Environmental Science and Pollution Research (2023) 30:35430–35449
https://doi.org/10.1007/s11356-022-24592-3

RESEARCH ARTICLE

Vulnerability of biological resources to potential oil spills in the Lower Amazon River, Amapá, Brazil

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Received: 6 September 2022 / Accepted: 1 December 2022 / Published online: 19 December 2022

Abstract

Ships that transport oil or derivatives on the Lower Amazon River waterway are at a considerably high risk of suffering spills, with severe environmental and socioeconomic consequences. The present study is aimed at modeling and simulating the oil dispersion and magnitude of these accidents in terms of the vulnerability of biological resources, considering two oil types most often transported by medium-sized tankers in the region (S500 and S10). The study method was as follows: (a) secondary data were collected from local species, and the coastal sensitivity index (CSI) was calculated, obtained from Brazil's Letters of Environmental Sensitivity to Oil Spill (*Cartas de Sensibilidade Ambiental ao Derramamento de Óleo* (SAO)); (b) ship traffic information was obtained from Brazil's Statistical Yearbook of Waterway (*Anuário Estatístico Aquaviário* (ANTAQ)); (c) modeling and numerical simulation of oil spills in water were performed, in order to investigate dispersion scenarios (SisBaHia); (d) three numerical scenarios of oil plume dispersion (in May and November) were integrated to assess species vulnerability in three zones of environmental interest (I, II, and III). Some species identified in zone II were considered to be the most vulnerable (fish, plankton, aquatic mammals, amphibians, aquatic invertebrates, trees, and plants), with the mammal *Sotalia fluviatilis* being at risk of extinction (Gervais & Deville, 1853). The simulated scenarios showed that contingency plans should have a minimum response time of 3 h and a maximum response time of 72 h to prevent the oil plumes from dispersing as far as 170 km longitudinally, depending on the zone, season, and tidal phase. Thus, a total of 62 sites of biological resources were identified in the literature recorded from 2016. Considering them, 324 species of flora and fauna were recorded, distributed in the following seven groups: (i) 49 tree and plant species, (ii) 37 amphibian species, (iii) 2 aquatic invertebrate species, (iv) 23 invertebrate species, (v) 1 aquatic mammal species, (vi) 95 fish species, and (vii) 117 planktonic species. A failure to respond to these accidents would impact immense intact aquatic areas and ecosystems, with unpredictable consequences for local biodiversity conservation.

Keywords Amazon estuary · Oil dispersion · Contingency and prevention · Modeling and simulation

Communicated by Marcus Schulz.

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Introduction

Accidents involving oil spills during transportation, or due to the inappropriate cleaning of oil-containing reservoirs, have been widely reported in the literature. This is mainly due to their severe impact on coastal regions and aquatic ecosystems (Euzebio et al. 2019). Several recent oil spills have been reported on the Brazilian coast despite the efforts of the oil industries to improve safety and develop preventive and corrective methods (Pena et al. 2020).

Brazil's Letters of Environmental Sensitivity to Oil Spill (*Cartas de Sensibilidade Ambiental ao Derramamento de Óleo*—SAO) were produced in the last three years to mitigate and prevent accidents throughout the Brazilian coast—they are used for contingency planning and for responding to oil accidents. SAO Letters can be helpful in a range of areas, including coastal protection and planning of clean-ups at specific sites, strategic planning on a regional scale, and in major accidents in remote areas (MMA 2004). Here, the SAO Letters from the mouth of the Amazonian Maritime Basin (IEPA 2017) were used. This area includes one of the most important estuarine ecosystems in Brazil, the Amazon River (Santos et al. 2016).

This region is significant due to the Amazon estuary's global ecological importance, with its peculiar seasonal dynamics for nutrients (Monteiro et al. 2015), natural habitats for the growth, and reproduction of many species (Santos et al. 2016), migratory birds (ICMBio 2019), rich biological diversity (Dias et al. 2016; Cunha et al. 2021), and biogeochemical processes that influence the regional and global balance of greenhouse gas emissions (respiration/degradation of organic matter) (Ward et al. 2013; Valério et al. 2021).

There is also a rapid economic revival in the region, as the Port of Santana is undergoing economic recovery. In 2012, during the heyday of the mineral sector in Amapá, Companhia Docas de Santana (CDSA) shipped approximately 230 ships (over 7.5 million tons' worth of products) (CDSA 2022). However, this was reduced to 49 loaded vessels in 2020, with a movement of 1,500,000 t. At the beginning of 2022, CDSA received a new private container port terminal from the Brazilian Federal Revenue (CDSA 2022). This terminal has a capacity to store and dispose of goods in the state of Amapá, promoting increased movement of ships and cargo in the region and serving as a warehouse where the containers can be sent to other ports in the Amazon (ANTAQ 2022). Thus, the Port of Santana is important for economic investments aiming at increasing the transport of oil (fuel) and derivatives (Cunha et al. 2021). In addition, it is a conduit for grain harvested in the central-western region of Brazil, reducing the travel time to Europe by at least three days in comparison to other ports (CDSA 2022).

There are environmentally sensitive and dynamic coastal ecosystems endowed with a rich tropical biodiversity along the Amazon River waterway, especially in the North Channel (Almeida 2008). This study therefore provides three new scientific contributions: (a) focus on the potential impact on biota species that have not yet been studied or identified in past studies (IEPA 2017; Araújo et al. 2021; Cunha et al. 2021); (b) simultaneous analyses of **S10** and **S500** oil, taking their different physicochemical and kinetic characteristics into account; and (c) inclusion of two new accident risk sites (in addition to the Port of Santana—P3): the potential industrial installation for fuel storage near the mouth of the Matapi River (P2) and the rectilinear stretch of the North Channel of the Amazon River (P1), upstream of P3 (Fig. 1).

Despite the importance of the subject to the scientific community, there is a significant lack of information on which species of the aquatic and terrestrial biota could be most impacted by oil spills. The literature on identified biological resources is outdated for mitigating impacts and managing emergencies and crises (Cunha et al. 2021; Araújo et al. 2021). In addition, there are few studies quantifying the environmental impact along critical stretches of this waterway that considers the residence time and the concentration of the oil plume at the place of any possible accidents which may occur (Cunha et al. 2021). The main reason for this is that the database of species vulnerable to oil has not been updated since the last official studies were carried out in 2016 (IEPA 2017).

The literature needs to be updated, as it defines, with great geospatial precision, the scope of biodiversity conservation management in joint emergency actions or contingency plans in the event of accidents. The current study thus contains the most up-to-date information on the biological resources, feeding this data into oil plume dispersion models. It significantly updates the information available on biological resources, going up to 2021. The original data, described in the SAO Letters, goes up to 2016 for the North Channel of the Maritime Basin, at the mouth of the Amazonian Maritime Basin (Santos et al. 2016).

In addition to the movement of small and medium-sized vessels (10,000 to 50,000 dwt) on the North Channel waterway carrying different commodities (including oil and petroleum products) (Santos et al. 2016), passenger vessels are a potential source of oil emissions, although on a smaller scale (Fragoso Neto et al. 2018). The 50,000 t limit for tankers on the waterway is due to the restriction of the dynamic draft of up to 22.5 m (Leal and Góes 2018). However, the risk of potential accidents is increased by aspects such as the frequent non-compliance with the maximum speed limit on the waterway of up to 10 knots (Pereira et al. 2014).

The nearshore navigation route in this stretch of the Amazon River depends on local characteristics like

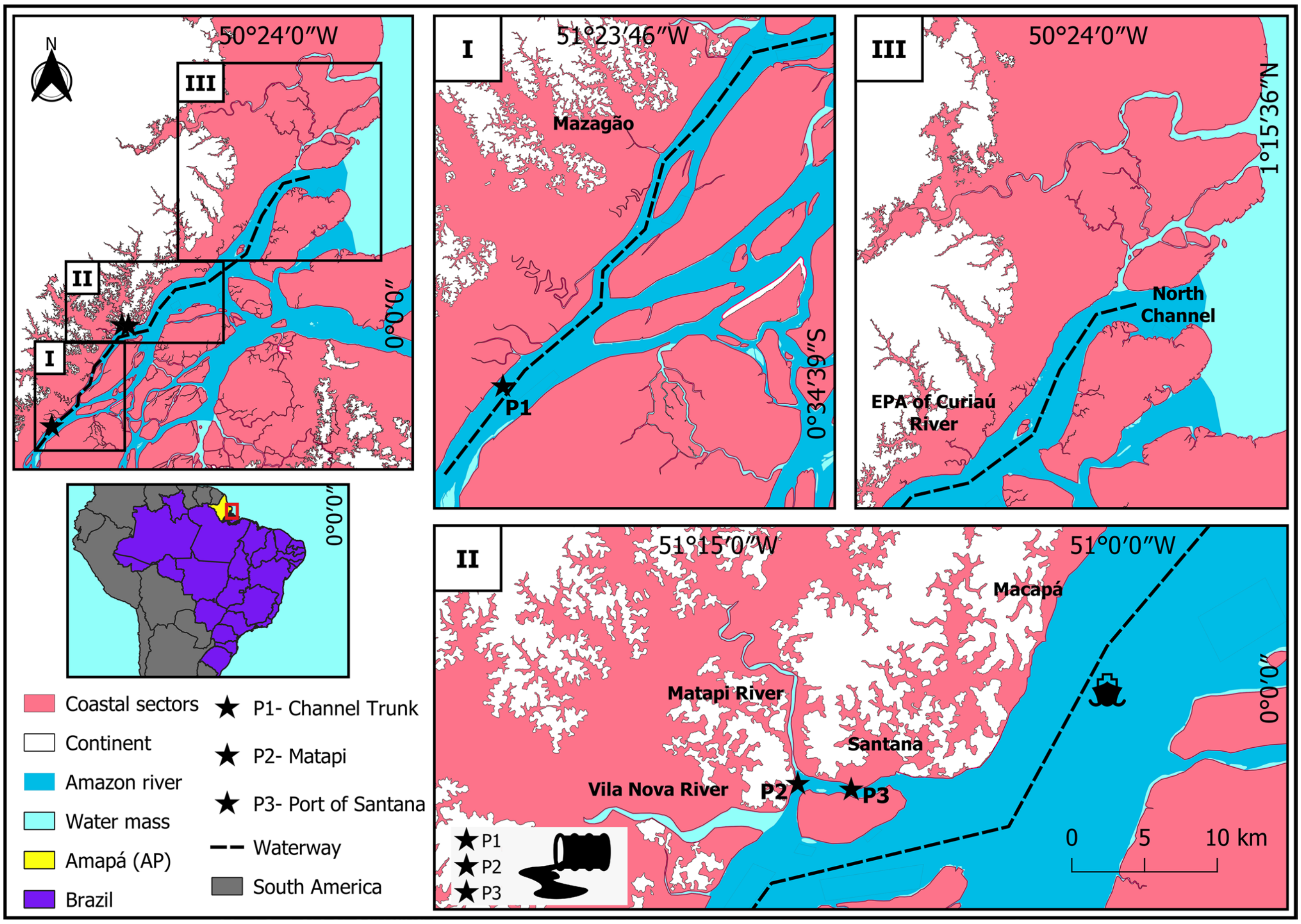

Fig. 1 Study area. Source: Authors (2022). Spatial data: IEPA (2017)

