Article

Marine Accidents in the Brazilian Amazon: The Problems and Challenges in the Initiatives for Their Prevention Focused on Passenger Ships

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Abstract: The Brazilian Amazon is part of one of the largest river systems in the world, in which the transport of cargo and passengers is commonplace. However, several accidents still occur to passenger ships, causing fatalities. Transportation occurs commonly in remote regions, where there are transport inequalities, and emergency assistance is hard to find. This can affect sustainability in communities with considerable levels of economic and social vulnerability. More information is needed about accidents involving inland transport in the Amazon, to identify the threats to ships and propose strategies for accident prevention. This paper addresses the main problems that long-distance passenger ships face in the Brazilian Amazon, presenting an integrated framework towards accident prevention. First, the present situation is characterized in terms of ship description, spatial distribution, and regulations that are applicable. Next, possible causes of passenger ship accidents are discussed, including topics of concern that should be considered in the Amazon waterways. Finally, measures to help minimize passenger ship accidents are proposed, and the social relevance is discussed. It was found that accidents in the Amazon are due to a combination of human and environmental factors. Stakeholders should strengthen the technical and legal training of ship operators. The use of new technologies for navigational aid and necessary maintenance of ships is suggested. Marine accident prevention initiatives should consider local conditions, such as environmental preservation, cultural respect, and difficulties related to navigation through the complex riverine system of the Amazon region.

Keywords: inland navigation; causalities; transportation; maritime accidents; safety risks; ship stability

1. Introduction

Ensuring the health and well-being of all people is the focus of the third objective of the United Nations for sustainable development [1]. Therefore, preventing accidents that risk the safety of people in any means of transportation is included in this aim. The work presented here examines the problem of marine accidents occurring in inland passenger transportation in the Amazon, one of the most important ecosystem regions in the world. This problem can significantly affect sustainability in communities with a high level of economic and social vulnerability, which are common in the region.

Figure 1a shows the Amazon region, which has one of the largest hydrographic basins on the planet, with a complex distribution of waterways (see Appendix A) that makes inland transport a challenge for daily activities. There are about 25 thousand kilometers of navigable rivers, in seven countries [2], with Brazil having the most territory. River navigation is crucial in the regional systems of transport, fishing, and other economic activities, and is vital for remote communities with little access to roadways and infrastructure [3]. Every day, vessels (i.e., large boats or ships [4]) of different types perform activities related to the transport of passengers and cargo in the Amazon region, as illustrated in Figure 1b, which shows an example of a pusher-barge system transporting cargo in an regional waterway. Furthermore, educational and food services, fishing, scientific research, and health campaigns, among other activities, are also performed in the rivers.

(**a**)

(**b**)

Figure 1. (**a**) The Amazon region and its complex river system (Adapted from [5]). (**b**) An illustration of cargo transport on the Amazon waterways (Adapted from [6]). Source of (**a**) is Catalog of NASA (National Aeronautics and Space Administration; https://visibleearth.nasa.gov/images, Accessed on 27 July 2022). Figure (**b**) was used under a Creative Commons CC-BY 4.0 license (http://creativecommons.org/licenses/by/4.0/, Accessed on 27 July 2022).

In the Brazilian Amazon, there are many riverside communities, far from the main cities, in which the use of ships of different sizes is crucial for transport and socioeconomic growth. In fact, due to the rise in river levels, there are times in the year when some communities are partially or completely flooded [7], with inland vessels being the only means of carrying out basic and commercial activities. These vessels are also required to provide civil protection and disaster response. However, many of these vessels were developed and built without or with little professional/technical expertise [8]. In addition, the need to navigate in remote regions often makes maritime inspections and surveys difficult, thus making operations unsafe, with an increase in the probability of accidents.

Figure 2 presents the definition of main accidents that occur in the maritime industry, which are also common in Amazonian inland transport.
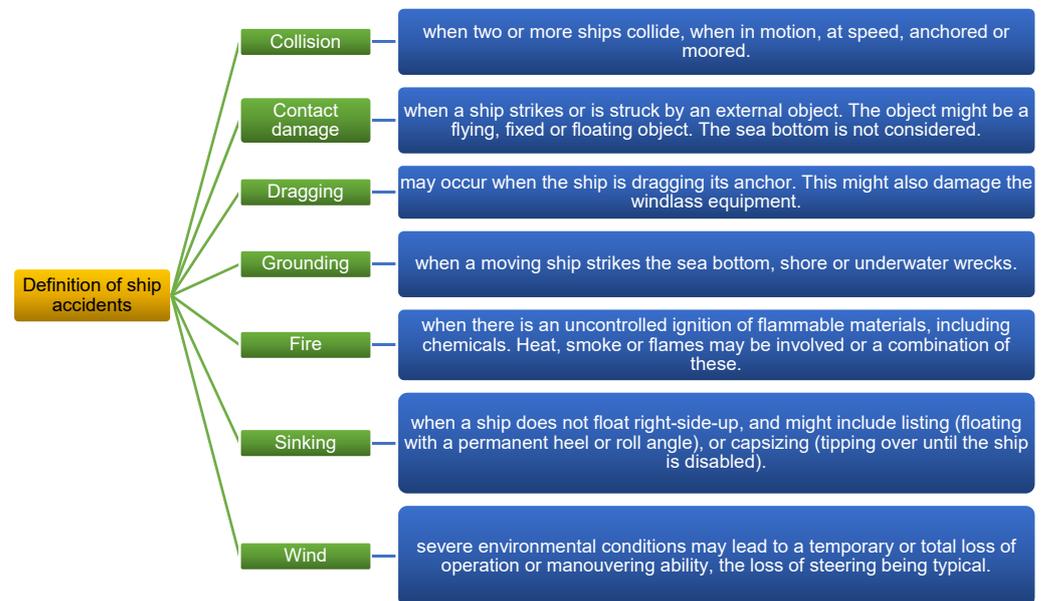

Figure 2. Definition of main ship accidents. Adapted from [9,10].

