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Marine Accidents in the Brazilian Amazon: Potential Risks to the Aquatic Environment

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Abstract: Although the Brazilian Amazon is still one of the most well-conserved environments in the world, it contains an extensive network of waterways that are used by a wide range of vessels that transport both people and cargo, as well as undertaking other activities. To plan environmental risk disaster strategies here, the potential effects of technological disasters, including marine accidents, must be taken into consideration. This paper seeks to redress this by providing a review of the possible risks to the Amazon aquatic environment that could result from various types of marine accidents. While the Amazon region has been researched worldwide, both extensively and intensively, regarding land use, climate, and environmental characterization, work in this field is scarce. A review of the main environmental characteristics of the Amazon is provided, including a description of common marine accidents that have occurred in this region. The environmental impacts experienced by the aquatic environment due to marine accidents worldwide were reviewed from the scientific literature to examine potential risks to the Amazon waterways. It was found that marine accidents, such as fire/explosions and the sinking of ships with different types of cargo, can cause the spillage of oil and other hazardous materials, causing catastrophic damage to the aquatic environment. Changes in the hydrological characteristics of rivers, including unexpected changes in the weather, such as heavy rain and winds, may also influence pollutant dispersion. Initiatives to deal with these technological hazards in the Amazon basin should also consider the potential social and environmental impacts in the protected areas of this region. It is hoped that this paper can serve as a starting point toward the governance and planning of risk disaster management actions, which are aimed at reducing the negative environmental impacts caused by marine accidents in the region.

Keywords: Amazon basin; environmental impact; marine accident; risk management; technological disaster; sinking

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1. Introduction

The Amazon basin is one of the largest river networks on the planet, with complex hydrological processes that occur across extensive floodplains, constant precipitation events, dense forests, complex topography, and variations in freshwater discharge and storage [1]. The basin covers a total surface area of ~6 million km^2, contributing to ~16–18% of the world's freshwater flow, ~210,000 m^3/s [2]. The protection of the Amazon basin is important in mitigating climate change, as well as conserving biodiversity and freshwater resources [3]. Although the basin extends over seven countries, the Brazilian Amazon possesses the main hydrographic network, with ~10.5 million km of waterways [4] coursing through nine states, including mainly Amazonas and Pará [5], Figure 1.

Figure 1. The Brazilian Amazon region.

As in other river systems in the world [6,7], marine activities abound in the Brazilian Amazon, such as the transport of passengers and cargo, research, health and security services, and fishing [8]. The availability of the waterways and the lack of roadways in the region [9] mean that many types of ships are commonly found in the state of Amazonas, in the central Amazon, and in the state of Pará, which connects the inland waterway system to the Atlantic Ocean. Vessels of many sizes are to be seen performing a wide range of commercial activities [8] in the larger, deeper waterways that connect main cities but also in the smaller waterways that run between less populous settlements. As stated in [5], there are many technical and socioeconomic factors that can cause marine accidents in the Amazon waterways, which are of importance to the local government, industry, and academia.

As recently explained by [4], the Amazon is a region where, if technological hazards (i.e., the possibility of potentially damaging events occurring, which are the result of the application of technology [10]) occur, catastrophic social and environmental damage could be triggered. In Brazil, the Disaster Codification and Classification system (COBRADE—*Codificação Brasileira de Desastres*, in Portuguese) was created from the National Civil Protection and Defense Policy. In COBRADE, the groups of technological disasters were classified according to the relationship between the hazard and civil works, dangerous products, radioactive substances, urban fires, and the transportation of passengers and non-hazardous cargo.

As described by [4], ~31% of the population in the Amazon region live in areas that are classified as having a high risk of technological disaster. The research of these authors suggests that technological disasters are most likely to occur in the more developed regions of the Brazilian Amazon, where there are technological hazards in relation to gold mining activities [11], fires in fuel storage facilities [12], the transportation of dangerous products [13], oil spills [14], marine accidents [5,15,16], and so on. Moreover, infrastructure and human actions have been shown to be the main factor in most of these accidents, as seen in data from the Integrated Disaster Information System of the Brazilian Ministry of Regional Development [17].

In previous research, Fontes et al. [5] discussed marine accidents in the Brazilian Amazon, focusing on passenger ships. The possible causes of these accidents, including regional challenges and alternatives for their prevention, were evaluated. However, an analysis of the possible impacts on the marine environment derived from marine accidents has not been discussed. This type of information is important when planning initiatives to improve the sustainability of the region, the development of society, and preserving the environment since the identification of hazards in a given location is vital for disaster risk management [18]. Research on risks to the aquatic environment from marine accidents is still scarce, as pointed out by [19], for the case of sunken containers. The present research, therefore, provides a comprehensive review of the possible impacts on the aquatic environment that could result from marine accidents in the Brazilian Amazon. The present work is a continuation of [5] and aims to show the most significant marine pollution risks derived from accidents involving vessels in the waterways of this region. The main objective of this research is to provide relevant information and considerations on possible marine pollution in the region, which could be used in future planning to prevent technological disasters. The Amazon basin is introduced in Section 3, followed by a description of possible marine accidents in the Brazilian Amazon (Section 4) and a review of the main impacts on the aquatic environment that could occur because of these (Section 5). Section 6 presents some options to preserve the marine environment in the Amazon waterways, and Section 7 provides the main conclusions.

2. Methodology

The present research has been organized into three parts, as shown in Figure 2.

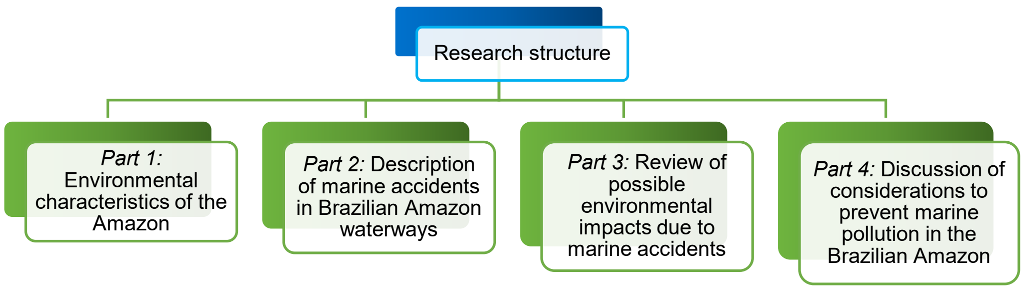


Figure 2. Main structure of the present work.

