments classified by the Sensitivity Maps for Oil Spill Response (Carta SAO) as moderately sensitive (CSI 5, CSI 6, CSI 7 and CSI 8), oil residues were also observed, and sighting records in these environments represented 17% of the total sampling carried out along the coast. In Impermeable Substrates with Abundant Epifauna (CSI 8) the oil tends to persist for a long time due to the lack of hydrodynamics capable of removal. In Exposed Tidal Flats (CSI 7) the oil tends not to percolate in the saturated sandy sediments, being transported along the coast by tidal currents. It has a tendency to transfer oil into deeper layers of sediment through trampling or other response actions.

Oil on Mixed Beaches (CSI 5) tends to have high persistence if there is burial or retention in substrate irregularities. Oil penetration normally goes up to about 50 cm deep, but in all these environments there is the possibility of easier cleaning, which is why in January there were no more records. The exception is Gravel Beaches (CSI 6), which are easier for oil to percolate, reaching up to about 100 cm. These environments are more difficult to remove and oil persistence can be high (Brasil, 2004), as the smallest particles of waste remain for several years in the environment (Brum et al., 2020).

The results analyzed in this work indicate that, out of the aforementioned environments, that is, those classified as moderately sensitive by the Sensitivity Maps for Oil Spill Response (Carta SAO), Impermeable substrates with abundant epifauna (CSI 8) were the most affected by dense oil slicks and Gravel Beaches showed greater persistence of residues. Of the total sightings carried out in Impermeable substrates with abundant epifauna (CSI 8), 23.7% were of oil slicks. Gravel Beaches (CSI 6) had 2.6% of records with oil slicks; Exposed Tidal Flats (CSI 7) 1.9%; and Mixed Beaches (CSI 5) 0.6%.

Sparse traces of oil were more intense in the Terraces at low tide (CSI 7), occurring in 36% of the samplings; followed by Gravel Beaches with these residues in 33.6% of the samples taken in this environment; and in 29% of Mixed Beaches (CSI 5). In January, only Gravel Beaches (CSI 6) still had sparse traces of oil in 4.7% of the records.

In general, even if in January only one environment had oil residues visible to the naked eye, these results are still worrying, since in any environment long-term toxicity affects marine life, which is not immediately killed by the spill: and the oil can be incorporated into the meat of animals, making it unsuitable for human consumption (Szewcyk, 2006), affecting not only the economy, but endangering public health. In addition, pollution represents one of the main threats to the maintenance of biodiversity in the marine environment (Amaral and Jablonski, 2005) and can make the ecosystem vulnerable to secondary disturbances, or result in a recovered ecosystem different from the conditions prior to the spill (Ainsworth et al., 2018).

Oil sighting records in low sensitivity environments (CSI 1, CSI 2, CSI 3 and CSI 4) represented 68% of the total samplings. Intermediate Beaches (CSI 4) had the highest number of sightings with oil residues, with 4% of oil slicks and 53.6% of sparse traces of oil. Dissipative Beaches (CSI 3) had 2.5% of sightings with oil slicks and 35.2% of sightings with sparse traces. And Rocky Shores (CSI 1 and CSI 2) presented respectively 0.9 and 1.8% of sightings with oil slicks, and 36.4 and 31.3% with sparse traces.

At the end of the analyzed period, there were still oil residues on Intermediate Beaches (CSI 4), which represented 39.5% of the sightings carried out in January, and on Dissipative Beaches (CSI 3), representing 11.6% of the total sightings of residues in January. CSI 4 environments are difficult to clean, as the mobility of the sediment tends to bury the oil residues, which can penetrate up to about 25 cm in depth. There is a tendency for cleaning equipment to further mix the oil with the sediment. CSI 3, on the other hand, has much lower possibilities of oil burial due to the slow mobility of the sedimentary mass, with oil penetration generally less than 10 cm deep. Cleaning is easier and more necessary at high tide. The habitats depicted in CSI 2 and CSI 1 have no oil penetration and have rapid oil removal by wave action. Removal tends to occur quickly and naturally (Brasil, 2004).

In addition to the impacts on the environment, it is important to highlight that crude oil contains several toxic chemicals, with carcinogenic, non-carcinogenic and mutagenic effects for humans, and the long-term effects on health, including the development of cancer and degenerative disorders resulting from such exposure, may result in a substantial burden of disease in the exposed population (Euzébio et al., 2019).

Conclusions

This cross-referencing analysis of oil residue sightings with the Sensitivity Maps for Oil Spill Response (Carta SAO) using Geographic Information Systems allowed an understanding of the main habitats affected by the spill along the coast. It is estimated that more than 5,000 tons of oil residues have been removed from coastal environments (Brum et al., 2020) in this event. In general, the coastal environments mostly affected by residues, representing more than 50% of the records with oil residues, were Mangroves/Salt Marshes (CSI 10), Reefs/Tide Plains (CSI 9) and Intermediate Beaches (CSI 4). Another important observation of this work is that the environments that still had oil residues in January were Intermediate Beaches (CSI 4), Dissipative Beaches (CSI 3), Gravel Beaches (CSI 6) and Mangroves/Salt Marshes (CSI 10).