Many accidents have occurred in the Amazon region involving various types of vessels [11], including passenger accidents, causing considerable human loss [12]. There is a need to understand which factors cause the high accident rates seen in the region as the causes are diverse.

In this research, the accidents involving inland passenger vessels in the Brazilian Amazon are examined. The Amazon region is extensive, which makes signalization and regulations scarce in remote parts. Moreover, there may be environmental factors such as waterspouts, eventual strong winds, or waves [13] which, added to human factors, may be causes that need to be analyzed. It is known that accidents involving passenger ships in the region have caused great loss of life over the years. For example, in 1981, the "Titanic of the Amazon" tragedy occurred, in which about 300 people died between the port of Santarém, in Pará, and Manaus, in the State of Amazonas [14]. More recent figures show that since 2017, there have been more than 142 accidents in the region [15]. In the first four months of 2018, more than 30 accidents were reported [16]. In 2020, the Anna Karolinne III sank in Amapá, with more than 25 fatalities [17].

The prevention of passenger ship accidents in inland navigation is also of concern in other developing regions. For example, Uddin and Awal [18] published a study on the inland waters of Bangladesh, presenting a systems-theoretic approach for identifying the causal factors of passenger ship accidents. Their analysis concluded that most unsafe control actions occur on the bridge, with human failure being the most common reason for accidents.

A statistical and comparative analysis of inland ship accidents near the Three Gorges Reservoir, on the Yangtze River, China, was presented in [10]. The analysis considered ship types, the severity of the accidents, and their frequency of occurrence. The authors found that grounding was one of the most common types of accident and that the main causes of these accidents were human error, severe traffic environmental conditions, and unsafe ship conditions.

Although there has been some research on shipping accidents in the Amazon region, this has been very general and mainly for national readership (e.g., [11,19]). For example, Aziz et al. [20] described some types of marine accidents that are frequent in the region, whereas Filho et al. [21] used data provided by local authorities to identify trends in the

occurrence of accidents in some parts of the Brazilian Amazon. Legal concerns related to marine accidents in the Amazon have been topics of discussion, as presented by [22]. From a military perspective, Iunes [23] discussed applicable legislation and risks in inland navigation. More recently, Padovezi [24] presented a conference paper discussing some risk factors common in the Brazilian inland navigation. Also, injuries that may occur during navigation in Amazonian waterways have been topics of research [25–27].

Yet, there have been no integrated studies that incorporate work on marine accidents in the Amazon region, discussing regional barriers and proposing alternatives for their prevention. To contribute to this purpose, this work presents the problem of marine accidents in the Brazilian Amazon involving long-distance passenger ships, considering the problems and challenges in initiatives for their prevention. An integrated framework that presents the characteristics of regional vessels, possible causes of accidents, preventive measures, and social relevance is proposed, increasing previous knowledge on the topic, and providing some guidelines for decision-making. First, a review of the main types of passenger vessels is presented, followed by a brief description of the maritime regulations applicable in the different regions. Next, the possible causes of ship accidents are discussed, including regional barriers that should be considered in accident prevention initiatives. Some means of preventing these accidents are presented, and, finally, the social relevance of researching this problem in the Amazon region is discussed.

2. Methodology

In this study, an integrated framework towards the prevention of passenger ship accidents in the Amazon region is presented. Figure 3 presents the structure of the research, which includes some relevant topics that were grouped into four parts.
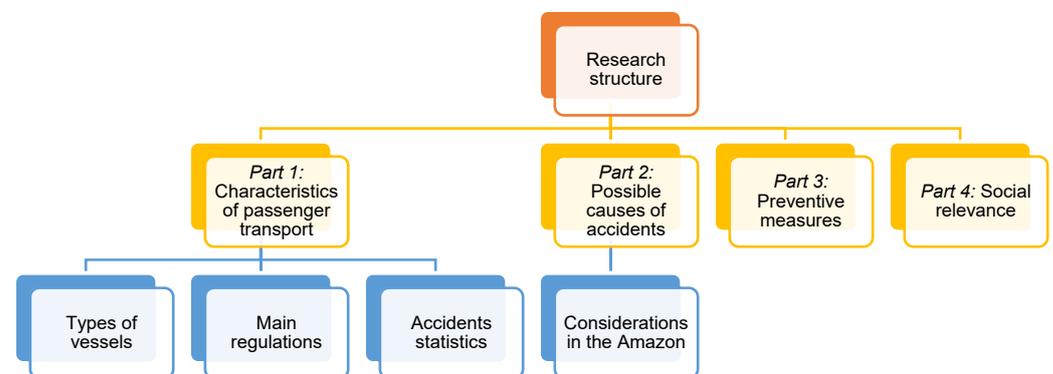

Figure 3. Main structure of the present research, including topics (yellow boxes) and subtopics (blue boxes).