In the first part of this research, the main environmental characteristics of the Amazon region are presented (see Section 3), including the relevant characteristics of its hydrology, geomorphology, climate, and biodiversity. This information was mainly taken from scientific research published in peer-reviewed journals over the last decade. Well-known scientific databases and editorials were consulted, including the Web of Science, Scopus, MDPI, ScienceDirect, Springer, and Frontiers.

The second part of this research offers a brief description of the main types of ships operating and common accidents occurring on the Amazon waterways (Section 4). The data were taken from the scientific literature and regional news, and some of the photographic evidence was gained from fieldwork on the Rio Negro River, Manaus.

In the third part, a bibliographic review of the main environmental impacts resulting from marine accidents is detailed (see Section 5) after consulting international scientific databases, as in the first part of the paper. Over fifty papers, mainly from the last ten years, were consulted. Special attention was given to environmental impacts resulting from the most serious marine accidents, such as sinking and spillage. Thus, the search was made using phrases such as “accidents and marine pollution”, “environmental risks due to sinking”, “marine spills impacts”, and others that combined these words. Information on the diverse types of marine pollution found was used to build the structure of Section 5.

Information found in commonly reviewed publications was considered for discussion. It is worth mentioning that although some information reviewed concerned accidents in other regions, the main goal was to document the possible scenarios that could occur in the Amazon, as similar accidents could also occur here.

The fourth part of the research (Section 6) was based on the above. Considerations are listed for the planning of risk prevention initiatives that aim to prevent aquatic pollution derived from marine accidents in the region, evidencing recommendations from international and national articles, the news, and websites.

3. Main Environmental Characteristics of the Amazon Basin

To plan disaster prevention initiatives in relation to marine accidents in the Amazon region, it is important to consider the main environmental aspects, such as hydrology, geomorphology, climate, and biodiversity. Extensive reviews and technical concepts of these topics can be found elsewhere in the scientific literature, such as in [1,2,20–25], respectively.

Figure 3 shows a representation of the hydrology of the Amazon basin, from [1], who made extensive research on the scientific advances and future challenges in Amazon Hydrology. In the figure, the words in black represent the main rivers in the basin and those in red describe hydrological processes in the region discussed in [1].

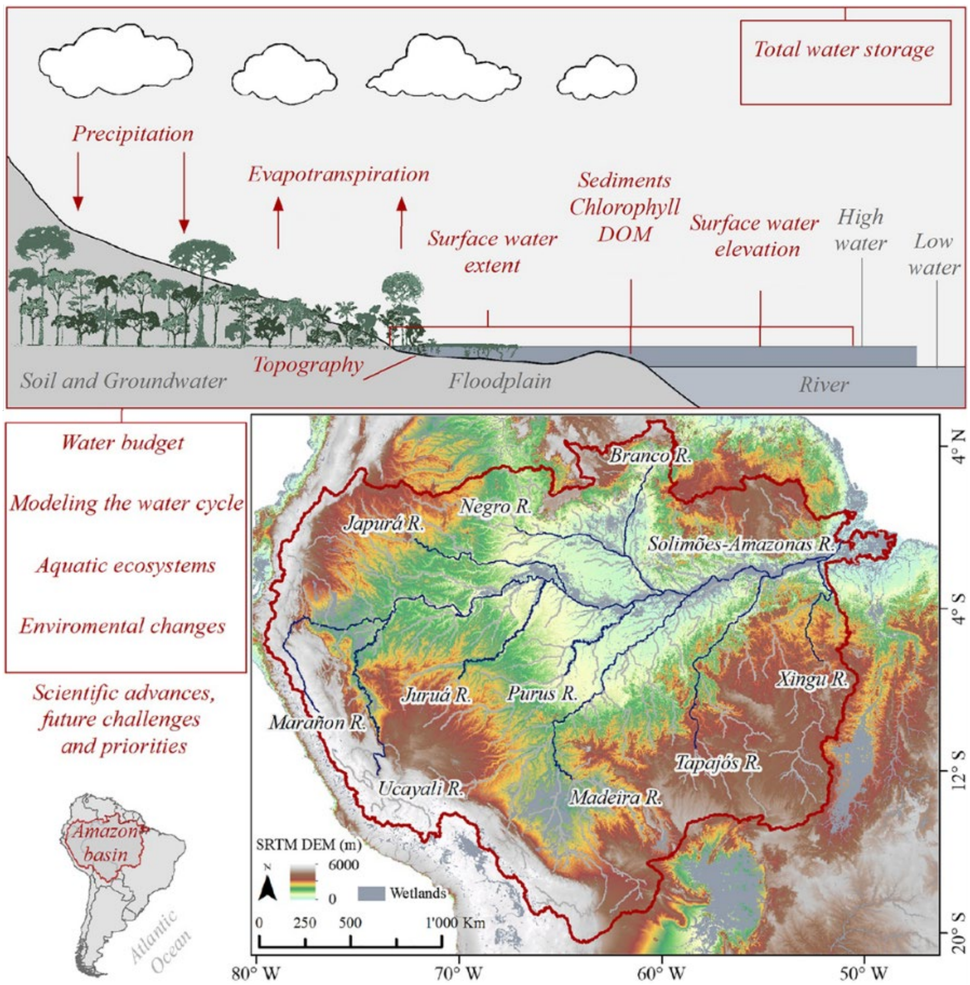


Figure 3. The Amazon basin showing the hydrological variables (the words in red) evaluated in [1]. The map shows the main rivers in the basin (words in black). The figure was adapted from [1] using the license Creative Commons CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/ accessed on 15 March 2023).

In [1,26], the Amazon basin is defined as a complex system of waterways that are composed of interacting mega rivers (i.e., river systems with an average net discharge of over 17,000 m^3/s [26]) and large rivers with extensive confluence networks, covering varying morphologies and hydrodynamic processes. At the confluence of the river channels, important hydraulic and morphological changes occur in the fluvial system, which produces significant effects on the geomorphology and ecology of the region [27], including different climates, geology, and hydrological regimes. This is particularly true at the confluence of the three main mega rivers, which are tributaries of the Amazon, the Madera, Negro, and Japurá rivers (Figure 3).

The geomorphological characteristics of the Amazon are complex, according to [2], who investigated the main geomorphological characteristics of the Amazon Basin. From geomorphological variables, the authors proposed a means of river classification. Homogeneous elementary river units were classified into three groups in relation to (a) river energy and elevation (e.g., high slope and elevation), (b) valley bottom morphology and channel lateral dynamics (e.g., bar coverage, sinuosity, confinement ratio, and channel width), and (c) the size and lateral dynamics of the river (e.g., drainage area, island coverage). This work underlines the many factors involved in the geomorphological characteristics and physical behavior of the Amazon waterways. The main geological characteristics of the Amazon can be seen in the maps of [2].