geomorphology, CSI, bathymetry, hydrology, and hydrodynamics. As these are hyperdynamic (varying significantly in time and space), they are relevant not only to the waterway but also to the oil and gas industries (Almeida 2008). They are interdependent, since the natural hydrodynamics in the North Channel waterway of the Amazon River are virtually unknown, except when within the waterway's route (currents, tides, bathymetry, etc.) (Abreu et al. 2020; Cunha et al. 2021). However, the amount of information available decreases closer to the coast. This research seeks to answer the main question of whether the available information on biological resources is sufficient for decision-making to prevent, mitigate, or remedy any environmental impacts on this busy stretch of water.

The general objective of this study was to analyze the spatial-seasonal changes in the vulnerability of biological resources due to potential oil spills involving medium-sized tankers (up to 50,000 t) traveling or anchored along the North Channel waterway of the Amazon River. For this purpose, a simulation of this vulnerability, as described by the CSI in relation to the reach and concentration of oil plumes (**S500** and **S10**), is considered in the analysis. Three areas of the greatest vulnerability of biological resources to accidents were identified (P1, P2, and P3). These scenarios considered both the physical environment and the biotics of the areas at greatest environmental risk. This information is critical for planning and management purposes in the maritime-inland transport sector and, more importantly, for biodiversity conservation.

The main novelty of the present research is the integration of updated information from the literature on species of local tropical biodiversity already identified (state of the art) and accidental oil spill scenarios with the help of modeling and numerical simulation of pollutant dispersion. Such integration provided insights into areas and periods potentially more impacted by eventual oil spills and the vulnerability of species or groups of species that inhabit the coastal-estuarine zone of the Lower Amazon River.

This study tested the hypothesis that the updated database of biological resources significantly improves assessment of the regional biotic vulnerability during oil spills in the Amazon River waterway. The choice of the geographical area under study, where local species have been identified in the literature, significantly improves quantification of the vulnerability of species that have not been identified since 2016. We also considered that plume displacement and permanence in sensitive and vulnerable areas depend on the launch site (zones I, II, and III; sites P1, P2, and P3), season (rainy or dry), and tidal phase (ebb or flood). This approach brings together several areas of knowledge, leading to better identification of groups or species of interest for biodiversity conservation.

Materials and methods

Study area

The study area covers the North Channel waterway of the Amazon River (Fig. 1), located in the coastal zone of the state of Amapá (AP), between the Atlantic Ocean and the municipalities of Macapá (AP) and Santana (AP) (Torres and El-Robrini 2006). This area was conveniently subdivided into three zones (I, II, and III) near the mouth of the Amazon River, with a total area of about 221 km^2. The geographic coordinates of these zones are 0° 8′ 37.22″ N and 50° 50′ 46.55″ W. Two seasons (May 2019, rainy; November 2019, dry) were considered in the hydrological scenarios due to the availability of data for calibrating the hydrodynamic model (Cunha et al. 2021).

This area is characterized by hyperdynamic coastal ecosystems subject to complex physical and biogeochemical processes in the transition zone between the Atlantic Ocean and land (Almeida 2008; Valério et al. 2021; Less et al. 2021). Macapá and Santana, the two most economically important municipalities in Amapá, are located in the North Channel, where the main movement of vessels and transportation of oil and derivatives occurs (Fragoso Neto et al. 2018; Cunha et al. 2021). These specific zones, involving the waterway and the port area, are of interest for the conservation of identified biological resources. The present study selected them for convenience, in order to obtain a better understanding of the geospatial analyses presented.

Conceptual model and experimental and numerical design

The conceptual model represents the hypothesis and the fundamental steps of the present research (Fig. S1), subdivided into four main steps: (a) collection and updating of secondary data on biological resources (Santos et al. 2016; IEPA 2017); (b) collection of updated information on the traffic of medium-sized tankers, which represent a higher risk of oil spill, in the North Channel of the Amazon River (ANTAQ 2022); (c) hydrodynamic and environmental modeling (dispersive), including hydrological information for oil plume dispersion scenarios; and (d) integration of numerical simulation scenarios of oil plume dispersion in the waterway and port area with spatial analysis of the vulnerability of biological resources, CSI, and tanker traffic (ANTAQ) (Cunha et al. 2021).

Step a: survey and update of secondary data on biological resources

The survey of biological resources was carried out using secondary data from the literature retrieved from research platforms (Web of Science, Scopus, Scielo, and Google Scholar) and regional technical studies published before 2016 and then updated between 2016 and 2021.

The references for biological resources contain new information but are restricted exclusively to the localities of the estuarine coastal zone (zones I, II, and III). The secondary data obtained from the literature followed the same methodological identification criteria used in the SAO letters for the mouth of the Amazonian Maritime Basin (Santos et al. 2016), meeting the criteria of the identification proposals and descriptions of specific and similar studies (Edmonds et al. 2021). This procedure allowed for mapping the local resources which would face the biggest threat by any potential oil spill (Cunha et al. 2021).

Sixty-two new sites of georeferenced studies on local biodiversity were identified, comprising a total of 324 species of fauna and flora distributed in seven groups, as follows: (1) trees and plants, (2) amphibians, (3) aquatic invertebrates, (4) invertebrates, (5) aquatic mammals, (6) fish, and (7) plankton. The sites and species were then organized and grouped in an Excel© table according to the following categories: (a) species; (b) conservation status (vulnerable, VU; near threatened, NT; least-concern, LC; data deficient, DD; not evaluated, NE); (c) sites; (d) geographical coordinates; (e) distance from the site to the waterway (km); (f) selected zones (I, II, and III); (g) CSI scale (1, 2, 3, 4, 5, 6, 7, 8, 9, and 10; IEPA 2017); (h) biological importance; and (i) references by author, sites, and species (Table S1).

Subsequently, the geographical coordinates of each site were saved in Google Earth Pro, and their location, in terms of degrees, minutes, and seconds (default), were obtained. They were then transformed into layers (shapefile) in QGIS 3.18. It is noteworthy that we georeferenced the coordinates for the SIRGAS 2000 datum in the QGIS; i.e., the coordinate system of the site was transformed, allowing the thematic layers to be integrated into the same reference system, avoiding site errors (Roque et al. 2006; Araújo et al. 2021).

The shapefile of the mouth of the Amazonian Maritime Basin cartographic base and the CSI of the study area, publicly available on the SAO Letters website (IEPA 2017), were also entered in QGIS. After entering the data, colors, symbology, categorization, labels, and map layout were adjusted on the website.

Step b: updated traffic information for medium-sized tankers (ANTAQ)

Traffic data from medium-sized tankers carrying oil or petroleum products on the North Channel waterway of the Amazon River were collected and updated to evaluate the specific sites with the highest risk of potential accidents with oil spills. Accidents would probably have the largest impact close to these routes (Pereira et al. Cunha et al. 2021), regardless of the season or tidal phase (Araújo et al. 2021).

Previous studies have used the Automatic Identification System (AIS) database (Marine Traffic 2021), an international on-board system responsible for the automatic exchange of information on voyages and vessels between ships or between ships and coastal stations (IALA AISM 2016; Pereira et al. 2014; Cunha et al. 2021). This information can be obtained by monitoring the ship routes individually in waterway stretches. In these studies, we identified a series of vessel parameters, such as the average traffic speed (Pereira et al. 2014; Cunha et al. 2021).

However, due to the current difficulties in accessing AIS data for the studied region, we used the vessel traffic data from the Waterway Statistical Yearbook of the National Waterway Transportation Agency (ANTAQ 2022), mainly of those referring to ports that handle liquid bulk and fuel derivatives in northern Brazil. It is worth mentioning that, although the Port of Santana does not move liquid bulk, bulk carriers circulate through the North Channel of the Amazon River. The data used for this study were the following: (1) number of port terminals, (2) number of moorings, (3) average consignment transported by ships in t, from 2019 to 2021 (Table S2).

Table S2 shows the number of port terminals that received bulk carriers from 2019 to 2021. It is important to highlight that two new terminals were built in Santarém (PA) in 2021. Table S3 shows the distribution of the number of moorings that occurred during the period in the port terminals. The Port of Santana does not handle liquid and gaseous bulk (ANTAQ 2022; CDSA 2022). There are a high number of moorings of bulk carriers in the region, mainly in the port of Manaus, due to its reception infrastructure (Almeida 2008; Pereira et al. 2014). Table S4 shows the ships' average consignment (in t). Solid bulk ships that dock at the Port of Santana have larger consignments in comparison to ships that carry liquid and gaseous bulk. Differences between port terminals are associated with the types of vessels received, as well as their physical characteristics and reception and operation infrastructures (Pereira et al. 2014; Cunha et al. 2021).

Step c: hydrodynamic and environmental modeling (dispersive)

The following information was included in the numerical simulation model: (1) physicochemical parameters of S500 and S10 oils, such as viscosity (kinematics), density, pour point, additives, distillation, and flash point (API 2021; Petrobras 2021; ANP 2022) (Tables S5 and S8). These parameters were obtained directly from the ADIOS 2.0 software (NOAA 2000) to calculate the decay rate of the oils: (2) analysis of the time intervals for visualization of the dispersion plume after hypothetical accidents: **S500** oil (9 h, 24 h, 36 h, and 72 h) and **S10** oil (3 h, 6 h, 9 h, and 12 h) (Abreu et al. 2020; Cunha et al. 2021; Araújo et al. 2021). The different dispersion times used for oil **S500** and **S10** were chosen because the plumes showed very similar dispersive and visual patterns for the same hydrodynamic scenarios. Therefore, differences in the plumes for the same observation times of the model outputs would not be easily noticeable: (3) site choice for the three scenarios—(P1) "Channel Trunk," a rectilinear stretch of the main channel waterway of the Amazon River, (P2) Matapi, and installation planned for fuel storage, and (P3) Port of Santana, scenarios S-1, S-2, and S-3; (4) hydrodynamic model calibrated based on two hydrological periods (May, rainy; November, dry); and (5) additional hydrological information for basic parameterization and calibration of the hydrodynamic model (Pinheiro et al. 2008; Cunha et al. 2012; Abreu et al. 2020; Cunha et al. 2021).