Part 1: Since the scope of the research was limited to the Brazilian Amazon, the first task was to review and present the characteristics of passenger transport in this region, as shown in Section 3. Three topics are presented in the section, including a description of main types of passenger vessels in the Amazon region, applicable regulations in Brazilian navigation areas, and some statistics of accidents that have occurred over the past two decades. For the description of the vessels (Section 3.1), technical visits were performed to some ports and navigation areas in the Amazon, mainly in the state of Amazonas, to capture pictures of representative ships. The pictures were taken with conventional cellphone cameras. The description of navigational areas in Brazil, including applicable regulations, were also analyzed (Section 3.2). To describe the navigation areas, a map of the Naval Districts (NDs) in Brazil was elaborated using Wolfram Mathematica® software. In Section 3.3, statistics of passenger ship accidents were evaluated using the most up-to-date reports of Administrative Inquiries about Navigation Accidents and Facts (*IAFNs—Inquéritos Administrativos sobre Acidentes e Fatos da Navegação*, in Portuguese). These documents,

which are constantly updated, are available through the Directorate of Ports and Coasts (*DPC—Diretoria de Portos e Costas*, in Portuguese) of the Brazilian Navy [28].

Part 2: The second part consisted in presenting possible causes of passenger ship accidents, as shown in Section 4. Basically, scientific literature related to navigational risks was consulted, considering that the research performed by [10] served as a basis of the analysis. Moreover, some barriers that should be considered for accident prevention initiatives in the Amazon waterways are presented (Section 4.1). To describe the barriers, evidence was obtained through some field visits to capture pictures of real situations employing conventional cameras. The topics were discussed based on information found in scientific literature and regional news.

Parts 3 and 4: In the third and fourth parts of the research, preventing measures to reduce passenger ship accidents in the Amazon region (Section 5) and the social relevance of accident prevention initiatives (Section 6) were discussed. Both sections were discussed considering scientific findings published in literature. Literature review was performed using well-known scientific databases and editorials, including Web of Science, Scopus, MDPI, ScienceDirect, Springer, and Frontiers. Different papers, mainly from the last ten years, were considered to discuss the sections on means of accident prevention, and social relevance. Local and national news, articles, and technical reports, available on the internet, were used to complement the information.

3. Passenger Ship Accidents in the Brazilian Amazon

3.1. Main Types of Long-Distance Vessels for Passenger Transport

Perhaps, the most traditional type of long-distance vessels operating in the Brazilian Amazon region are those known locally as *gaiolas* or *recreios*. Figure 4 shows different pictures of these vessels, including some details of typical internal spaces. These vessels usually have many decks, thus forming tall, vertical walls at the sides of the vessel and significantly increasing the height to draft ratios. These are made of wood or steel, or a combination, and their operation is commonly performed in the displacement mode. Technically, the displacement mode of a vessel is an operation mode characterized by the Froude number, $F_n = U/(gL)^{0.5}$, where g is the acceleration due to gravity (in m/s^2), and U and L are the vessel speed (in m/s) and length (in m), respectively. If F_n is lower than 0.4, it can be considered that the vessel is in displacement mode (see details of operation modes in [29]).

Passengers in these vessels are seated or use cabins for the journey. There are also spaces for hammocks and baggage. However, these vessels also transport items such as food, electronics, and furniture, as seen in Figure 4. Although regulations exist on the amount and type of cargo and passengers allowed on these vessels, the lack of enforcement of these means that unsuitable cargo is often transported.