Regarding the characteristics of the Amazon climate, it is mostly tropical, with sporadic extreme events of heavy rain and strong winds. In the Brazilian Amazon, the potential for severe weather and intensive downbursts is enormous. These may cause significant technological and environmental disasters to buildings and forests, respectively, as discussed by [28], who researched the downburst-related damage to Brazilian buildings, documenting the main regions of occurrence in the Amazon.

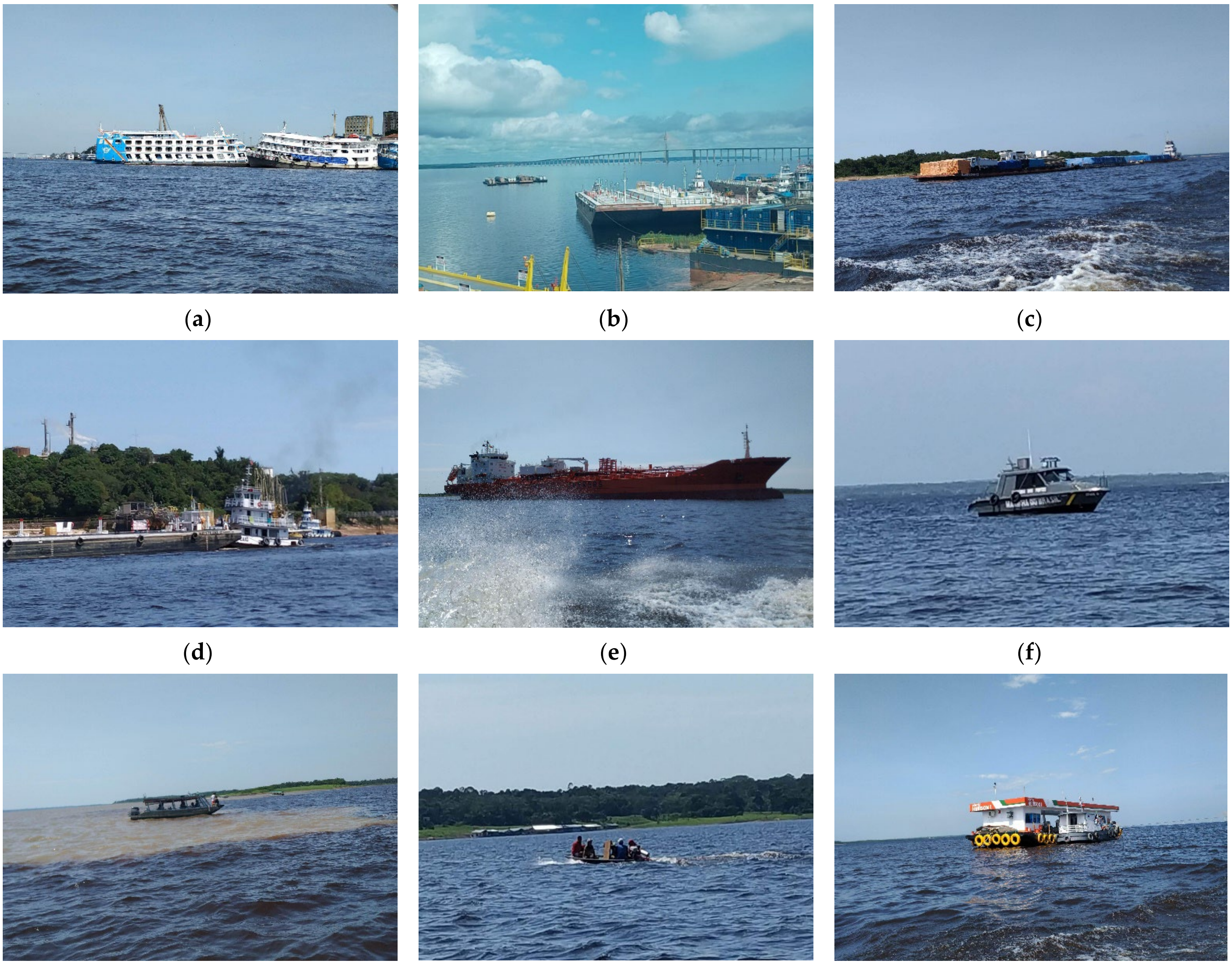
Unusual windstorms often occur in the Amazon region [29] due to the effects of convective cloud downdrafts, which cause large blowdowns in the Amazon rainforest. The vulnerability of the Amazon forests is described by [30], who emphasizes the importance of considering wind effects when predicting the future of tropical forests in the central Amazon.

The Amazon forests have a great diversity of plant and animal life, including undiscovered species [31]. This huge biodiversity of animal and plant species is one reason that the Amazon is considered a unique bioma, justifying its preservation [32]. With respect to aquatic life, the Amazon basin contains the highest freshwater biodiversity on earth [33]. Jézéquel et al. [33] presented a thorough study to classify the aquatic species in the Amazon Basin, providing an open-source database of freshwater fish species.

4. Marine Accidents in the Brazilian Amazon

The waterways of the Brazilian Amazon are used for a range of different activities [8], including the large and small-scale transport of cargo and passengers, by various types of vessels, as seen in Figure 4a–i.

Most of the ~24,000 km network of Amazon waterways is navigable and is used to transport agricultural, mineral, and industrial materials [34]. Ports of different sizes can be found, which are potential hotspots for environmental pollution resulting from marine accidents. In addition to passenger transport of various types and scales, general cargoes are shipped between the ports, including containers, fertilizers, live cattle, and timber, as well as raw materials (e.g., alumina, bauxite, wood), refined minerals such as aluminum ingots, animals (e.g., oxen), and other materials (e.g., oil, tar, coke, caustic soda) [34,35]. The potential risks of environmental pollution resulting from accidents involving these vessels are a cause for concern. The spread of these pollutants in the environment has yet to be given serious consideration.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

(**g**) (**h**) (**i**)

Figure 4. Examples of vessels operating on the Rio Negro River, Manaus, in the Brazilian Amazon. (**a**) Passenger ships at the port of Manaus. (**b**) Cargo barges. (**c**) A pusher-barge system, used to transport different types of cargo. (**d**) Detail of a pusher coupled to a cargo barge. (**e**) Large cargo ship. (**f**) High-speed vessel belonging to the Brazilian Navy. (**g**) Small, recreational passenger ship at *Encontro das Águas*, Manaus. (**h**) Small boat transporting both people and cargo. (**i**) A floating fuel station. Photo Credits: (**a**,**c**–**i**) Jassiel V. H. Fontes, 2021; (**b**) Vinícius Soares Bechman, 2023.