The initial and boundary conditions of the dispersion model require high-quality environmental data and should therefore be carefully integrated into the dispersive oil spill model. These parameters were inserted in different modeling stages in the ADIOS 2.0 (NOAA 2000) and SisBaHia (Rosman 2021) computer programs. To simulate the hydrodynamic and dispersive behavior of the oil plume, we parameterized and analyzed (1) the previously calibrated 2DH hydrodynamic model and (2) Lagrangian (coupled dispersive) model, according to a similar analysis by Cunha et al. (2021).

SisBaHia uses a 2DH hydrodynamic circulation model optimized for natural water bodies, in addition to Eurelian and Lagrangian models (pollutant dispersion), to describe transport phenomena (Rosman 2021). The hydrodynamic behavior of the pollutant was then simulated (Eqs. 1, 2, and 3).

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{Ux} + V\frac{\partial U}{\partial y} = -g\frac{\partial \zeta}{\partial x} - \frac{gH}{2\rho_\circ}\frac{\partial \hat{\rho}}{\partial x} + \frac{1}{H\rho_\circ}\left(\frac{\partial(H\hat{\tau}_{xx})}{\partial x} + \frac{\partial(H\hat{\tau}_{xy})}{\partial y}\right) + \frac{1}{H\rho_\circ}\left(\tau_x^S - \tau_x^B\right) - \frac{1}{H\rho_\circ}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) + 2\Phi senV - \frac{U}{H}\Sigma q \quad (1)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{Ux} + V\frac{\partial V}{\partial y} = -g\frac{\partial \zeta}{\partial y} - \frac{gH}{2\rho_\circ}\frac{\partial \hat{\rho}}{\partial x} + \frac{1}{H\rho_\circ}\left(\frac{\partial(H\hat{\tau}_{xy})}{\partial x} + \frac{\partial(H\hat{\tau}_{xy})}{\partial y}\right) + \frac{1}{H\rho_\circ}\left(\tau_y^S - \tau_y^B\right) - \frac{1}{H\rho_\circ}\left(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{xy}}{\partial x}\right) - 2\Phi senU - \frac{V}{H}\Sigma q \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial UH}{Ux} + \frac{\partial VH}{\partial y} = \Sigma q \quad (3)$$

where u is the velocity on the x-axis (m s^{-1}); V is the velocity on the y-axis (m s^{-1}); ζ is the free elevation of the water surface (m); H is the depth of the water column (m); ρ_o is the average water density (kg m^{-3}); ρ_r is the reference water density (kg m^{-3}); g is the acceleration of gravity (m s^{-2}); τ_{ij} is the turbulent stress tensor; (i, j) are the indices on the horizontal plane $(x; y)$; $\left(\tau_x^S - \tau_x^B\right)$ and $\left(\tau_y^S - \tau_y^B\right)$ represent the wind stress on the water surface and the lowest friction stress, respectively (kg m^{-1} s^{-2}); $2\Phi senU$ and $2\Phi senV$ are the Coriolis acceleration; Φ is the angular velocity of the Earth's rotation (rad s^{-1}); φ is the latitude angle; $\sum q$ is the water balance based on atmospheric precipitation, infiltration, and evaporation; and Sij is the effect of radiation stresses (Rosman 2021; Cunha et al. 2021).

The polluting sources in the Lagrangian model are represented by several particles released at regular time intervals in the region of origin. The particles, randomly arranged in the source region, are carried by the currents calculated by the hydrodynamic model (Eq. 4).

$$P^{n+1} = P^n + \Delta t\frac{dP^n}{dt} + \frac{\Delta t^2}{2!}\frac{d^2P^n}{dt^2} + O^3 \quad (4)$$

With respect to effluents from any source, the amount of mass (Ma) of a given species observed in each particle when it enters the modeled domain is given by Eq. 5.

$$M_a = \frac{QC_a x\Delta\tau}{N_P} \quad (5)$$

where Q is the effluent discharge from the source (m^3 s^{-1}), C_a is the concentration of the substance found in the source discharge (kg m^{-3}), and N_P is the number of particles entering the domain through the source in the time interval $\Delta\tau$ (s) (Rosman 2021).

Step d: analysis and integration of data for decision-making

After collecting and tabulating the data of biological resources, an integrated analysis was performed involving all the steps described by the conceptual model (Fig. S1). These include information on the traffic of tankers and simulations with **S500** and **S10** oils, indicating the areas of the greatest potential accidents and strategic risk for crisis or emergency management, close to P1, P2, and P3.

The spatial analysis performed in QGIS 3.18 generated six numerical output maps: (a) one map with the sites of the species, the biological importance of the area, and the CSI; (b) four simulation maps containing all integrated data; and (c) one map with the plume dispersion at the three oil spill sites in order to identify a zone of maximum risk of eventual spill of oil or derivatives (Cunha et al. 2021; Araújo et al. 2021).

It is important to highlight that the hypothetical oil spill scenarios, caused by eventual accidents in the Amazon River waterway, were only simulated for two extreme hydrological periods (May and November). In these cases, we use the maximum physical capacity of up to 40 thousand tons of the tankers (12 reservoirs) traveling in the waterway. To make the simulation scenarios more realistic as possiblme we simulated a spill of 1/6 of this total capacity. That is, the hypothetical accidental oil spill would result from the rupture of only two internal reservoirs, and this spill would be continuous (about 6.7 thousand tons/3 days or 72 h).

Univariate and multivariate statistical analyses were used using the R-Project software ($p < 0.05$) to test some general hypotheses. The Shapiro–Wilk and Kruskal–Wallis tests were applied to evaluate, respectively, the normality and significance of the influence of independent variables or factors on the variability of dependent variables (pollutant concentration). Linear regressions were used to test the correlation and/or explainability between independent variables (CSI, AIS, hydrological period, tidal phase, and others) with dependent variables (species, vulnerability, conservation status, and others) (Crawley 2007).

The conservation status of the species was classified based on CNCFlora (2018) and ICMBio (2018) (Edmonds et al. 2021). The objective was to correlate the degree of vulnerability or risk with potential oil spills in the stretch of the North Channel of the Amazon River (Fig. S2). This analysis is essential to understand which species are considered threatened or more susceptible to oil spills and to relate the information to tactical or strategic decision-making required for contingency planning in the estuarine coastal zone (Araújo et al. 2021; Cunha et al. 2021).

Results and discussion

Spatial analysis of biological resources

A total of 62 sites of biological resources were identified in the literature recorded from 2016 (Fig. 2). Considering them, 324 species of flora and fauna were recorded, distributed in the following seven groups: (a) 49 tree and plant species, (b)

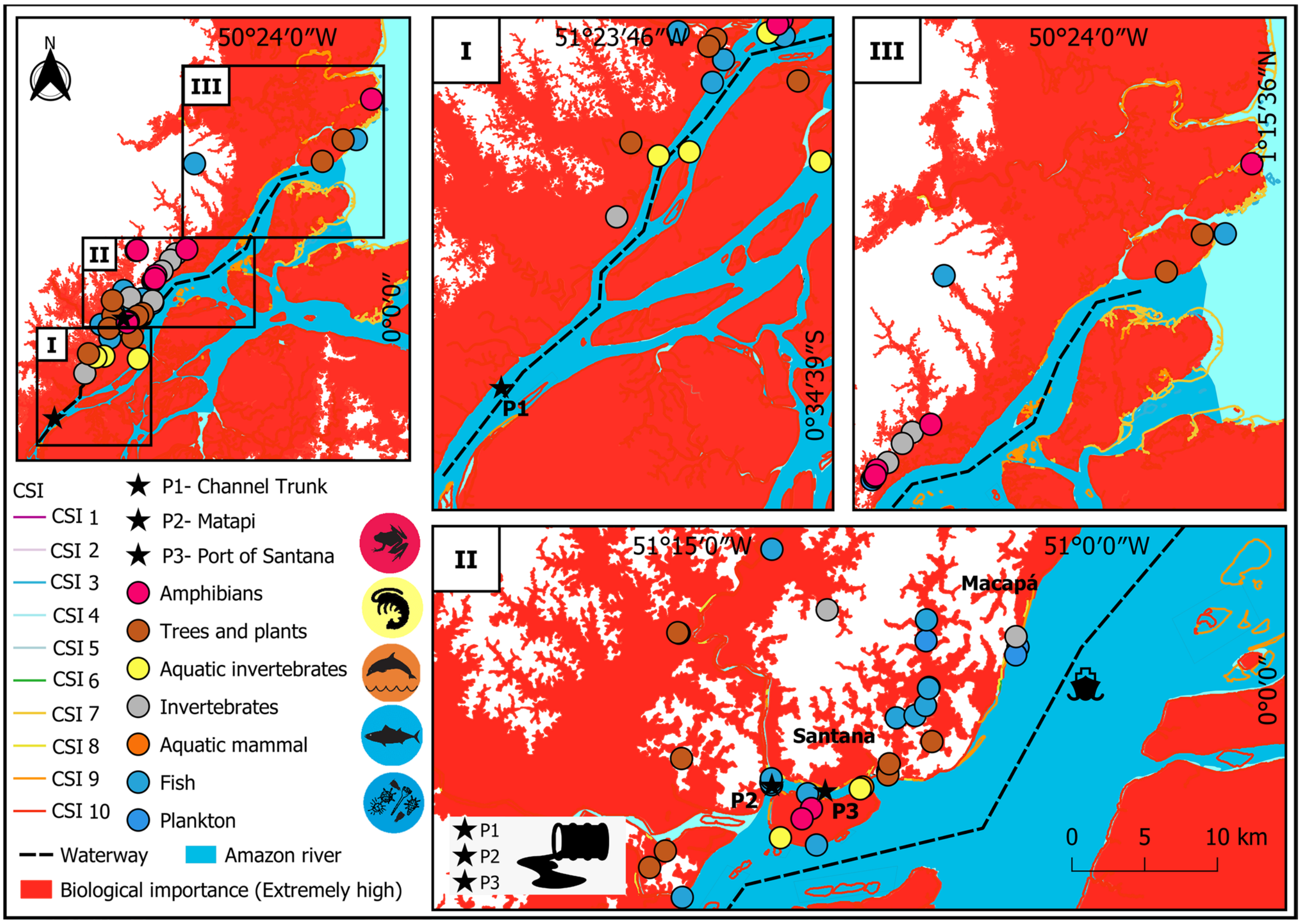

Fig. 2 Location of biological resources. Source: Authors (2022). Spatial database: IEPA (2017), MMA (2018), ICMBio (2018)

37 amphibian species, (c) 2 aquatic invertebrate species, (d) 23 invertebrate species, (e) 1 aquatic mammal species, (f) 95 fish species, and (g) 117 planktonic species (Table S1).