Figure 5 shows some pictures of mixed vessels, which carry cargo as well as passengers and are commonly known in the region as "ferries". These ships are generally made of steel, and, as with the vessels shown in Figure 4, commonly operate in displacement mode. The passengers travel seated or in hammocks on specific decks, but there are also large spaces for the transport of road vehicles and other heavy cargo. This type of vessels is often found connecting the highways found in the Brazilian Amazon.
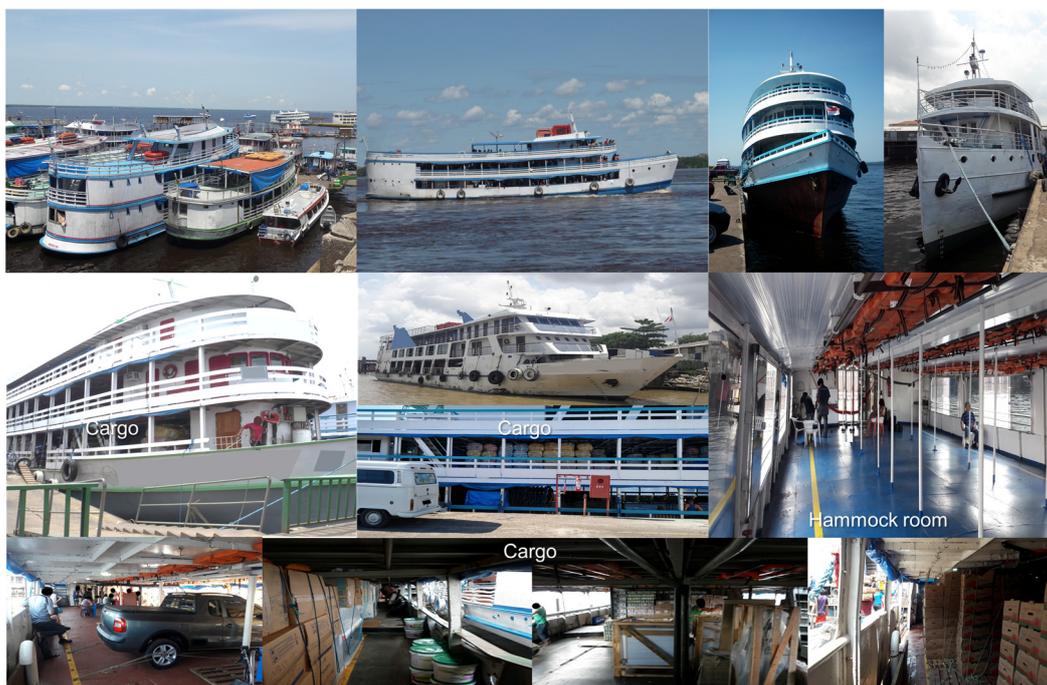
Figure 4. Long-distance vessels in the Brazilian Amazon for the transport of passengers and diverse cargo, sometimes irregularly distributed cargo. These vessels can be regionally named "gaiolas" or "recreios". Photo credits: Ricardo de Almeida Sanches.
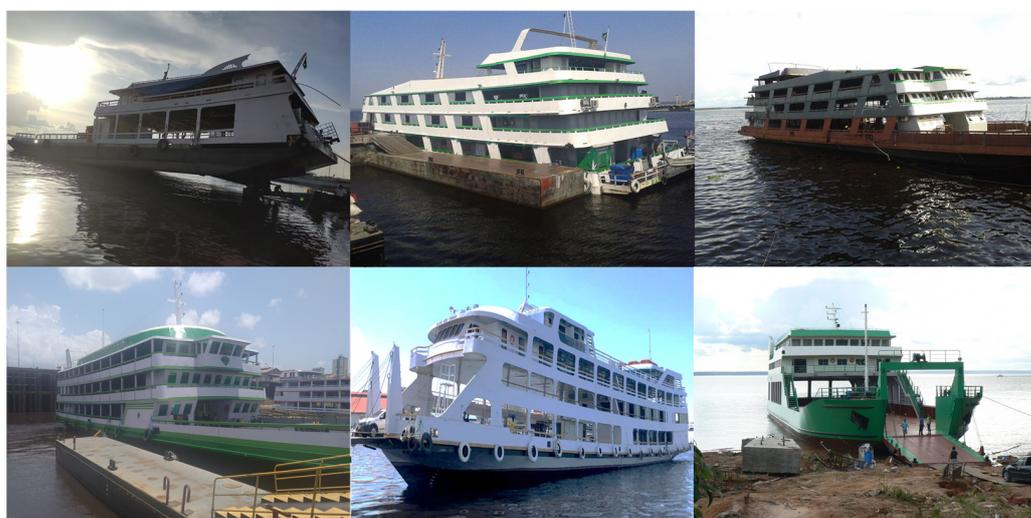

Figure 5. Long-distance vessels in the Brazilian Amazon that transport passengers and diverse cargo, including heavy cargo such as cars. These vessels can be regionally known as "ferries". Photo credits, from left to right: 1st to 4th, and 6th pictures: Ricardo de Almeida Sanches; 5th picture: Thiago Miranda Farias.

The third type of long-distance vessel found in the region are known as "expressos", Figure 6. They are smaller, but faster, than those described above, commonly operating in the semi-displacement mode, i.e., F_n is higher than ~0.4, as described by [29]. They are made from a range of materials, including steel, aluminum, and fiberglass pieces, and often a combination of these. Passengers usually travel seated, as in a bus, (Figure 6), and they are far faster than other passenger vessels over long distances. Details regarding the evolution of these and other Amazonian transport vessels can be found in [30].

Figure 6. Long-distance passenger transport vessels in the Brazilian Amazon, regionally known as "expressos". Photo credits, from left to right: 1st, 3rd, and 6th pictures: Ricardo Almeida Sanches. 2nd, 4th, and 5th pictures: Jonatas Inácio Cordeiro.

3.2. Brazilian Navigation Regulations

While the causes of some passenger ship accidents in the Amazon region have been analyzed in scientific research, as in [19], it is of concern that scarce technical and scientific information is considered in the maritime regulations applicable in the region.

Figure 7 shows a flowchart of maritime regulations applicable in Brazil. Worldwide, the International Maritime Organization (IMO) of the United Nations regulates standards designed to prevent maritime accidents. Various conventions, codes and resolutions are implemented by individual countries. In Brazil, the Brazilian Authority Maritime Norms (NORMAMs—*Normas da Autoridade Marítima*, in Portuguese), managed by the Directorate of Ports and Coasts (DPC) of the Brazilian Navy [31] are responsible for national legislation. Brazil is an active and representative member of the IMO [32]. According to the Coordinating Committee for IMO affairs (CCA-IMO), which is a commission of the Brazilian Navy specializing in the internalization of regulatory standards for international maritime transport adopted by the IMO, the consolidated text of the International Convention for the Safety of Life at Sea (SOLAS 1974/1988), with the amendments until 2014, are internalized into the NORMAM rules (see details in [33]).

To implement the maritime regulations, Brazil is divided into nine regions, or Naval Districts (NDs), as shown in Figure 8. The NDs are composed of one or more states, and the Brazilian Navy is responsible for implementing the procedures for naval operations, aeronautics, safety of navigation, coordination of coastal guard, naval inspection, maritime relief and salvage, social assistance to riverine communities, and so on, in each of them [35].