Regional academic research and information regarding marine accidents in the Brazilian Amazon are available in the public domain, such as in [15,36,37] and mainly in Portuguese. Fontes et al. [5] described the main factors that lead to accidents in marine passenger transport in the Brazilian Amazon, presenting their main causes and special considerations to be taken into account for prevention initiatives. Their findings show that most incidents involve collision, contact damage, dragging, grounding, fire, sinking, and wind. Stability or watertightness issues and adverse climatic conditions are aggravating factors, as well as heavy river traffic, vessel conditions, and operational issues that are related to malpractice and human errors [5,14]. Operational velocities surpassing the allowed maximums (e.g., over ~10 knots) also increase the risk of accidents [14].

Data on registered marine accidents are made available every year by the Brazilian Navy in their Administrative Inquiries about Navigation Accidents and Facts (IAFNs—*Inquéritos Administrativos sobre Acidentes e Fatos da Navegação*) [38]. Some representative statistics of these registered accidents that have occurred in the States of the Brazilian

Amazon over the years can be found in [5]. More information regarding Brazilian Maritime Regulations can be found in [5,39].

Figure 5 shows some evidence of marine accidents that occurred in Amazon Basin waterways, including the sinking of a pusher tug and an artisanal passenger ship (Figure 5a,b, respectively), the grounding of a cargo barge that caused structural damage (Figure 5c), an oil spill from a passenger vessel (Figure 5d), the containment of spillages during the flooding of a barge (Figure 5e), and the flooding of a cargo barge (Figure 5f).

(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 5. Some evidence of marine accidents in the Brazilian Amazon waterways. (**a**) A pusher tug capsized after barge grounding; this photo was taken from the barge. A sinking pusher, taken from the barge. (**b**) A sunk old artisanal passenger ship that appears every dry season. (**c**) A general cargo barge with structural damage after grounding. (**d**) Oil leakage from a ship operating in Rio Negro River, Manaus. (**e**) Containment of spillage during the flooding of a barge. (**f**) Flooding in a general cargo barge due to a fracture in the hull. Photo Credits: (**a**–**c**,**e**) Ricardo Almeida Sanches, 2023; (**d**) Rayrima T. D. F. Marques, 2023; (**f**) Eliana Brandão da Silva, 2021.

Although marine accidents are frequent in the Amazon basin, divulgation in international scientific communication is rare. Information can mainly be found in local and national media and, sometimes, in videos on social media. This work focuses on the possible impacts on the aquatic environment in the Brazilian Amazon caused by marine accidents such as sinking, fire/explosions, and spills, considered catastrophic technological events by [40].

5. Potential Impacts of Marine Accidents to the Aquatic Environment

Marine activities can pollute the aquatic environment via discharges and spillages of oil and other substances during operations, while marine accidents can also involve spillages of larger amounts of oil and other hazardous substances. As a result, problems affecting ecology, tourism, and the environment may occur [41]. The actual pollution status of marine protected areas around the world and their consequent negative effects on the environment is largely unknown [42]. However, such possibilities are described by [43] with respect to renewable energy devices. In the Amazon waterways, there are several potential hazards that can cause negative impacts on the environment. The next subsections describe work on marine accidents and their possible consequences on the aquatic environment in this region.

5.1. Spillages of Oil and Other Hazardous Materials

Oil and substances described as Hazardous and Noxious (HNS) are, perhaps, the most catastrophic environmental risk of marine accidents, mainly due to their toxic and persistent nature [44]. As conventional ships carry significant amounts of fuel oils, either for operational purposes and/or as cargo, research in relation to this type of risk assessment is available [44,45], and there are national agencies that are developing strategies to manage such disasters [46].

Regarding sunken vessels, Goodsir et al. [44] state that there is more potential risk of pollution from the corrosion effects of the metal in older shipwrecks than in more recent cases. However, an intervention to remove the oil in these to mitigate risks is no easy task, as the costs and the risks involved are very high [47]. It is, therefore, necessary to study and understand the involved risks before intervention.

A sunken or damaged vessel may present various hazards in terms of the types of oil being carried. Different types of oil can be found, such as light and heavy oils. Light and non-persistent oils, such as diesel or petrol, and heavy and persistent oils, like bunker oils, are the main concerns, with physical, biological, and chemical factors contributing to oil weathering, such as dispersion, evaporation, microbial degradation, and sedimentation, that affect its composition in the environment [44]. These factors also contribute to the behavior of the oil as it disperses.

Over recent years, the demand for raw materials from the chemical industry has increased, and so too has the transportation of chemicals and hazardous substances expanded. Galieriková et al. [48] presented an overview of accidents that have involved spillages of hazardous substances, particularly those classified as HNS and oily substances. The definition of these substances is established in the OPRC-HNS Protocol of the International Maritime Organization [49], and a few examples are listed in Figure 6. Basically, the term oil shipment means petroleum hydrocarbons, whereas an HNS is a substance in the marine environment other than oil, which is dangerous to human health, can harm marine life, damage amenities, or affect other legitimate uses of the sea or other aquatic environments [48,50]. A complete inventory of hazardous materials can be found in documents from the Hong Kong international convention for the safe and environmentally sound recycling of ships [51,52].

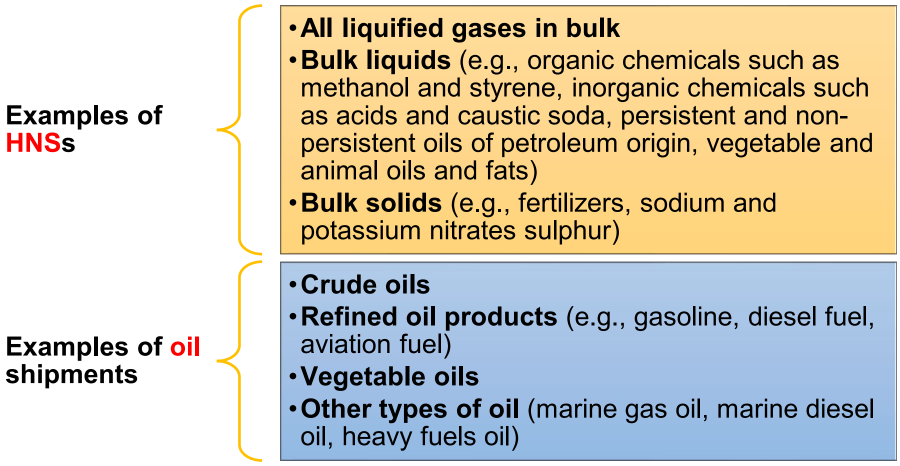


Figure 6. Examples of common HNS and oil derivatives in maritime transport. Adapted from [48] under a CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0 accessed on 6 February 2023).