Biological resources are highlighted by colored circles (conventional symbols). The species identified in the literature are distributed in the three coastal zones (I, II, and III). The blue dots, representing fish and plankton, were the most commonly found in the three zones, with the highest number of species recorded in the literature to date. In contrast, the aquatic mammal group (orange dot) was the least represented in this study, containing only one species, *Sotalia fluviatilis* (Gervais & Deville, 1853). *Sotalia fluviatilis* was found in the Amazon River, near Santana Island (Miranda et al. 2021) (Table S1).

Studies on aquatic invertebrates (yellow dots) were found only for zones I and II. This result may be due to the low number of similar studies in the coastal region. The problem was observed for all groups, as evidenced by areas on the map where no study was conducted or there is no species record. This gap may be linked to the challenge of investing in research or the logistical complexity in these difficult-to-access areas in the coastal and estuarine regions, relatively far from Macapá and Santana (Torres et al. 2018).

The biological importance of this coastal zone is extremely high (MMA 2018). It is home to a high diversity and biological variation of living organisms, such as animals, plants, and microorganisms, comprising terrestrial and aquatic ecosystems and their ecological transition complexes (ICMBio 2018; Da Cunha and Sternberg 2018).

Another classification for the coastal zone is based on the CSI, which ranges on a scale from 1 to 10. The CSI frequently ranged between 9 and 10 in zones I, II, and III. This index is characterized by the substrate type on which the biological resource is located (IEPA 2017). These high values indicate that this coastal zone has high environmental vulnerability due to possible impacts caused by accidental oil spills (Cunha et al. 2021; Araújo et al. 2021).

Biological resources can also be classified by species; in the present study, the conservation status was used for this purpose (Supplement 1). For example, in the tree and plant species group, 1 NT, 1 VU, 8 LC, and 39 NE species were found (CNCFlora 2018). The amphibian group had 32 LC and only 5 NE species. The aquatic invertebrates were represented by 1 LC and 1 DD species.

The invertebrate group had 20 LC, 2 N, and 1 DD species. In addition, the only aquatic mammal species analyzed so far is classified as NT. In contrast, the fish group comprised 78 LC, 4 DD species, and 13 NE species. Finally, no species was evaluated in the plankton group, which was then classified as NE (ICMBio 2018).

The independent variable "distance" is a relevant measure of the risks of accidents in zones I, II, and III (Cunha et al. 2021; Fig. 2; Table S6). This study found that the species identified in the respective geographical sites are statistically sensitive to the proximity of the ship traffic route or even possible accident sites on the waterway. For example, *Macrobrachium carcinus* (Linnaeus, 1758) was observed at a distance of 1.22 km from the main route of the waterway and therefore is at a higher risk, while *Mesonauta festivus* (Heckel, 1840) is about 48.24 km, which represent a lower risk of exposure to an accident (Table S1).

Thus, the distance between the potential source of pollution and the species habitat is a critical variable that can influence the species' vulnerability, as will be discussed in the next section of this article. The closer the potential oil spill, the more vulnerable the species identified along the waterway or port area, a hypothesis previously supported by Edmonds et al. (2021).

Statistical analysis of independent environmental parameters (abiotic) and biological resources (species)

The Kruskal–Wallis test was used to verify whether the studied "species" are influenced by other independent environmental variables or factors. Of the nine tests performed, eight were significant in relation to the influences of the relevant independent variables (Table S6).

The variable "BioImport" did not show significant variability in its results, which were almost constant. On the other hand, the variables "species x distance" (degree of freedom 42 df, $\chi^2 = 239.6$) were significant. This suggests that distance is a critical variable in the selection of new environmental protection areas in the region (Table S6). In addition to distance dependence, the species identified could also be sensitive to the following environmental variables: geographical sites (within the estuary), geographical coordinates, proximity to the port area (I, II, and III), CSI, and investigation date. With regard to the last variable, the best interpretation is a significant correlation between increased studies of different species in the region in the last six years.

Fig. S3 was constructed as a complement to Table S6, which represents multiple-comparison Kruskal–Wallis tests to assess the conservation status of the species. Differences were observed in the average conservation status levels of the 324 species, with 95% reliability. Among the five classifications, the most significant difference occurred between VU and NT. Based on the category, this can explain that the two variables fall into the threatened category. The species in this category, for example, *Virola surinamensis* (Rol. ex Rottb.) Warb. and *Pouteria franciscana* Baehni, are threatened floristic species in the coastal zone of the Amazon River (CNCFlora 2018). Thus, variables with homogeneous categories tend to present more significant differences than variables with heterogeneous categories, such as NE and DD.

The linear regression analysis, which correlated biological resources with the independent variable CSI, was very significant in relation to the distance to the coast and significant in relation to the factor "zones" (I, II, and III). Thus, the CSI is moderately sensitive with respect to the zones (Table S7). Regarding the citation year (related to the timeliness of the information), the statistical explainability was at the limit of the significance interval. The CSI was significant in relation to the citation year (update), favoring areas with lower CSI (however, with negative angular coefficient $= -0.050$) or the more updated the study, the greater the number of studies in less sensitive areas. Based on the results, the new studies should be prioritized in the areas with the highest CSI (most sensitive).

Numerical simulation of S500 and S10 oil dispersion in the Lower Amazon River

In the simulated scenarios with **S500** oil, zone II would be the most critical if it was reached by the plumes at any of the three spill sites (P1, P2, and P3). The most critical seasonal hydrological phase would be during the rainy season (May) when the plume would reach greater longitudinal dispersion among all studied scenarios (maximum plume size in km^2). For example, 9 h after the spill, the **S500** oil plume would reach a distance of approximately 20 km during the ebb tide, expanding rapidly in 24 and 36 h and reaching distances of up to 124 km in only 72 h after the release (Fig. 3).

Regarding the dry hydrological period (November), at the beginning of the ebb tide, the **S500** oil plume (yellow spot) could reach approximately 12 km in 9 h and 88 km in 72 h after the oil spill (Fig. 4). It is important to note that the **S500** oil plumes in November have a smaller longitudinal dispersion compared to the rainy season in May. Although they are shorter, they tend to become wider and more segregated due to the hydrodynamic behavior of the currents (recirculations) added to the more intense effect of the wind, typical of the drier period. Consequently, the plumes are more concentrated in the region of the launch site (Clark et al. 2010; Cunha et al. 2021; Araújo et al. 2021).

The trend of the displacement of oil particles in relation to the combination of the effects of winds, currents, and

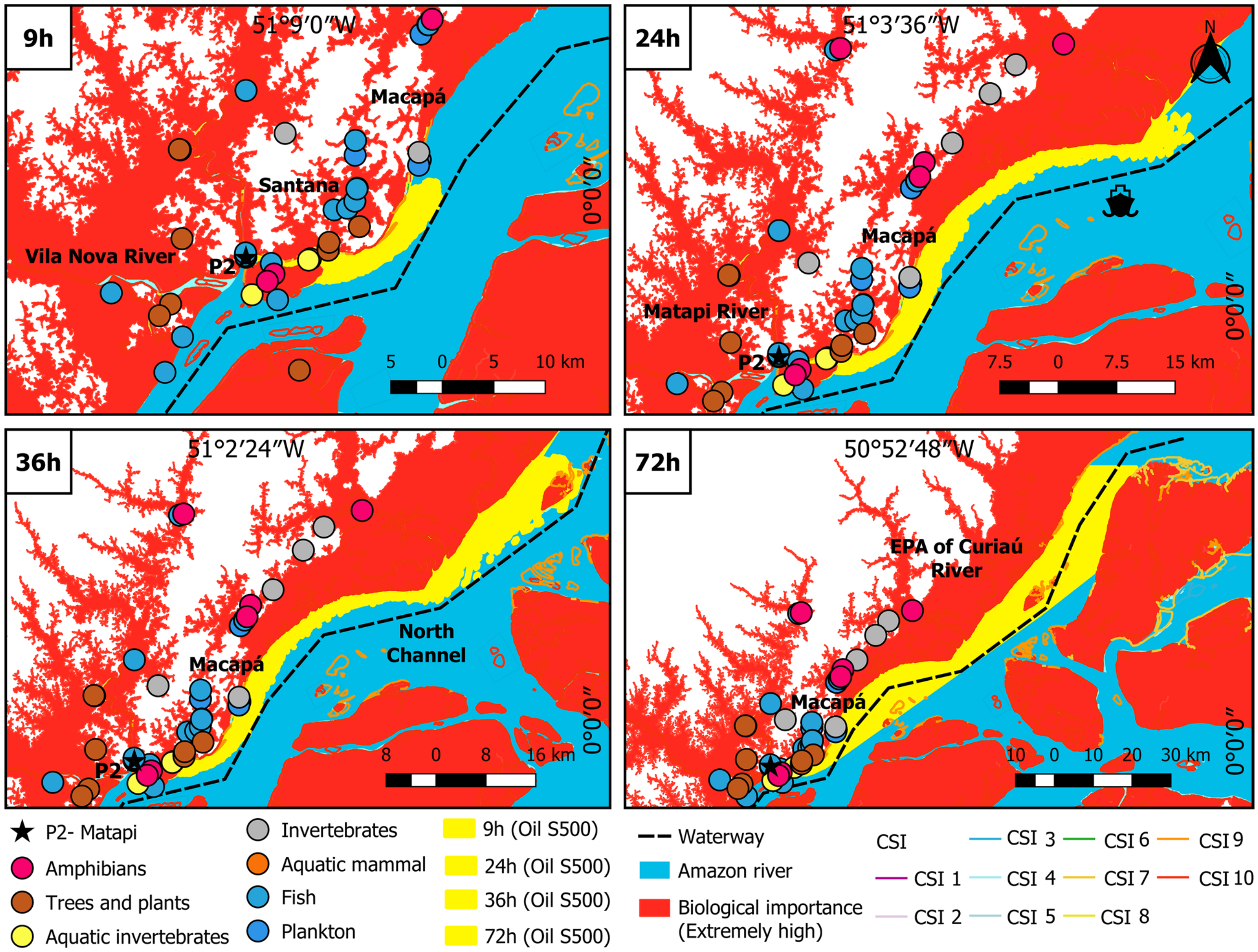

Fig. 3 Numerical dispersion output of the **S500** oil (yellow spot) at Matapi (P2), Amapá, Brazil, at time intervals of 9 h (a), 24 h (b), 36 h (c), and 72 h (d) after continuous oil spill in zone II during the ebb tide and rainy season (May). Source: Authors (2022)

discharge of the tributaries of Lagoa dos Patos (port region of the city of Rio Grande, RS, Brazil) was analyzed by Lopes et al. (2019). The results showed that different regimes of floods, leaks, and wind conditions could create different interactions and effects on the trajectories of oil particles, which can intensify or slow the speed of oil displacement in estuarine environments.