In Figure 8, the Brazilian Amazon region is shown by a continuous line. It includes eight complete states (Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins) and part of the state of Maranhão. For administrative purposes, the region is therefore considered in the fourth, sixth, seventh, and ninth NDs. Most of the river system of the Amazon region is in the fourth and ninth NDs, mainly in the states of Amazonas and Pará, whose capitals are the cities of Manaus and Belém, respectively.

The Brazilian Amazon is also referred to as the Legal Amazon (*Amazônia Legal*—in Portuguese), an area of ~5,220,000 km^2 (~61% of the Brazilian territory). This concept was instituted by the Brazilian government to plan and promote the social and economic development of the states in the region that historically share similar economic, political, and social characteristics [36]. More information on the geographical characteristics of the Legal Amazon is available via the Brazilian Institute of Geography and Statistics (IBGE [37]).
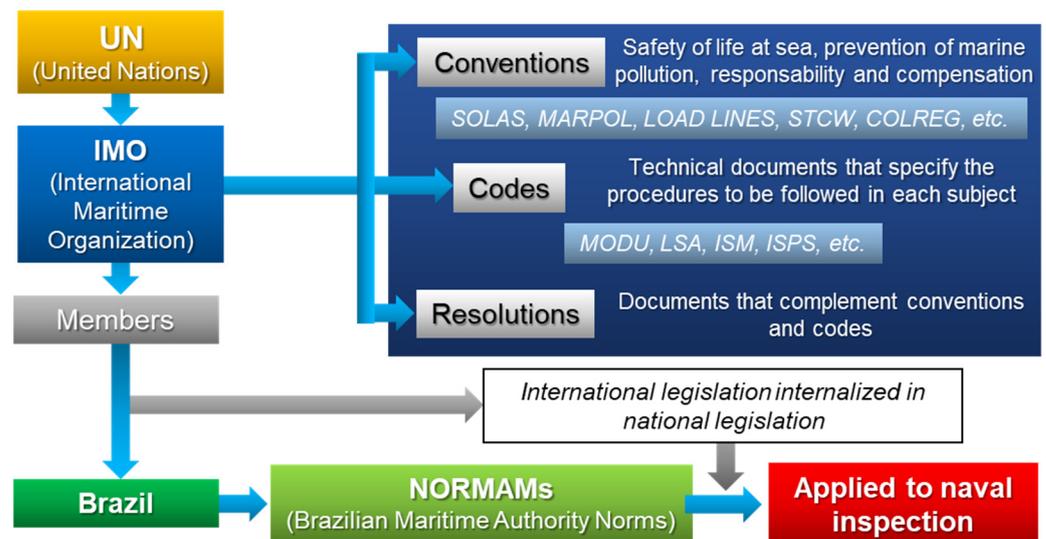
Figure 7. Flowchart of regulations, as applied in Brazilian navigation. Adapted from [34].
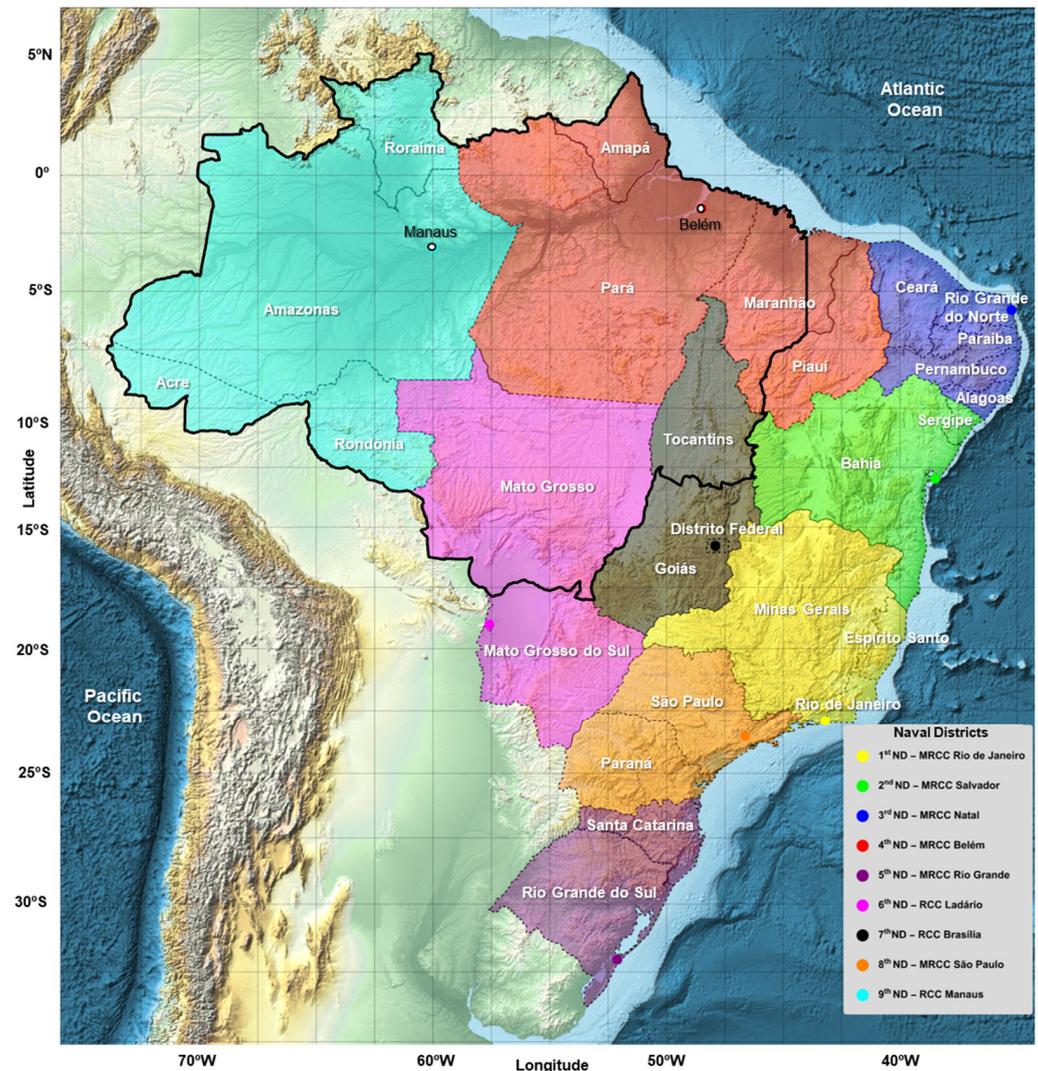