With the exception of Mangroves and Salt Marshes, all other environments that presented oil residues receive visitors and have been explored for tourism in Brazil. The concern about human contamination by oil, as well as the depreciation of the landscape, could result in economic losses due to the reduction of tourist activities. However, it is important to emphasize that all environments without exception incur possible negative effects on biodiversity and fishery resources. Furthermore, it is important to consider that contamination by hydrocarbons can persist for several years in the environment without records of visible oil to the naked eye.

All these factors make the situation serious and require decision-making towards the conclusion of accountability for environmental and socioeconomic damage, as well as guaranteeing strategies for more efficient future actions in controlling this type of disaster. As a guideline for combating future oil spills, this work suggested that it is important to structure mechanisms for transparency and data integration of Brazilian databases. In this sense, the development of a WebGIS portal with a record of all government combat tools, such as the Sensitivity Maps for Oil Spill Response (Carta SAO), could be an interesting integrating tool to manage records of all oil spills, and also making these types of events more transparent for society.

We must remember that the extraction of oil on the Pre-salt layer already warns of risk to the Brazilian coast (Viglio et al., 2017), and this event showed the total lack of preparation of the Brazilian government in the fight against oil. The data on the consecutive oil spills that occur on the coast, of course on a smaller scale, are difficult to access, and often are not even reported by the media. Even with the National Contingency Plan for Oil Pollution Incidents in Waters under National Jurisdiction (Decree No. 8127/2013), systematic leaks have occurred in oil extraction in Brazil. In official notes, the government and the National Petroleum Agency recognize their structural and logistical limitations to carry out adequate monitoring of these operations on the high seas today.

Thus, a transparency approach, making data available in the Geographic Information Systems, would be fundamental for the conservation of habitats, biodiversity and all associated goods and ecosystem services. In addition, this approach establishes continuous surveillance of this type of event, which currently does not occur. An example of this is the demobilization of the unified teams involved in containing the oil from the event that took place in the Northeast and Southeast of Brazil on March 20, 2020 (Ibama, 2020).

If this type of integrated data system had already been implemented, this would even facilitate the use of the Sensitivity Maps for Oil Spill Response (Carta SAO) by all spheres of society, making the organization of oil containment actions more organized, precisely meeting the needs of places with habitats that are more sensitive and more difficult to self-clean. The Sensitivity Maps for Oil Spill Response (Carta SAO) available, together with the constant records of all oil spills disclosed in a public and accessible way through a free WebGIS system, are fundamental for the protection of the natural resources of the Brazilian coast and for the minimization of economic losses and socio-cultural damage.

Therefore, it is understood that continuous environmental monitoring of the affected environment must be carried out, and the adoption of transparency and technological measures can aid in the structuring of effective oil combat mechanisms which minimize the negative ecological, economic and social impacts of any oil spills on the Brazilian coast.

Contribution of authors:

MUSSI, C.: Conceptualization; Data curation; Formal Analysis; Funding; Acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing — original draft; Writing — review & editing. ZAGO, N.: Conceptualization; Data curation; Formal Analysis; Funding; Acquisition; Investigation; Project administration; Resources; Supervision; Validation; Visualization; Writing — original draft; Writing — review & editing. MARENZI, R.: Conceptualization; Data curation; Formal Analysis; Funding; Acquisition; Investigation; Project administration; Resources; Supervision; Validation; Visualization; Writing — original draft; Writing — original draft. POLETTE, M.: Conceptualization; Data curation; Formal Analysis; Funding; Acquisition; Investigation; Project administration; Resources; Supervision; Validation; Visualization; Writing — original draft; Writing — original draft.

References

Ainsworth, C.H.; Paris, C.B.; Perlin, N.; Dornberger, L.N.; Patterson, W.F.; Chancellor, E.; Murawski, S.; Hollander, D.; Daly, K.; Romero, I.C.; Coleman, F.; Perryman, H., 2018. Impacts of the Deepwater Horizon oil spill evaluated using an end-to-end ecosystem model. PLoS One, v. 13, (1), e0190840. https://doi.org/10.1371/journal.pone.0190840.

Amaral, A.C.Z.; Jablonski, S., 2005. Conservação da biodiversidade marinha e costeira no Brasil. Revista Megadiversidade, v. 1, (1), 43-51.