Similar simulations were performed with **S10** oil. To show other details of the plumes, we evaluated different start times of the **S500** oil spill (3 h, 6 h, 9 h, and 12 h). In this case, a high similarity was observed between both simulations for 9 h, 24 h, 36 h, and 72 h, and the plumes were virtually indistinguishable. Thus, among the scenarios simulated with **S10** oil (rainy and dry season), the most impacted area would also be zone II.

Regarding zone II, the **S10** oil plume would initially disperse upstream at the Matapi site (P2) in the rainy season (May). Thus, at 3 h, the behavior would also be similar to that obtained in the same sites with the **S500** oil because the spill would happen at the beginning of the flood tide (Fig. 5). The plume would disperse as far as the mouth of the Vila Nova River and then circulate to Santana Island until the beginning of the flood tide (6 h). Subsequently, the plume would be transported naturally downstream, along the coast (9 and 12 h), soon after the change to the flood tide (Fig. 5).

In the dry period (November) and during the beginning of the ebb tide (Fig. 6), the **S10** oil plume has a less longitudinal expansion compared to the rainy season (green spot). The plumes simulated at the Matapi site (P2) reached significant distances of at least 8.0 km in only 3 h and a maximum of 22.4 km in 12 h. However, although they would not reach longer distances like the **S500** oil, they pose similar risks to the coastal zone of the Amazon River and its biological resources (Cunha et al. 2021; Araújo et al. 2021), tending to completely circumvent the Santana Island with the plume in higher concentrations (Fig. 6).

Based on the simulations carried out with the two oil types, we found that the largest possible extension in these

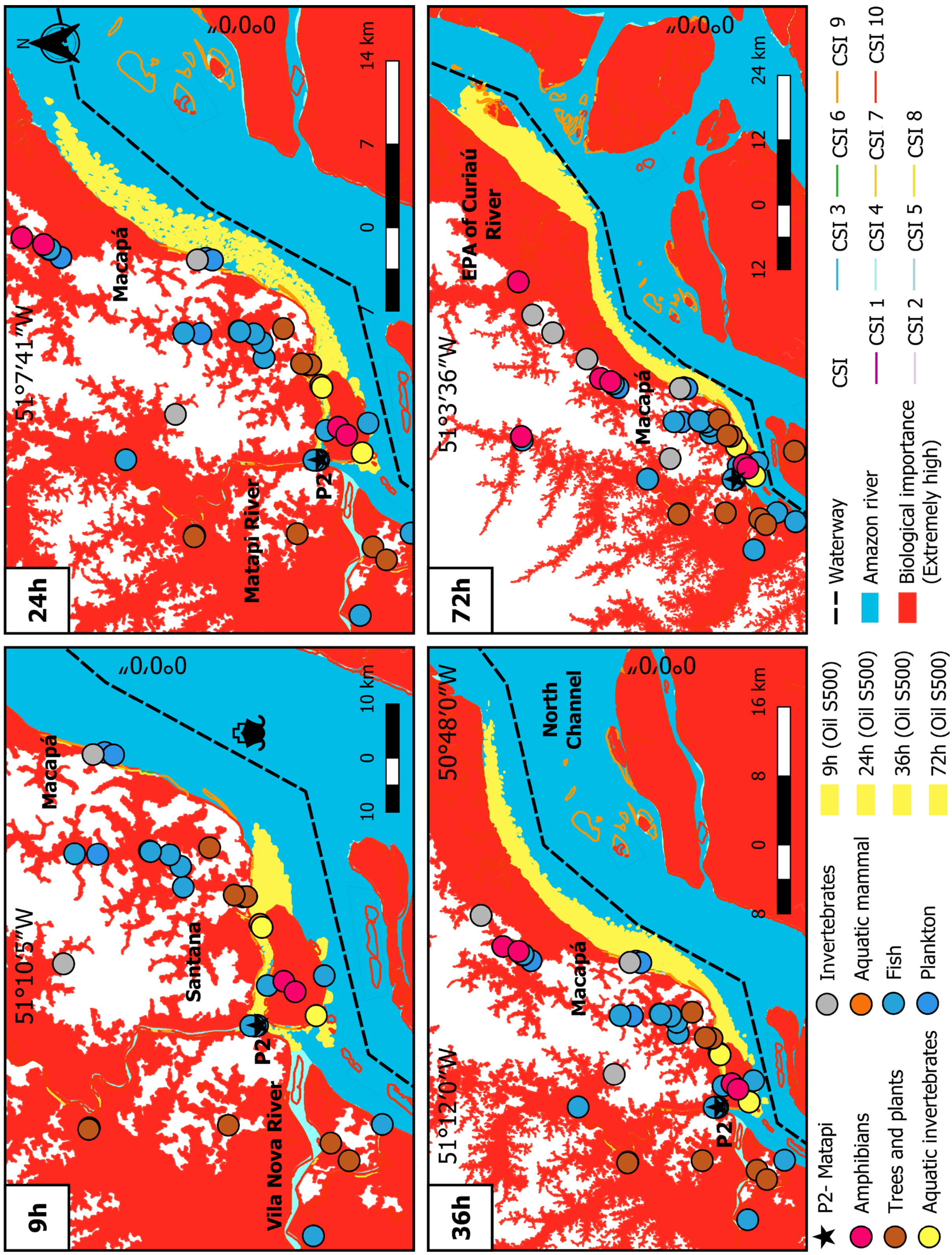

Fig. 4 Numerical output of dispersion of the **S500** oil (yellow spot) at Matapi (P2), Amapá, Brazil, at time intervals 9 h (a), 24 h (b), 36 h (c), and 72 h (d) after continuous oil spill in zone II during the beginning of the ebb tide and dry period (November). Source: Authors (2022)

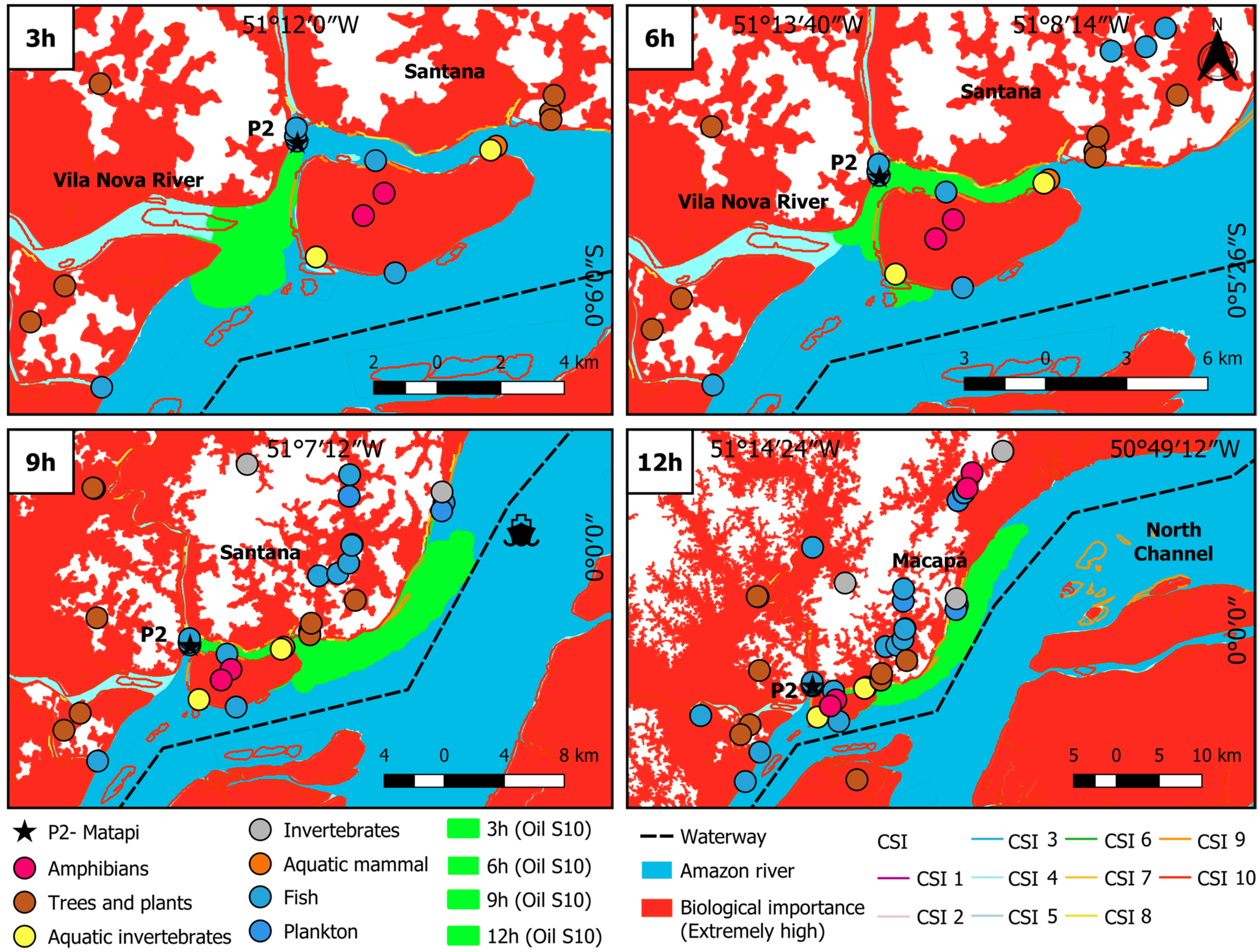

Fig. 5 Numerical output of dispersion of the **S10** oil (green spot) at Matapi (P2), Amapá, Brazil, at time intervals 3 h (a), 6 h (b), 9 h (c), and 12 h (d) after a continuous oil spill in zone II with tide and rainy season (May). Source: Authors (2022)

scenarios would be at 72 h, with the **S500** oil, during the ebb tide and the rainy season (May). In this case, the plume dispersion from the Channel Trunk (P1) would reach a distance of approximately 170 km longitudinally, which has never been simulated before. This scenario would be the most critical among all the simulations of the present study, where the plume would impact a total area of 221 km^2. Consequently, all 324 biological resources recorded would be severely impacted (Fig. 7). It is important to note that P1 is significantly distant from the sites of the greatest risk (upstream of the port area of Santana). Hypothetically, it would have the greatest potential of causing significant environmental impacts, affecting areas never before considered by similar studies.