Figure 8. Brazilian Naval Districts (NDs) defined by regions of different color. White words denote Brazil's state names. The continuous black line contour delimits the Brazilian Amazon.

3.3. Passenger Ship Accident Statistics

Maritime accidents in Brazil are registered by the Directorate of Ports and Coasts of the Brazilian Navy through the Administrative Inquiries on Navigation and Accidents and Facts (IAFN—*Inquéritos Administrativos sobre Acidentes e Fatos da Navegação*, in Portuguese), whose report is updated every semester. The national regulation NORMAN-09/DPC [38] defines and differentiates the Navigation Accidents and Facts separately and establishes rules for the registration and instruction of IAFNs, their formalities and processes.

NORMAN-09/DPC covers common navigation accidents, including shipwrecks, grounding, collision, flooding, explosion, fire, and jettisoning. Navigation accidents are characterized as being caused by a breakdown, or defect, in the ship, or in its installations or equipment, which puts the vessel and lives on board at risk. Navigation facts covered in this standard include bad rigging or inadequacy of the vessel for the intended service, and deficiencies in the equipment.

Every year the Brazilian Navy reports on the *IAFN*s. Based on the latest report [39], some statistics of accidents are presented in Figures 9 and 10. Figure 9a shows the number of *IAFN*s that have been registered in the Brazilian NDs in the last two decades, for various activities. From these results, most accidents have occurred in sport and pleasure and cargo activities. For the same period, Figure 9b shows the number of people registered as having disappeared or died in the NDs, for all vessel activities reported.

Figure 10a shows the number of *IAFN*s registered from 2003 until the first semester of 2022, considering only passenger transport in the NDs. Within this period, more than 100 *IAFN* were registered in the years 2009 and 2019. Figure 10b shows the number of victims classified as injured, disappeared, and deaths in this period: there were more injured people in 2017 (~100 victims), and more deaths in 2008 and 2020. It suggests that despite recent technological advances, negative social impacts continue to occur in Amazonian transport.

Figure 10c,d show the percentage of IAFNs and victims (disappeared and deaths together) in passenger transport activities occurring in the first semester of 2022 for each ND. The fourth ND, located in the Amazon region (Figure 8), had the highest percentage of accidents and number of victims in Brazil.
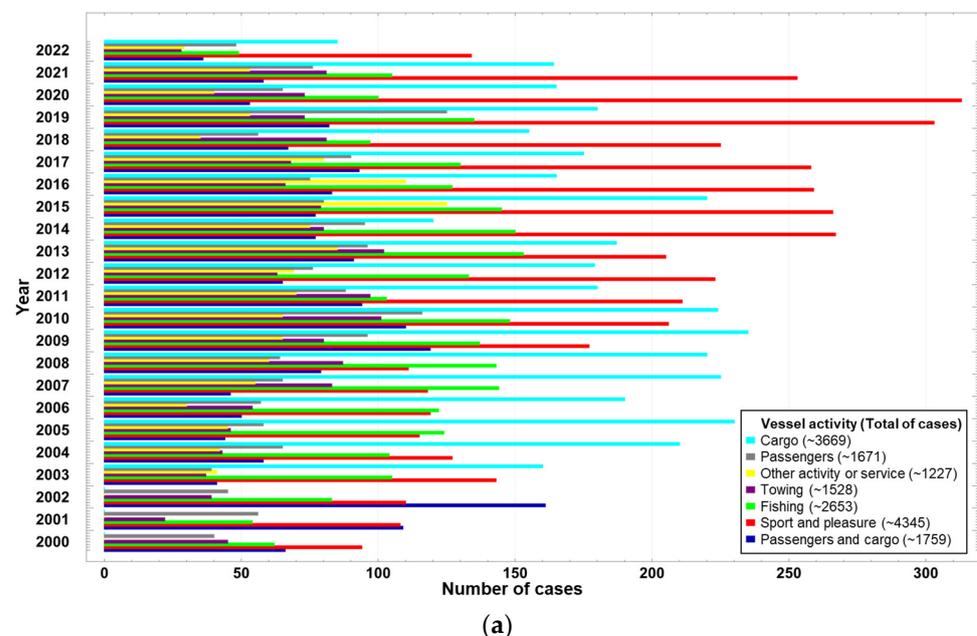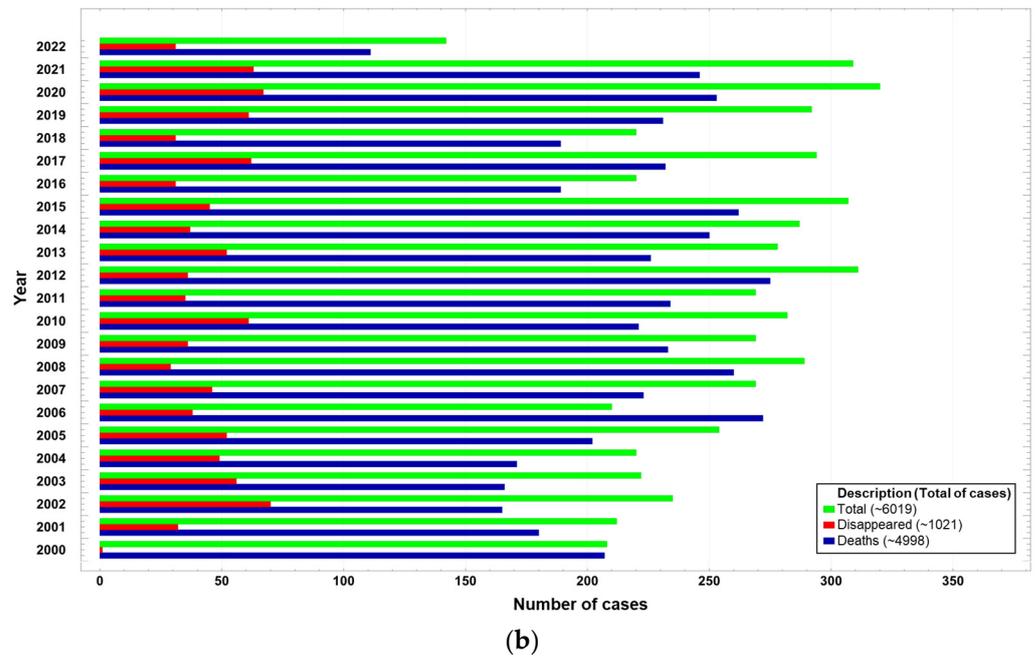