The exact negative effects of a potential spill of these substances depend on environmental factors, including weather conditions, the spill location, the properties of the hazardous substance itself, and the way these are packaged and stowed [50]. The behavior of HNSs and oil spills is also different [48,53]. For example, when oil is spilled in water, it tends to spread out, moving on the water's surface because of the effect of wind and currents, presenting changes in its physical and chemical properties, such as specific gravity, viscosity, distillation, and pour point. Marine accidents causing an oil spill are mainly caused by collision, grounding, and leakage involving vessels, storage facilities, and pipelines [54]. Oil tankers, which carry great amounts of oil, account for the most severe accidents. Some of the most well-known, catastrophic marine accidents involving oil spills are shown in [55]: Torrey Canyon (1967), Amoco Cadiz (1967), Atlantic Express (1979), Exxon Valdez (1990), ABT Summer (1991).

On the other hand, as HNSs can be transported in a variety of ways, their means of propagation vary. For example, liquids and solids may sink or float on the surface; liquids may, partially or totally, evaporate; liquids, gases, and solids may dissolve into water partially or totally; gases spilled in water may form gas clouds in the air with different dispersion velocities, depending on the environmental conditions [48].

Cunha et al. [50] reviewed the HNS involved in marine spill accidents and provided an online database for their results. These authors affirmed that HNS spills and dispersion behavior in aquatic environments have been poorly documented. Although spilled oil can initially float on the water surface and is immiscible with water, HNS chemicals behave differently. The behavior of HNSs involved in marine accidents at sea allows them to be classified as sinkers, dissolvers, floaters, and gases/evaporators. The authors highlight the importance of documenting data on hazards for humans and marine life regarding HNS, suggesting that HNS detection, forecasting, and risk analysis must be used to improve crisis management by applying knowledge at an operational level.

The hazardous products that are most often involved in marine spill accidents are summarized by [50] as chemical products; petrochemical and coal products; pesticides; ores and concentrated metals; fertilizers; alcohols; cereals, seeds, and beans; and vegetable oils. The products most often found in their research were found to be ammonium nitrate, sulfuric acid, calcium hypochlorite, sodium hydroxide, lead sulfide, methanol, acrylonitrile, tetraethyl lead, zinc sulfide, and iron ore. Examples are shown in Table 1.

Table 1. Some examples of HNS according to the classification performed by [50], who provided a public database of HNS spill incidents (http://www.ciimar.up.pt/hns accessed on 4 March 2023).

HNS Class	Examples (HNS Involved)
Nontoxic dissolvers	Hydrochloric acid Lye/NaOH, acrylonitrile sulfuric acid, methyl ethyl ketone, isopropanol chromium, ammonium nitrate
Nontoxic sinkers	Cocoa beans, coal, wheat, sugar cane, rice, copra
Persistent floaters	Coconut oil, vegetable oil, palm oil, sunflower oil
Marine pollutants	Cypermethrin, lindane, permethrin, pentachlorophenol, and radioactive materials

The impacts of the MT Sanchi ship incident, in the East China Sea, in 2018 were investigated by Xing and Zhu [41]. This spillage produced catastrophic oil pollution damage and was one of the most serious accidents of this type in China. The authors examined Chinese law, concluding that the procedures and regulations to respond to oil spills in the open sea are lacking. They suggested making action plans to increase national and international collaboration on oil spill prevention to improve the emergency response capabilities for oil spills in the open sea and compensation standards.

Chen et al. [56] also investigated the causes and governance of the MT Sanchi tanker collision and subsequent explosion, which caused a serious oil spill. They explained that although the number of oil tanker accidents has fallen, the hazards of pollution from these are still significant, and governance strategies are needed. In their research, they discussed the impacts caused by different stages of the accident: the fire, oil spill, oil burning and explosion, and the sinking of the tanker.

Oil spills can also be due to accidents with Liquified Natural Gas (LNG) ships, as pointed out by [57], who discussed the problem of leakage and diffusion in LNG ships during emergency transfer operations in coastal waters. In these accidents, the aquatic environment can be affected by a low-concentration vapor cloud, which is generated by the effects of a possible fire on the water's surface.

Research into the spillages of oil and its derivatives in waterways with heavy traffic in the Lower Amazon basin was performed by Da Cunha et al. [14]. They modeled possible scenarios to identify the areas of most risk and assessed the possible impacts of dispersion plumes on humans and on coastal biota. They concluded that rainy periods were the most critical times for plume dispersion. They also found that for the estuarine zone of the coastal state of Amapá, this could be up to 132 km along the coast within 72 h, affecting the biodiversity, protected areas, and the water supply in urban and rural communities.

To identify and assess the accident risk factors and reduce the probabilities of their occurrence, it is important to know the policies applicable, as in [54], and the severity of this type of accident for different types of ships, as found in [55], in order to make references that can be used for guidance regarding spills in marine accidents in the Amazon region.

5.2. Release of Substances after Fires/Explosions: Lessons from the MV X-Press Accident

Fires and explosions on ships or other marine structures are destructive phenomena that can produce serious air, water, and soil pollution. A thorough review of the causes and effects of these can be found in [58].

One of the most alarming marine disasters ever [59–61] occurred in 2021, in the Indian Ocean, when the cargo vessel MV X-Press Pearl burned for almost two weeks following an explosion on 25 May. The incident was called a "new kind of oil spill" [62] as a toxic mix of plastics and chemicals spread into the water.

According to [59], hazardous chemicals, plastic nurdles (tiny granules of *plastic* less than 5 mm in size, used to manufacture all kinds of *plastic*), metals (e.g., lead and copper), and fuel oil, were being loaded onto the ship at the time of the explosion. The ship was carrying ~1486 containers of chemicals, including low and high-density polyethene, methanol, sodium methoxide, nitric acid, urea, and lubricant oil [61]. After it sank, the beaches of Sri Lanka, Indonesia, Malaysia, and Somalia, were polluted with plastic nurdles and residuals of burnt plastics. Apart from the environmental impacts on Sri Lanka, the accident also produced economic consequences, and several research initiatives are still being implemented to assess the impacts due to the microplastic dispersion [63], evaluate the environmental consequences [61], and plan disaster prevention strategies [60].