The results of the simulations carried out with **S500** and **S10** oil suggest that the rainy season (May) during the ebb tide is the most critical and intense phase of plume dispersion. In the rainy season, the Amazon River has the most intense flow; consequently, there is greater dispersion of the oil plume. In addition, the effects of the tide are stronger during the dry period, when the flood effect is more pronounced due to the decreased flow of the Amazon River (Abreu et al. 2020). These conditions will lead to the longest longitudinal plume dispersion. The plume stretches upstream and then downstream from the pouring point. According to the simulations, if accidents occurred at one of these three sites, the plumes would disperse close to, and along, the very sensitive coast ($9 < CSI < 10$), reaching medium distances (> 7.5 km) in a few hours and long distances (170 km) in up to three days, due to the huge flow of the Amazon River.

In any of the possible scenarios, with the plume dispersion varying by up to 72 h and considering the two oil types and the two hydrological periods, the potential impact would compromise a significant part of the biological resources; i.e., virtually, all species would be negatively impacted. In addition, the impact would have socioenvironmental effects in urban areas of Macapá and Santana (AP), the environmental protection areas (APA) of Curiaú and Fazendinha,

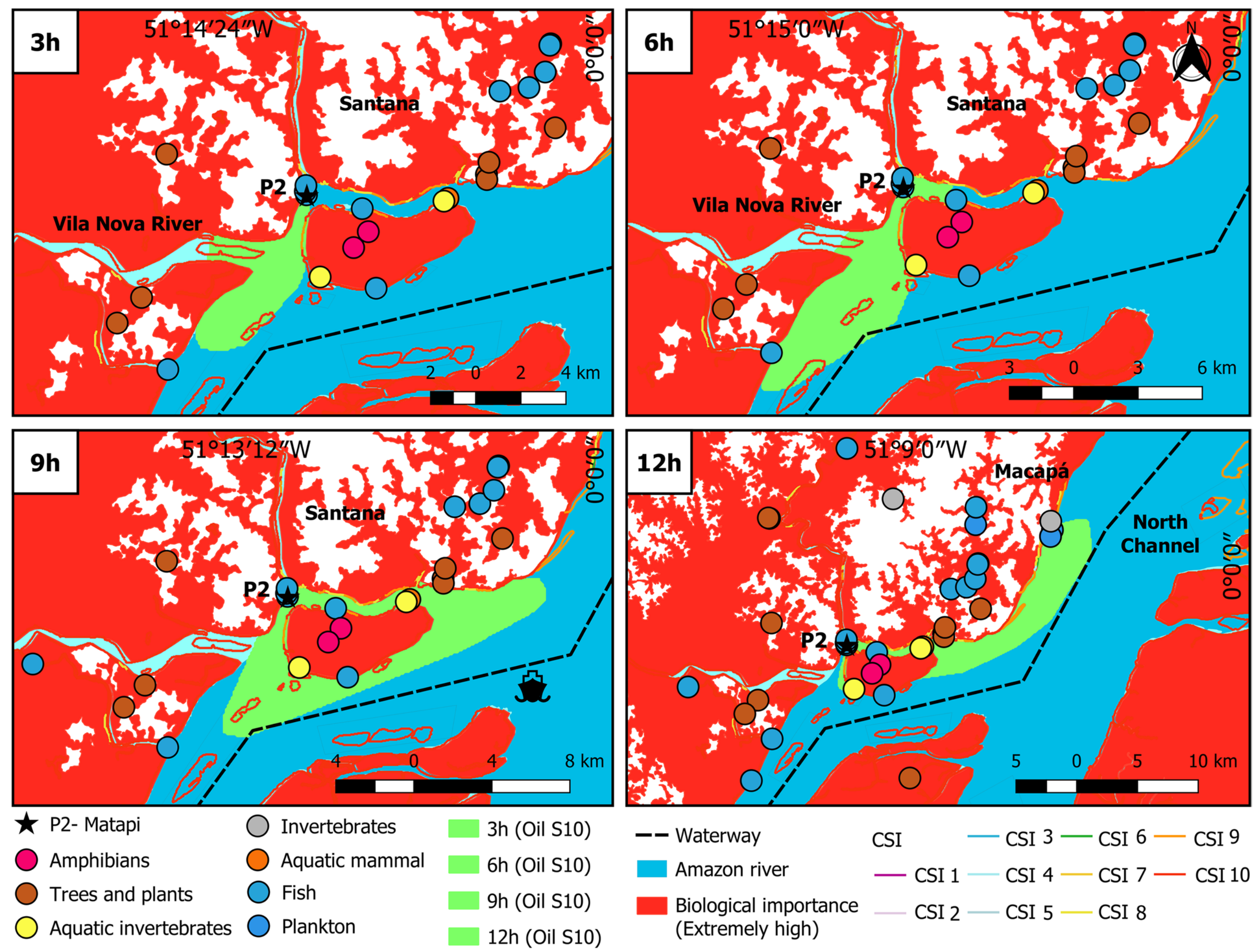

Fig. 6 Numerical output of dispersion of the **S10** oil (green spot) at Matapi (P2), Amapá, Brazil, at time intervals 3 h (a), 6 h (b), 9 h (c), and 12 h (d) after continuous oil spill in zone II during the beginning of the ebb tide and dry period (November). Source: Authors (2022)

as well as riverside communities (Cunha et al. 2021; Araújo et al. 2021). The plumes would also reach the mouths of the Matapi and Vila Nova rivers during a significant phase of the flood tide (Figs. 5 and 6), seriously compromising coastal aquatic biota (Santos et al. 2016). Water contamination and direct and indirect effects could compromise the species in the estuarine area, the fishing sector of the region, in addition to the health, safety, and well-being of the population since the oil has chemical components that are highly toxic to living beings (Clark et al. 2010; De Carolis et al. 2013; De Padova et al. 2017; Souza et al. 2019).

Some studies sought to identify the variability of the displacement of oil particles using numerical simulations of spills. Bozkurtoğlu (2017) simulated the oil dispersion in the Bosphorus Strait region in Turkey, generating the definition of the site and the time of arrival of the oil on the slope of the Bosphorus Strait region. Liu et al. (2016) also used numerical software to simulate oil spill scenarios in the Bohai Basin, northeast China. The results were satisfactory in defining which regions would be most susceptible to oil contamination.

Leal et al. (2019) and Lopes et al. (2019) used software to simulate oil spill scenarios in the Lagoa dos Patos estuary, Rio Grande, Rio Grande do Sul, Brazil, designing risk maps. Their results showed the importance of estimating the transport time and the destination of the oil particles as a mitigation response to contamination, enabling the generation of specific contingency plans.

Potential environmental and ecological impacts of the S500 and S10 oil plumes on the coastline of Amapá

The S500 and S10 oils have different chemical and physical properties that tend to influence the diffusive processes of the plumes when flowing naturally, even though these differences did not result in sufficiently noticeable numerical