(a)

Figure 9. *Cont.*

Figure 9. Statistics of Administrative Inquiries about Navigation Accidents and Facts (IAFNs) in Brazil: (**a**) IAFN by vessel activity for all NDs. (**b**) Number of Disappeared and Fatalities. Numbers between parentheses indicate the total number of cases from the year 2000 until the middle of 2022.

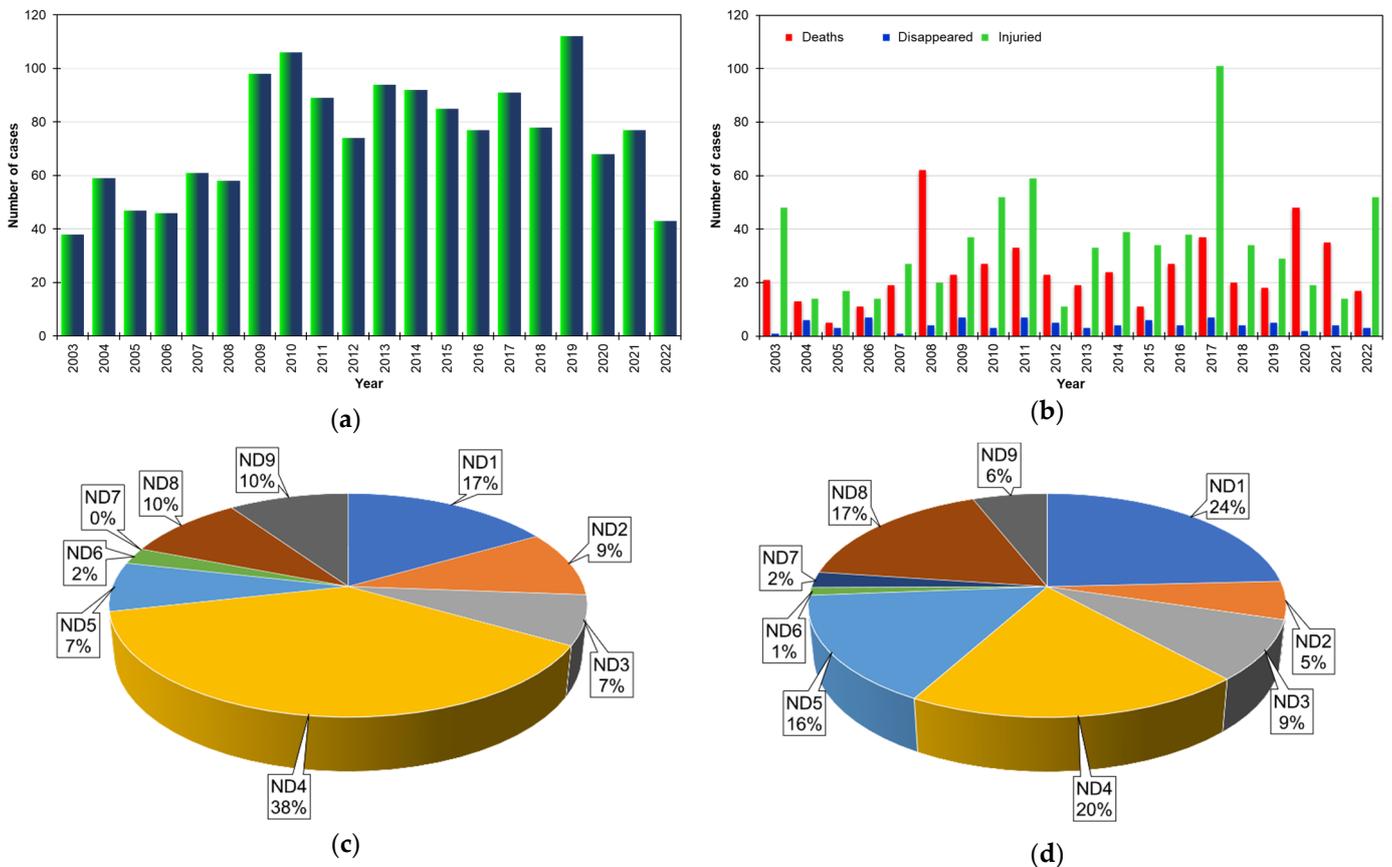**Figure 10.** Some examples of statistics of accidents with passenger transport that have been registered as IAFNs (for all NDs): (**a**) IAFNs across years. (**b**) Disappeared, injured and deaths over the years. (**c**) Percentage of IAFN occurrence during the first semester of 2022. (**d**) Percentage of disappearances and deaths during the first semester of 2022. Source: IAFN report updated until June, 2022 [39].