Sewwandi et al. [63] showed evidence of the plastic nurdles and pyrolytic debris derived from this accident, describing it as the worst accident with a chemical and plastic-boarded vessel. Among the debris identified, they reported low-density polyethylene, epoxy resins, olefin copolymers, aromatic polyamides, natural rubber, and polyethylene terephthatale.

Possible pollutants from the MV X-Press Pearl incident and their possible distribution in the water column can be seen in Figure 7. A technical report describing the possible effects of each pollutant in detail, as well as the clean-up and mitigation efforts, was made available by the Centre for Environmental Justice of Sri Lanka [62]. Although this type of accident pollution is not common [59], it is wise to take into account the information about it to prepare for any possible pollution from fire/explosion accidents in the Amazon region involving vessels carrying similar substances.

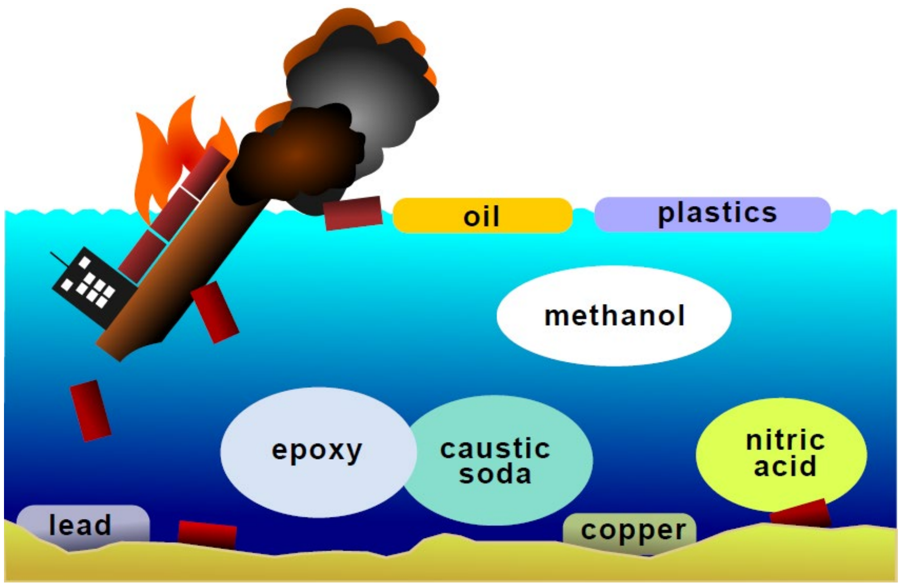


Figure 7. Conceptual image of possible pollutants leaked from the X-press Pearl, in and after the fire, including how these could be distributed in the water column. Adapted from [62].

5.3. Possible Impacts Derived from Containership Accidents

In 2022, Wan et al. [19] presented former integrated research on the emerging problems of marine pollution derived from container ship accidents: one of the most common forms of cargo transportation worldwide nowadays. The authors discussed the main risks and response strategies to attend accidents with containerships. Although the characteristics of pollution due to sunken containers are unpredictable, it is difficult to evaluate potential damage due to the different categories of products inside a single container.

Figure 8 illustrates the potential pollution and risks that could be expected, in general, from a sunken container ship, based on [19]. The leakage of fuel oil and HNSs, as well as heavy metals and plastic fiber products from the containers, including the sunken cargo, could threaten aquatic habitats and affect the food chain, which, in turn, might have negative impacts on human health. Management actions to prevent pollution from sunken container ships have not been completely established. It is important to develop protocols and contingency plans, to promote cooperation frameworks as well as encourage public awareness on dealing with potential pollution issues. Although the pollution impacts due to sunken containers is a topic of relevance, it is still in its discussion stage by international regulations [64].

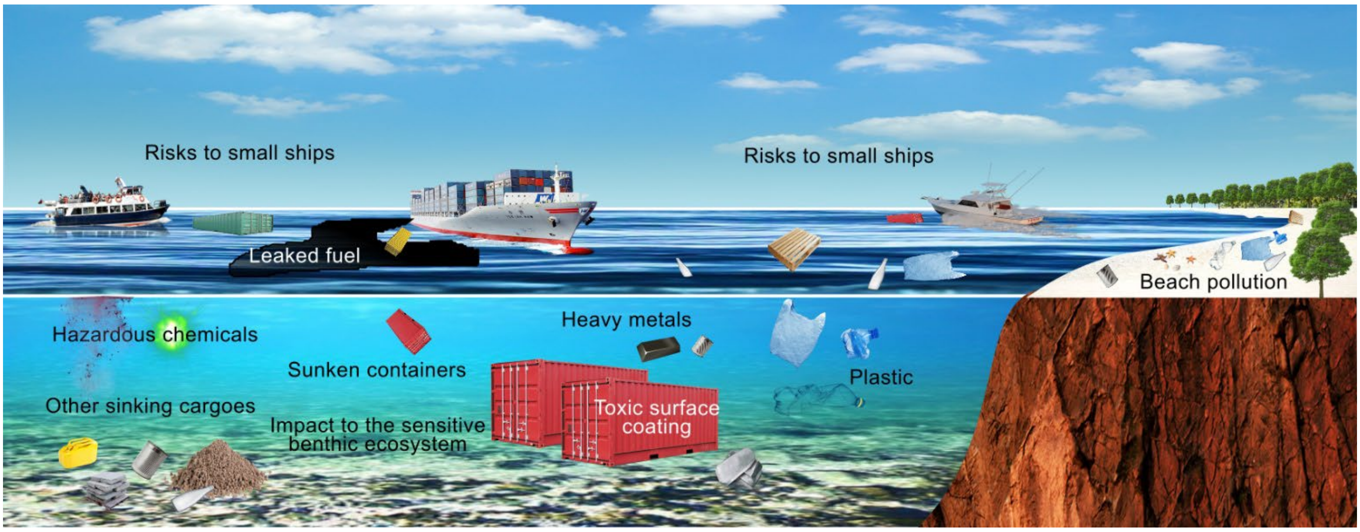


Figure 8. Pollution and subsequent risks caused by containers that sink in marine accidents. Figure inspired on [19].

In the principal Amazon waterways, where river depths allow it, container ships are commonly found, transporting various cargoes between the main cities. Neto and Nogueira [65] and ANTAQ [66] discussed the main containership routes in the Brazilian Amazon waterways. Furthermore, statistics of this type of transport in the Amazon region can be found in [67].