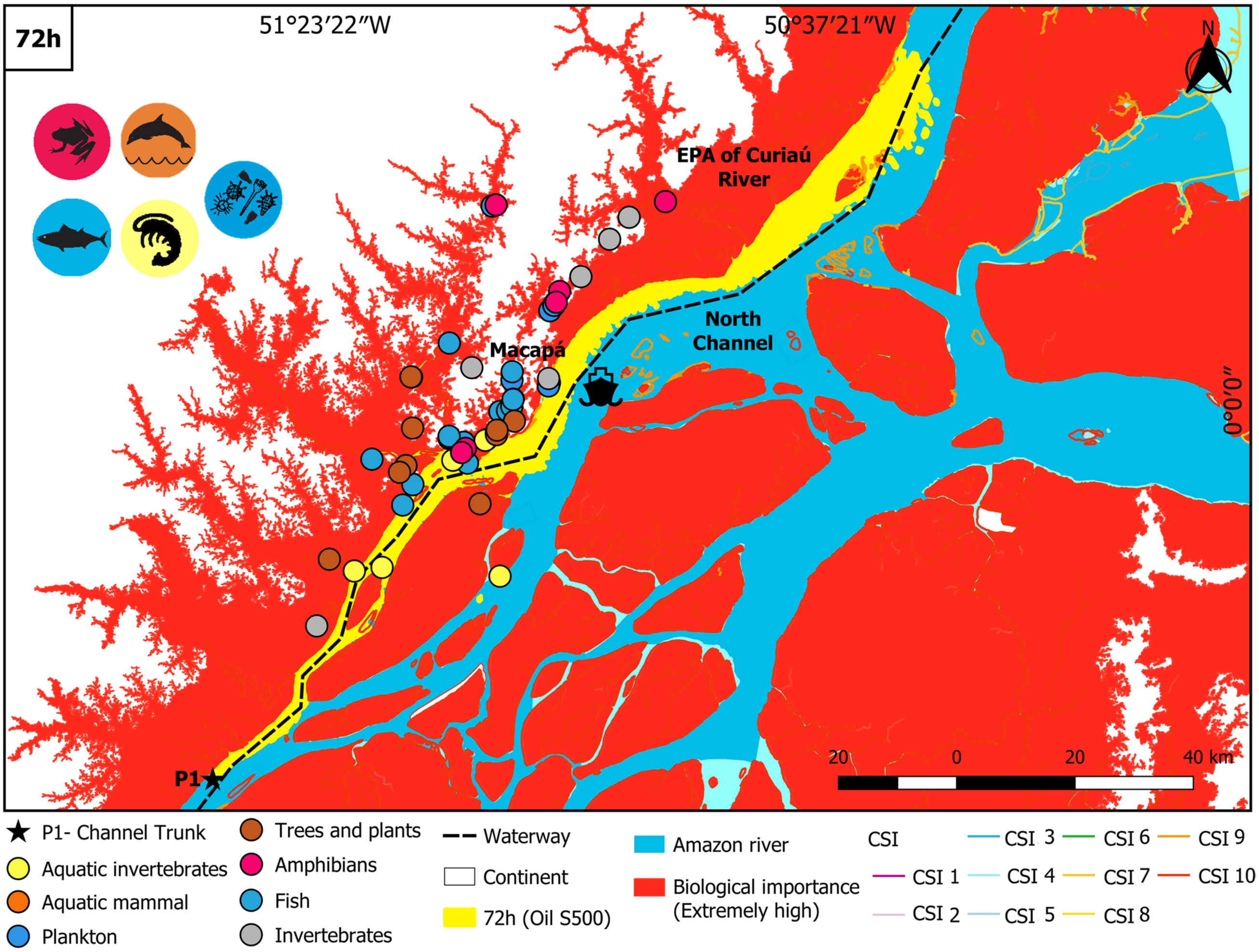

Fig. 7 Numerical output of dispersion of the **S500** oil (yellow spot) at the Channel Trunk site (P1), Amapá, Brazil, at a 72-h time interval after a continuous oil spill in zone I during the ebb tide and rainy season (May). Source: Authors (2022)

outputs when considering both plumes (**S500** and **S10**). However, some hydrodynamic parameters, such as oceanic forces of the estuary (currents, recirculations, tides, bathymetry, temperature, kinetic rate of oil decay, and others), may change the behavior of the plumes with the dispersion time, even if this is not noticeable on the maps and satellite images (Adamo et al. 2009; Leifer et al. 2011; De Carolis et al. 2013).

We observed that plumes tended to remain close to the margins or in a given area for relatively prolonged periods in all scenarios due to the influence of the superficial renewal rate (Short 2017; Abreu et al. 2020). For example, the currents of the Amazon River and many estuary rivers tend to flow parallel to the banks (Less et al. 2021; Cunha et al. 2021), which makes evaluation of these parameters more complex in coastal-estuarine aquatic ecosystems (Duan et al. 2018). For instance, when the main results of the oil pollution transport model show that the oil slick is primarily moved by the action of surface currents, whose variability in turn depends strongly on winds, rather than on other forces, thus, the intensity and direction of the surface currents drive the dispersion of the oil slick, determining its shape and size (Armenio et al. 2019). The natural interaction between oil droplets and suspended sediments forms stable microaggregates that disperse in the water column. This type of structure, referred to as oil-suspended particulate matter aggregate (OSA), promotes the dispersion and permanence of the oil and even the acceleration of biodegradation (Moreira 2014; Pinheiro 2019).

Table 1 summarizes part of these geometric and dispersive characteristics of the oil plumes for the three simulated scenarios (P1, P2, and P3) with S500 and S10 oils. They represent the most likely geographical sites for potential accidents during dry and rainy periods.

The May scenarios (S-1, P1, Channel Trunk, and zone I) are set in italics, indicating the most critical and environmentally hazardous situation among the other scenarios of potential oil spills. In this case, the plume would extend

Table 1 Dispersive characteristics of the plumes for different launch sites and simulated scenarios of a continuous oil spill with S500 and S10 oils. Source: Authors (2022)

Site/month (Spill)		Time after oil spill S500 started (h)				CSI (*)	Wind effect (**)	Ranking risk A, B, C (***)
Site	Month	9	24	36	72			
S-1 P1 (Channel Trunk—zone I)	May	W: 2.7 L: 6.1 D: 22.3	W: 6.6 L: 6.1 D: 63.6	W: 7.0 L: 6.1 D: 94	*W: 9.6* *L: 6.1* *D: 170*	10	EN	A, B, C
	November	W: 2.3 L: 6.1 D: 7.5	W: 6.0 L: 6.1 D + 37	W: 6.8 L: 6.1 D: 45.2	W: 7.0 L: 6.1 D: 85.5	10	NF	A, B, C
S-2 P2 (Matapi—zone II)	May	W: 3.5 L: 9.2 D: 20	W: 4.0 L: 9.2 D: 70.7	W: 8.1 L: 9.2 D: 84.7	*W 15* *L: 9.2* *D: 124*	10	EN	A, B, C
	November	W: 2.6 L: 9.2 D: 12	W: 3.5 L: 9.2 D: 36.3	W: 4.2 L: 9.2 D + 52	W: 8.0 L: 9.2 D: 88	10	F	A, B, C
S-3 P3 (Port of Santana—zone II)	May	W: 3.5 L: 7.2 D: 21.5	W: 5.0 L: 7.2 D: 63.1	W: 9.7 L: 7.2 D: 87	*W: 10* *L: 7.2* *D: 123*	9	EN	B C
	November	W: 3.0 L: 7.2 D: 18.2	W: 4.0 L: 7.2 D: 41.2	W: 5.4 L: 7.2 D: 58.4	W: 11 L: 7.2 D 90	9	F	B C
Site/month (Spill)		Time after oil spill S10 started (h)				CSI (*)	Wind effect (**)	Ranking risk A, B, C (***)
Site	Month	3	6	9	12			
S-1 P1 (Channel Trunk—zone I)	May	W: 1.8 L: 6.1 D: 6.4	W: 2.0 L: 6.1 D: 8.0	W: 2.6 L: 6.1 D: 22.1	*W: 5.7* *L: 6.1* *D: 37.0*	10	EN	A, B, C
	November	W: 1.6 L: 6.1 D: 5.0	W: 1.7 L: 6.1 D: 5.8	W: 2.3 L: 6.1 D: 7.5	W: 3.0 L: 6.1 D: 18.3	10	NF	C, A
S-2 P2 (Matapi—zone II)	May	W: 2.6 L: 9.2 D: 5.6	W: 3.0 L: 9.2 D: 7.8	W: 3.7 L: 9.2 D: 20.2	*W: 4.0* *L: 9.2* *D: 31.2*	10	EN	A, B, C
	November	W: 4.2 L: 9.2 D: 8.0	W: 4.3 L: 9.2 D: 12.7	W: 4.4 L: 9.2 D: 18.0	W: 4.1 L: 9.2 D: 22.4	10	F	A, B, C
S-3 P3 (Port of Santana—zone II)	May	W: 1.3 L: 7.2 D: 3.8	W: 2.2 L: 7.2 D: 10.3	W: 3.7 L: 7.2 D: 21.2	*W: 3.8* *L: 7.2* *D: 34.2*	9	EN	A, B, C
	November	W: 3.2 L: 7.2 D.7.1	W: 3.3 L: 7.2 D: 12.5	W: 3.0 L: 7.2 D: 18.5	W: 3.6 L: 7.2 D: 26.6	9	F	A, B, C

W plume width (maximum value, km), *D* plume length (extension of the oil spill site, km), *L* minimum distance from the coast (or coastline, km), *P* oil spill source

***Typology of environmental impact A (environmental protection areas), B (water treatment station—CAESA), and C (ecological/biota)

**Wind effect (*F* favorable to dispersion on the coast, *NF* not favorable to dispersion on the coast, *NE* no effect or neutral)

*Coastal sensitivity index (CSI–ESI Letters) = 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 (IEPA 2017). Scenarios in italics represent the most disadvantaged situation. In other words, the greater the expansion of the plume, the greater the environmental impact on the coastline

170 km in length, with a width of up to 9.6 km in the broader stretches of the North Channel, therefore reaching huge areas of the coastline with high CSI values (CSI > 9) and virtually all species identified in the three study areas analyzed, covering all types and rankings of risk (A, B, and C).

In zone I, just after the beginning of the flood tide, the acceleration of the plume seems to occur due to the narrower characteristics of the channel, boosting the mass of oil spilled at P1 further away, compared to P2 and P3. These sites are geographically more protected from the strongest currents from Santana Island (Fig. S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, and S15).

We also found that the longest plume lengths (D = extension of the spill site) would occur with **S500** oil within 72 h of the spill, during the flood tide and rainy season. For example, in zone I (Channel Trunk—P1), the length of the plume was approximately 170 km (Fig. 7). Subsequently, the longitudinal extension of the plume in zone II (Matapi—P2) would reach 124 km. In the Port of Santana (P3), the plume would disperse up to 123 km away. In width, the **S500** oil plume would travel between 2.3 km (minimum) and 15 km (maximum) in different stretches along the channel and for a period of up to 72 h. That is, the more geographically protected the launch site, the smaller the distance that it would travel. However, if the spill is maintained, the concentration of the plume will also be higher (Cunha et al. 2021).

In the November simulations, the size of the **S500** oil plume reached about 7.5 km in length, 9 h after the oil was released into the Channel Trunk (P1) and during the ebb tide (Table 1). In this condition, the plume represents the site and time least impacted by oil spillage in zone I. This plume would disperse longitudinally, extending approximately 86 km in up to 72 h in zone II. The intensity and scope of the impact along the coastline would depend on the launch site (P1, P2, and P3), the seasonal hydrological period (May or November), and the tide phase (flood or ebb).

In the Port of Santana (P3), the concentration of the **S500** oil plume at 24 h and 72 h and during the ebb tide would severely impact the coast of Macapá, reaching the water treatment station (CAESA), as well as the coast of APA of the Curiaú River (Fig. 1).

Regarding the **S10** oil simulations, the plumes would not disperse differently at P1, P2, and P3, even for long distances, compared to the **S500** oil (Table 1). For example, the shortest distance 3.8 km and a minimum width of 1.3 km would occur in P3 (Port of Santana) during the rainy and flood season, 3 h after the spill. On the other hand, the largest extension of the plume would be 37 km, with a maximum width of 5.7 km, if it occurred in the Channel Trunk (P1) during the rainy season, 12 h after the spill, as the plumes at P1 would be further away from the influence of the Amazon River tide and, consequently, would disperse over greater distances.