Araújo, M.E.D.; Ramalho, C.W.N.; Melo, P.W.D., 2020. Pescadores artesanais, consumidores e meio ambiente: consequências imediatas do vazamento de petróleo no Estado de Pernambuco, Nordeste do Brasil. Cadernos de Saúde Pública, v. 36, (1), e00230319. https://doi.org/10.1590/0102-311x00230319.

Barron, M.G.; Vivian, D.N.; Heintz, R.A.; Yim, U.H., 2020. Long-term ecological impacts from oil spills: comparison of Exxon Valdez, Hebei Spirit, and deepwater horizon. Ciência e Tecnologia Ambiental, v. 54, (11), 6456-6467. https://doi.org/10.1021%2Facs.est.9b05020.

Brasil, 2000. Lei nº 9.966, de 28 de abril de 2000. Dispõe sobre a prevenção, o controle e a fiscalização da poluição causada por lançamento de óleo e outras substâncias nocivas ou perigosas em águas sob jurisdição nacional e dá outras providências. Brasil (Accessed Jan, 2023) at:. https://www.planalto.gov.br/ccivil_03/leis/l9966.htm.

Brasil, 2004. Ministério do Meio Ambiente. Secretaria de Qualidade Ambiental nos Assentamentos Humanos. Programa de Gerenciamento Ambiental Territorial. Projeto de Gestão Integrada dos Ambientes Costeiro e Marinho. Especificações e Normas Técnicas para Elaboração de Cartas de Sensibilidade Ambiental para Derramamentos de Óleo. Brasília: Ministério do Meio Ambiente, 107 pp.

Brum, H.D.; Campo-Silva, J.V.; Oliveira, E.G., 2020. Brazil oil spill response: government inaction. Science, v. 367, (6474), 155-156. https://doi.org/10.1126/science.aba0369.

Buckingham-Howes, S.; Holmes, K.; Glenn Morris, J.; Grattan, L.M., 2019. Prolonged financial distress after the deepwater horizon oil spill predicts behavioral health. Journal of Behavioral Health Services & Research, v. 46, (2), 294-305. https://doi.org/10.1007/s11414-018-9602-2.

Euzébio, C.S.; Rangel, G. da S.; Marques, R.C., 2019. Derramamento de petróleo e seus impactos no ambiente e na saúde humana. Revista Brasileira de Ciências Ambientais (Online), (52), 79-98. https://doi.org/10.5327/Z2176-947820190472.

Franco, E.D.S.S.; Oliveira, O.M.C.; Santos, N.C.; Bonfim, P.; Silva, J.V.; Reis, C.Y.; Ferreira, F.L., 2016. Potencial de resposta do Mangue Preto aplicado em sistema de fitorremediação de sedimentos de manguezal contaminados com óleo cru. In: Congresso Baiano de Engenharia Sanitária e Ambiental, 4., 2016, Cruz das Almas. Anais.

Godefroid, R.S.; Spach, H.S.; Queiroz, G.M.L.N.; Oliveira Neto, J.F., 2003. Efeito da lua e da maré na captura de peixes em uma planície de maré da Baía de Paranaguá, Paraná, Brasil. Boletim do Instituto de Pesca, v. 29, (1), 47-55.

Hoff, N.T.; Takase, L.S.; Siegle, E.; Dias, J.F., 2022. Mapeamento da sensibilidade ambiental a derrames de óleo no arquipélago dos Alcatrazes (São Paulo, Brasil). Journal of Integrated Coastal Zone Management, v. 22, (1), 43-80. https://doi.org/10.5894/rgci-n452.

Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis (Ibama), 2020. Localidades afetadas pelo derramamento de óleo. Ibama (Accessed Aug, 2022) at:. http://www.ibama.gov.br/manchasdeoleo-localidades-atingidas.

IPIECA-IMO-OGP, 2012. Sensitivity mapping for oil spill response. OGP Report Number 477. PIECA/IMO/OGP, London.

Kimura, T.; Dai, C.F.; Park, H.; Hui, H.; Ang, P.O., 2008. Status of Coral Reefs in East and North Asia (China, Hong Kong, Taiwan, South Korea and Japan). In: Wilkinson, C. (Ed.), Status of coral reefs of the world. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre. Townsville, Australia, pp. 145-158.

Lessa, G.C.; Teixeira, C.E.P.; Pereira, J.; Santos, F.M., 2021. The 2019 Brazilian oil spill: Insights on the physics behind the drift. Journal of Marine Systems, v. 222, 103586. https://doi.org/10.1016/j.jmarsys.2021.103586.

Lourenço, R.A.; Combib, T.; Alexandre, M.R.; Sasakid, S.T.; Zanardi-Lamardo, E.; Yoguie, G.T., 2020. Mysterious oil spill along Brazil's northeast and southeast seaboard (2019–2020): Trying to find answers and filling data gaps. Marine Pollution Bulletin, v. 156, 111219. https://doi.org/10.1016/j.marpolbul.2020.111219.