5.4. Other Possible Sources of Marine Pollution

Release of organic matter: In the Amazon, the transportation of animals, such as oxen and cows, through the river system is common. In October 2015, a cargo ship containing 5000 oxen sank in the Port of Vila do Conde, northern Brazil: one of the largest ports in the Amazon region. Large amounts of organic matter (animal tissue) and diesel oil were dispersed into the marine environment. Pinheiro et al. [34] investigated the results of the accident. They explained that ports on the Amazon are potential regions that cause environmental impacts due to the intensive navigation activities that take place there. The contaminating materials spread in the aquatic environment thanks to the hydrodynamics of the region, which meant that it reached the islands and beaches of cities nearby, causing environmental and socioeconomic problems in the region. The authors have suggested that the continuous biomonitoring of plankton communities is necessary and could contribute to establishing local biodiversity management and conservation actions. They also suggested more effective public policies to control anthropogenic activities in environmentally preserved regions.

The release of pollutants from military vessels: Rogowska et al. [68] studied their impacts on the marine environment caused by sunken military ships; notably, a German hospital ship, the *s/s Stuttgard*, was sunk off the Polish coast in 1943. The large amounts of fuel, ammunition and chemical weapons, and substances in the holds of military vessels mean that they can be a threat to the environment on sinking, and over time, due to the corrosion, could lead to the release of dangerous substances. Oil derivatives were found to be considerably polluting the sea bottom near the wreck of the *s/s Stuttgard*.

Maser et al. [69] performed a risk assessment on the leakage and distribution effects of toxic explosives into the marine environment from the wrecks of warships, considering a case study of a warship sunk in 1942 (Figure 9). They investigated the effects of the munition cargo on the environment and on humans, finding that the leaking of energetic compounds from munitions, such as TNT, were very toxic, mutagenic, carcinogenic substances that could cause potential negative effects on marine ecosystems. The resultant impacts on the food chain could have negative effects on human health. The munition casings on military wrecks tend to corrode with time, releasing toxic chemicals, such as nitroaromatic energetic compounds. These substances were found in the water and sediments around the wreck and in farmed mussels and wild fish living close to the wreck.

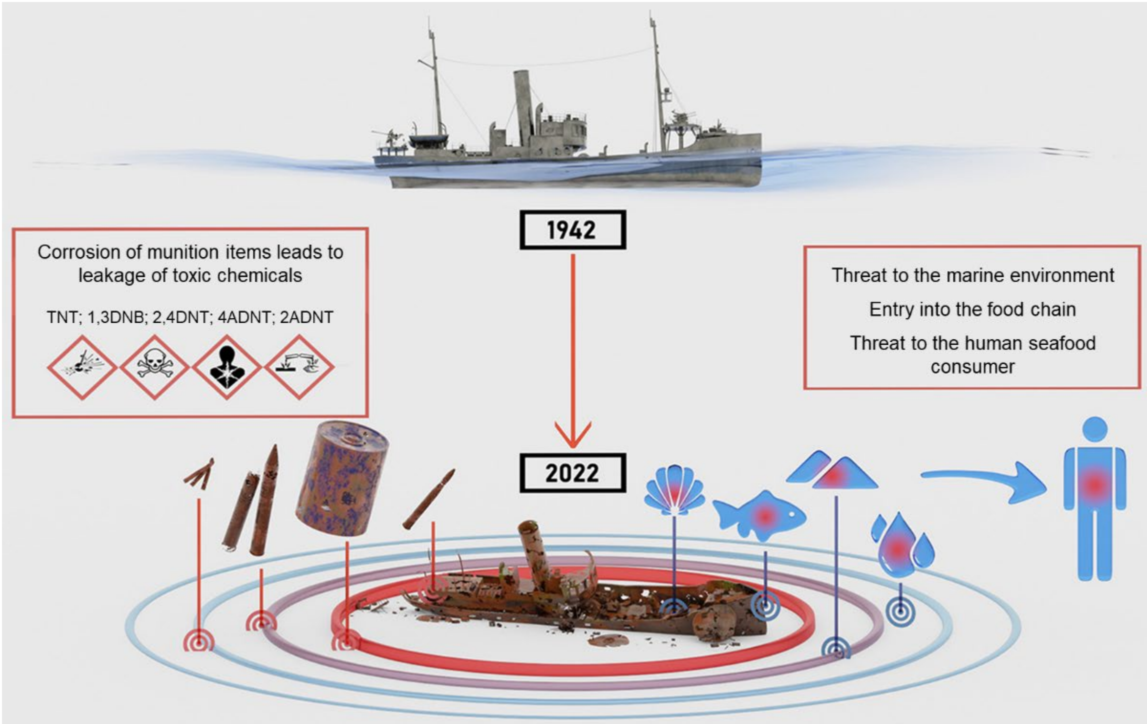


Figure 9. The possible impacts of wrecks with munitions on board are a point source of environmental risk due to the possible leakage of energetic chemicals [69]. The image corresponds to an example of a warship carrying ammunition, which sank in 1942 (from [69]), and was used under a CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/ (accessed on 17 February 2023)).

To the best of the author's knowledge, no sinking of military vessels has been reported in the Amazon. Nonetheless, it is important to consider the possible impacts of other types of wrecks or sunken devices that have been carrying munitions which could release nitroaromatic energetic compounds, such as in the illegal activities in the Amazon region, including piracy and drug trafficking [70,71] that may involve the use of weapons [72].

Foulants release from paint and wastewater: Marine pollution and risks to the environment are also produced when foulants are released from ship hulls, mainly during cleaning and painting procedures. In marine accidents such as fire/explosions or collisions, as well as in ship repair and maintenance, paint residues can be released into the aquatic environment.

Antifouling paints may release toxic substances into the environment. This was discussed by [73], who considered the in-water cleaning of ship hulls to remove foulants. In uncontrolled cleaning procedures, antifouling paint residues with toxic substances may be released into the environment. These toxic substances can also be significant in the long term when ships, containers, or other painted structures are in the sea for long periods and subjected to weathering.

The characterization of the hazards and environmental risks of wastewater effluents in ship cleaning procedures was performed by [74]. They analyzed the concentrations of metals in the effluents from dry-dock cleaning using hydro-blasting procedures and found that copper and zinc concentrations were the most common, which could cause harmful effects to most marine organisms. Hydrodynamic factors, the location of the cleaning and paint release site, and the scale of operations affected the risks these activities had on marine environments.

Wastewater from ships may be released into the aquatic environment during marine accidents. This can include contaminants from modern society, such as pharmaceuticals, psychostimulants, personal-care products, hormones, etc. Rico et al. [75] presented research on these contaminants regarding the wastewater that is delivered into the Amazonian rivers from urban areas. This is, perhaps, one of the first initiatives to evaluate the distribution of chemicals into the Amazon River, including the potential risks to freshwater biodiversity. The accidental leakage of industrial wastewater from ships during marine accidents can also have potential ecological and human health risks. The study performed by [76] could be useful when analyzing ecological and human exposure and vulnerability to this problem.