Based on the scenarios analyzed, even without a record of a serious oil spill in the region, it is essential to understand that there are imminent environmental risks to the local biota, classified as very vulnerable. It should be noted that these data were considered only for vessels transporting liquid and gaseous-derived bulk. The vessels that frequent the Port of Santana represented, from 2019 to 2021, about 514 moorings, which, even when not carrying oil and derivatives, contained fuel in their tanks (Tables S2, S3, and S4) (CDSA 2022). In the Port of Manaus, the flow of vessels carrying oil totaled 5958 moorings, and these merchant ships must pass through the North Channel of the Amazon River (ANTAQ 2022). That is, even vessels that do not dock at the Port of Santana pose an environmental risk to the waterway (Cunha et al. 2021; Araújo et al. 2021).

There is also a significant movement of smaller vessels in the region, such as ferries, traditional transport boats, tourist ships, and others, which are not intended for the transport of large volumes of oil and that use less fuel. Although they present a lower risk than medium and large ships, these smaller vessels still pose a considerable risk (Fragoso Neto et al. 2018).

Vessel traffic on the North Channel of the Amazon River waterway is intensifying, resulting in higher risks of accidents with significant impacts (Santos et al. 2016; Cunha et al. 2021). It is worth mentioning that, in August 2019, an extensive oil spill occurred on the Brazilian coast, reaching more than 11 states, 120 municipalities, and 724 localities. This accident affected the entire coastal marine biota of the region, coral reef, and mangrove ecosystems, in addition to causing 112 deaths of marine and coastal animals such as turtles, fish, and birds, among other biological resources (IBAMA 2020).

Oil can cause a decrease in biota populations through contamination by toxic substances that cause carcinogenic, neurological, and teratogenic effects, in addition to causing deaths of aquatic animals by asphyxiation. Birds, for example, may lose their body thermal balance capacity due to oil fouling, eventually dying from hypothermia or hyperthermia (Carmo and Teixeira 2020). Disasters have also been occurring in several other countries and even at larger magnitudes, such as the oil spill from the Exxon Valdez ship off the coast of Alaska in 1989. This accident caused the death of birds, otters, fish, and whales and was considered the largest ecological disaster in the history of the United States (Magris and Giarrizzo 2020).

When analyzing an environmental impact in relation to the oil spill, it is necessary to consider not only the characteristics of the oil and its persistence in the environment but also whether the impact on a community will be greater or lesser, depending on the resistance or resilience of the biological community (Edmonds et al. 2021). Resistance refers to the ability of the community to not change functionally after an impact. Resilience is the ability of a community to return to its original conditions after being impacted the faster their ability to return, the greater their resilience. Therefore, resistance and resilience will depend on the structural characteristics of the community (richness, diversity, sensitivity of the species present, maturity level of the population, succession level, life cycle, and dispersion, among other biological aspects) (Wieczorek 2006).

It is also important to highlight that biological resources vary seasonally. Depending on the time of year, environments such as estuaries can house species that are in certain highly sensitive life cycles and reproduction stages (Wieczorek 2006). Therefore, the conservation status of the species is an essential factor to consider in case of an oil spill, as it indicates the most vulnerable species to extinction risk. Endangered species have a restricted distribution and low genetic variability. The few remaining representatives of these species are usually isolated, a factor that can increase their inbreeding degree (Higa and Silva 2006). Conservation of genetic variability is therefore necessary to ensure the perpetuation of the species in the studied area and should be considered in the scenarios of contingency actions in case of accidents.

Finally, as presented in the simulations for 3 h, the oil plumes would reach a distance of 5.6 km in zone II. According to Resolution 398 of June 11, 2008, of the National Environment Council (CONAMA), the requirements on the minimum content of the Individual Emergency Plan (PEI) for oil pollution incidents in Brazilian jurisdictional waters state that the time available to send resources to the place of occurrence for collecting the oil in the water must be within a maximum of 2 h for volumes up to 8 m^3. In rivers and other lotic environments, when the volumes are equal to 640 m^3/day and 1140 m^3/day, the maximum times for the containment and collection of the oil must be 36 h and 60 h, respectively. Additionally, in sensitive areas, the environmental regulatory agency may change the established criteria (CONAMA 2008). Thus, considering the novelty of the study, these results can be used by national regulatory bodies to direct the actions of availability of resources for prompt response and mitigation of accidents in the Amazon region.

It is worth emphasizing that the Amazon is not as economically integrated as the southern and southeastern Brazilian regions in terms of the availability of resources and port networks. However, the minimum response capacity must be consistent with the characteristics of the region and the availability of resources for the cooperation network (Souza Junior et al. 2018). Nevertheless, the present study exposed an extreme lack of information on the subject for the region. This fact evidences a critical fragility of the capacity to prevent accidents in the region. It is time to develop good contingency plans to avoid major environmental impacts in the region, the consequences of which would be unpredictable for the conservation of regional biodiversity.

Priority actions for biodiversity conservation in the North Channel of the Amazon River

It is essential to plan and implement accident prevention and mitigation strategies for conserving biological resources in the coastal and estuarine zones of the Amazon River. These actions must be directed before, during, and after an oil spill. In this sense, we propose a conceptual model with the most relevant aspects of priority actions for environmental contingency (Fig. S16).

The priority actions for conservation consist of three factors: (1) biological resources, several surveys, and categorizations of local biodiversity must be carried out (partially carried out in this research); (2) mitigation-inspection and control of activities of tanker traffic and oil handling in the Amazon River must be performed, considering the instruments of the contingency plans for oil spill (MMA 2004), instruments of territorial management such as the Amapá Economic-Ecological Zoning (EEZ), and municipal plans or master plans of basic sanitation, in addition to maintaining ecosystem services through payments for damages or environmental services (MMA 2018); (3) in management and governance, it is essential to establish river basin committees and biosphere reserve (instruments), extensions of Conservation Units for the protection of species close to the waterway, and risk management with immediate reactions. It would also be necessary to create a support network between the states that use the Amazon River to improve protection against accidents. Such mechanisms need to be coordinated between the federal state, civil defense, and society.

Conclusion

This study supported the hypothesis that the vulnerability of biological resources to potential oil spills in the Lower Amazon River, Amapá, Brazil, depends on several natural and anthropogenic factors. The species groups potentially most threatened by accidents would be those that inhabit or move within zone II (fish, plankton, aquatic mammal, amphibians, aquatic and tree invertebrates, and plants), in which at least one species, the aquatic mammal *Sotalia fluviatilis*, would be at risk of local extinction. Zone II is the one that presents the best information level on species, probably because it is closer to sites where the oil plume has the greatest tendency to touch the margin/ coastline.

The scenarios of impacts of oil plumes on the Lower Amazon River (North Channel) represent an unprecedented analysis of the subject for the region. We suggest that contingency plans should have a response capacity of less than 72 h to minimally prevent the plumes from dispersing over long distances (up to 170 km); if the launch sites were continuous and not previously contained, they should be able to reach large areas, of up to ≈221 km^2 during the rainy season and during the flood tide.

If an accident occurred in one of the three zones evaluated (I, II, or III), there would be a high probability of the urban areas of Macapá and Santana being severely affected, with a potential shutdown of the surface water supply system of the Amazon River (CAESA).

We found that both the rainy hydrological period (May) and the tidal phase (ebb) are critical to the plume dispersion process, depending on the launch site (P1, P2, or P3).

Therefore, the plumes change in dynamic and geometrical behavior (length, width, and proximity to the coastline) according to the evolution of the hydrodynamic and dispersive process (variations in currents, bathymetry, recirculations, water residence time, wind intensity and direction, and others).

In each studied scenario, the simulated plumes tended to touch and disperse near the sensitive coasts (CSI ranging between 9 and 10). The contact with the coast always occurred with long distances (above 30 km and up to 170 km). This could seriously compromise the fauna and flora in any of the three coastal zones studied, with emphasis on urban areas (Macapá and Santana) and protected areas (APA Curiaú and Fazendinha). Depending on the launch site, the plumes would sometimes reach the mouths of the Matapi and Vila Nova rivers, eventually compromising the Beija-Flor Channel in front of the council building of Mazagão. Some scenarios would be so impactful that they would affect the council building of the three municipalities—Macapá, Santana, and Mazagão—in less than 72 h.

Areas with oil-sensitive species were identified and unprecedentedly recorded for this region in terms of their conservation status. The literature shows that numerical simulation outputs can be used to test and investigate contingency situations to protect species sensitive to oil spillage, observing the characteristic sections of the Lower Amazon River (Cunha et al. 2021; Araújo et al. 2021). Our study provides a valuable contribution by adding new information about the known and studied species in the region (IEPA 2017).

Finally, we recommend that further experimental and simulation studies be carried out in different periods and stretches of the Amazon River, in addition to the port area, or including specific areas of high interest for the management of the waterway. This would allow studies with greater resolution and detailing possible actions and reactions to mitigate accidents. Moreover, these actions would be of tactical or operational interest (still nonexistent) to hold plumes issued in the risk zones.

Actions to mitigate and recover the environment impacted by possible accidents would have previous well-founded scenarios at their disposal. This type of information is essential because national and local agencies can use it to evaluate emergency plans and prompt response to oil spills, especially in a region of the Amazon as unknown as the estuary.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-24592-3.

Author contribution The study proposal was designed by advisors EPA and ACdC. CHMdA prepared the hydrodynamic simulations. EPA and ACdC prepared and reviewed the statistical analyses and spatial analysis and elaborated the figures. HFAC, AUB, and NNP performed all other steps and data analysis. All authors participated in data analysis and curation processes. All authors have read and approved the final manuscript.

Funding The sources of funding for the research were by CNPq/PPGBIO-UNIFAP program (CNPq grant: 132863/2020–0) and Funasa-Tedplan/TR 06/2018. The authors are grateful to the Laboratory of Chemistry, Sanitation and Environmental Systems Modeling (LQSMSA), as well as to the Brazilian Council of Scientific and Technological Development (CNPq grant: 309684/2018–8, FAPESP grant: 08/58089–9, and NSF DEB Grant: 791 #1256724) for the support. The authors would also like to thank PAPESQ/DPq/PROPESPg/UNIFAP and FUNASA/TR-2018.

Availability of data and materials All data generated or analyzed during this study are included in this published article and its supplementary file.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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