Menghine, R.P., 2008. Dinâmica da recomposição natural em bosques de mangues impactados: Ilha Barnabé (Baixada Paulista), SP, Brasil. Tese de Doutorado em Oceanografia, Instituto Oceanográfico da Universidade de São Paulo, São Paulo.

Oliveira, M.; Riedel, P.S.; Romero, Á.F.; Abessa, D.M., 2022. Problems associated to the diagnosis of biological resources in developing of environmental sensitivity maps in Brazil. Brazilian Applied Science Review, v. 6, (2), 465-486.

Prasad, S.J.; Nair, B.; Rahaman, H.; Shenoi, S.S.C.; Vijayalakshmi, T., 2018. An assessment on oil spill trajectory prediction: Case study on oil spill off Ennore Port. Journal of Earth System Science, v. 127, (8), 1-8. https://doi.org/10.1007/s12040-018-1015-3.

Pena, P.G.L.; Northcross, A.L.; Lima, M.A.G.; Rêgo, R.C.F., 2020. The crude oil spill on the Brazilian coast in 2019: the question of public health emergency. Cadernos de Saúde Pública, v. 36, (2), e00231019. https://doi.org/10.1590/0102-311X00231019.

Pinheiro, A.B.; Silva, A.L.C., 2021. Análise da sensibilidade ambiental do litoral de Paraty (Estado do Rio Janerio, Brasil) a potenciais derramamentos de óleo. Revista Geográfica de América Central, (66), 133-164. https://doi.org/10.15359/rgac.66-1.6.

Ribeiro, W.; Fari, N.S.; Baio, C.; Campos, R.C., 2021. Da corporeidade à localização: pesquisa artística em territórios insulares da Baía de Guanabara. Estudos de Desempenho Global, v. 4, (2).

Rosa, G.S., 2006. Avaliação do potencial de espécies vegetais na fitorremediação de solos contaminados por petróleo. Dissertação de Mestrado em Engenharia Ambiental, Universidade do Estado do Rio de Janeiro, Rio de Janeiro.

Rovai, A.S., 2012. Restauração de manguezais no Brasil: retrospectiva e perspectivas. Dissertação de Mestrado em Ecologia, Universidade Federal de Santa Catarina, Florianópolis.

Silva, A.S.; Souza, J.G.; Cunha, C.M.L., 2019. Cartas SAO: índices de sensibilidade ambiental a derrames de óleo e as condições espaciais de uso e ocupação. Revista Entre-Lugar, v. 10, (19), 151-176. https://doi.org/10.30612/el.v10i19.9894.

Silva, J.V.L.; Moreira, I.T.A.; Oliveira, M.C.; Santos, N.C.P.; Bonfim, M.P.S.; Franco, E.D.S., 2016. Eficiência da Rhizophora mangle na fotorremediação de sedimentos de manguezal contaminados por petróleo. In: Congresso Baiano de Engenharia Sanitária e Ambiental, 4., 2016, Cruz das Almas. Anais. pp. 1-6.

Soares, M.M.; Pereira, L.A.V.; Terceiro, A.M.; Walter, T., 2019. Cartas de Sensibilidade Ambiental a Derramamentos de Óleo (Cartas SAO): Análise da Componente Socioeconômica dos Municípios de Arambaré e Tapes/RS/Brasil. Anuário do Instituto de Geociências, v. 43, (2), 87-100. https://doi.org/10.11137/2020_2_87_100.

Soares, M.O.; Teixeira, C.E.P.; Bezerra, L.E.A.; Paiva, S.V.; Tavares, T.C.L.; Garcia, T.M.; Araújo, J.T.; Campos, C.C.; Ferreira, S.M.C., 2020. Oil spill in South Atlantic (Brazil): environmental and governmental disaster. Marine Policy, v. 115, 103879. https://doi.org/10.1016/j.marpol.2020.103879.

Szewcyk, S.B., 2006. Processos envolvidos em um derramamento de óleo no mar. Anais Seminário e Workshop em Engenharia Oceânica. Universidade do Rio Grande.

Tun, K.; Ming, C.L.; Yeemin, T.; Phongsuwan, N.; Amri, A.Y.; Ho, N.; Sour, K.; Van Long, N.; Nanola, C.; Lane, D.; Tuti, Y., 2008. Status of Coral Reefs in Southeast Asia. In Wilkinson, C. (Ed.), Status of coral reefs of the world. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, pp. 131-144.

Viglio, J.E.; Di Giulio, G.M.; Ferreira, L.C., 2017. Not all glitters in the black gold: uncertaintties and environemental threats of the Brazilian Pré-Sal. Ambiente e Sociedade, v. 20, (3), 21-38. https://doi.org/10.1590/1809-4422asoc58r3v2032017.