6. Considerations to Preserve Marine Environment in the Amazon Region

To allow the planning and implementation of disaster risk management actions, it is important that the possible environmental impacts derived from marine accidents in the Amazon are understood. As described by [77], protecting the Amazon region is of relevance in preventing the collapse of and preserving biodiversity, which could contribute to the negative effects of climate change. Some of the factors to consider in planning strategies to prevent marine accidents in the Amazon region are discussed below.

- While it is important that we preserve flora and fauna, there are indigenous and traditional peoples living in the Amazon forests. These people consume the fresh water nearby for drinking and basic activities, as well as eating food from the aquatic ecosystems. It is, therefore, vital to preserve the ecosystems and the food chains of the environment [32]. The Amazon is a source of food, raw materials for medicine (chemical compounds), and various other types of industry, which can be based outside this region.
- In recent years, the Amazon region has seen an increase in illegal activities such as illegal, small-scale mining, using artisanal dredges, and barges in aquatic environments, leading to considerable social, economic, and environmental problems. For example, most methods involved in gold mining include the use of mercury, which can affect soils, watersheds, animals, flora, and humans, with long-term consequences that have still to be quantified [11]. Similar effects can be expected from pollution derived from marine accidents in the Amazon region that involve the spread of chemicals and toxic substances in the environment, affecting the aquatic environment in the main rivers and their tributaries [11].
- In the Amazon waterways, it is common to find ships that come from the open sea, carrying ballast water that has high levels of salinity and coliforms. During ballast water exchange (i.e., the release of water in ballast tanks in inland waters), there is the potential risk of future invasion from exotic species [78]. Marine accidents involving ships coming from other regions different from the Amazon region may also present the leakage of ballast with foreign species.
- As the Amazon is an environmentally protected region, risk management actions should consider the protected areas, including conservation units, indigenous lands, undesignated public lands, and priority conservation areas, as shown in Table 2. Environmental vulnerability assessments are needed in these areas, such as that conducted recently by [79] for the case of indigenous lands. These authors concluded that to protect relevant areas of the Amazon, it is necessary to incentive the adoption and implementation of policies by the State, including combating illegal activities and strengthening the National Policy for Environmental and Territorial Management.

Table 2. Protected areas in the Amazon region that should be considered in risk management actions for technological risk disasters. Adapted from [77].

Area	Definition	Source
Conservation units	Private and public conservation areas are recognized by all government levels	Ministry of the Environment [80]
Indigenous lands	All indigenous lands are recognized by the federal government	National foundation of indigenous peoples [81]
Undesignated public lands	All polygons in undesignated public lands over 100 km^2 are recognized by the federal government	Ministry of agriculture and livestock/National registry of public forests [82]
Priority conservation areas	All priority conservation areas are recognized by the federal government but have not been classified as undesignated public lands	Ministry of the environment/Priority areas for biodiversity [83]

- Marine accidents involving different types of ships and activities are still common in the Amazon region and contribute to the growing problem of water pollution. Of global concern is the pollution from plastics, including microplastics in marine environments, as presented in [84], which describes some of the main negative ecological and socio-economic consequences of this. These include the dispersal and rafting of organisms, entanglements, the introduction of invasive species, the provision of new habitats, suffocation, starvation, and toxicological effects due to plastic ingestion [84]. Recent research performed in the Amazonian rivers by [85] has stated that despite microplastics being one of the most widespread contaminants, research on the risks they pose to river ecosystems is still scarce. Their field study involved sampling along the Amazon River and its main tributaries to characterize the microplastics found and assess ecotoxicological risks.
- The variation in hydrology, geomorphology, and the climate in the Amazon waterways cannot be overlooked. As pointed out by [5], the Amazon Basin has thousands of kilometers of river in which many types of vessels operate. The transport of sediments causes changes to the river's morphology, which can cause marine accidents. Changes in the hydrological characteristics of the rivers and climate can also influence the dispersion of pollutants. Sudden, unexpected changes in weather, with heavy rain and winds [5], are also risk factors for maritime accidents on the Amazon waterway network.
- There are several organizations that aim to prevent technological disasters and negative effects on aquatic environments in Brazil [38,86]. However, it is still necessary to seek collaboration from stakeholders in the government, industry, and academia, to effectively address these challenges and ensure the preservation of the marine environment in the Amazon waterways. The participation of local Amazonian state governments, as well as national and international non-governmental organizations, must be encouraged.
- Strategies for marine pollution prevention by these organizations should consider remote areas and regional challenges, as described in [5]. These strategies should include the divulgation of information on recommended practices for shipping operations and emergency plans for various types of accidents and hazards; increasing the inspection of ship operations to implement regulations even in remote locations; offering incentives for research and development activities to evaluate the potential effects of marine pollution dispersion and develop accident prevention technologies.

7. Conclusions

This paper presents a review of the possible environmental impacts in the Brazilian Amazon basin due to marine accidents. Although there have been many works on marine pollution worldwide, a comprehensive review, including the characteristics of the Brazilian Amazon and the effects on the aquatic environment of marine accidents, has been given here. Considerations aimed at preserving the aquatic environments of the Amazon Basin have also been made.

The main conclusions can be summarized as follows:

- Evidence of the use of different-sized vessels in the Brazilian Amazon waterways has been given, indicating a need to further research and development activities in the north of Brazil to develop safer ships and operations.
- Changes in the hydrology, geomorphology, climate, and biodiversity of the Brazilian Amazon basin have been described, indicating the need for more risk analyses in marine pollution caused by marine accidents, including their variables.
- That sinking solids and liquids derived from marine accidents could potentially pollute the marine environment in the short and long term has been underlined.
- The different sources of marine pollution in the aquatic environment of the Amazon, including those caused by spills (oil and HNS spills), sinking containers, explosions/fire accidents, and the sinking of organic matter, have been explained.
- The possible means of preventing marine accidents should take into consideration the characteristics of the Amazon basin, including social factors, respecting indigenous and traditional people, preserving biodiversity and protected areas, considering illegal activities common in the region, evaluating the pollution of microplastics and other pollutants, and evaluating the effects of climate and hydrological variations in the accumulation and dispersion of pollutants.
- The participation of central and local governments, industry, and academia is required in marine pollution prevention initiatives.

It is hoped that the results of this paper can serve as a basis for future initiatives from the government, academia, or industry that aim to prevent technological disasters due to marine accidents in the Amazon basin.

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