4. Causes of Accidents on the Amazon Waterways

The Amazon region is the largest hydrographic region in the world and the population depends on river transport as there are few roadways [40] and no railways [41] to connect remote regions. Unfortunately, river transport is often unsafe or uncertain; too often human errors and eventual adverse environmental conditions produce accidents involving cargo, passenger, or mixed vessels [21].

Tables 1–3 summarize possible human errors, risks related to the ship condition, and traffic and environmental risks, respectively, associated with the occurrence of marine accidents, considering the review presented by [10]. It is hoped that the risks and factors shown in these tables can be considered as a basis in the analysis of passenger ship accidents in the Amazon region, helping decision makers to know the main causes of accidents to seek means to prevent them.

Table 1. Possible human errors related to passenger ship accidents (adapted from [10]).

Risk Category	Factors
Ill health	Crew suffering from disease or physical discomfort
Fatigue	Particularly when it is composed of limited numbers, or limited shift changes (e.g., working periods of 8 h), crew fatigue can cause accidents.
Pilot-related incidents	The irresponsibility of the pilots may lead to accidents.
Violation of rules	Violation of the safety management system and regulations by the crew.
	Violation of the anti-collision rules, usually by the Officers On Watch (OOW).
	Violation of the crew duty rules (e.g., failure to hand over shifts).
Management errors	Heavy workload of the crew that may influence the navigation safety.
	Failure during supervision of crew equipment (e.g., lack of life jackets or lifeboats).
	Unqualified crew with inadequate certification or safety training.
Negligence	Lack of situational awareness, due to unfamiliarity with the surrounding traffic environment conditions.
	Lack of navigational attention or safety awareness, or distraction, with respect to risky situations (e.g., distance and speed between ships).
	Cooperation failure when ship's crew is not able to drive risky scenarios with themselves or other ship's crew.
	Confusion in communication between ships, probably due to misunderstanding caused by the different languages or dialects.
	Improper lookout or watch-keeping by the crew.
Operation errors (failure in operating equipment)	Misuse or non-use of navigation instruments: they might not to be ready when encountering danger.
	Inadequate position of the alarm system (e.g., bridge navigational watch alarm system, BNWAS).
Operation errors (decision failures)	Inadequate selection of navigation route to keep safe and save energy.
	Safety distance between ships not maintained.
	Over-safety speed to keep a safe distance between ships.
Operation errors (ship operation errors)	Deviation from the predefined route may cause a dangerous condition due to possible conditions of new route.
	Inadequate or inexistent emergency operation (e.g., during dragging accidents).

Table 2. Ship condition risks related to passenger ship accidents (adapted from [10]).

Risk Category	Factors
Problems in the transmission of information	Failure in the equipment used for communication, such as VHF, or equipment is inadequate.
	Possible failure or improper use of the system used to prevent collision. E.g., the ECDIS (Electronic Chart Display and Information System) and ARPA (Automatic Radar Plotting Aids).
Mechanical problems	Engine problems, including loss of power or engine fire.
	Failure of steering gears, causing difficulties in maintaining course.
Poor condition of the ships	Appropriate maintenance is required for ships to avoid unsafe or inefficient navigation conditions. For example, corrosion can be mitigated through regular maintenance, reducing possible structural damage due to collision or grounding accidents.
	The ship is operating beyond its useful life or is in a critical condition due to overuse.

Table 3. Traffic and environmental risks related to passenger ship accidents (adapted from [10]).

Risk Category	Factors
Channel conditions	The ship is operating with inadequate or insufficient navigation aids. This risk gets worse if there is no bathymetric knowledge of the regions.
	Poor waterway conditions and complex geographic environments.
Natural environment	Noisy environments can influence the decision-making of crew or officers.
	Adverse weather conditions, such as fog, wind, rain, etc., reduce the visibility of the crew or of radar.
	Complex sailing conditions because of falling and rising tides, currents, waves, wind, etc.
Traffic conditions	High traffic density and limited maneuvering capacity.
	Intense traffic of fishing vessels in the waterway.

Table 1 lists several human factors, related mainly to the health conditions of the ship´s crew, including fatigue, pilot-related incidents, violation of navigational procedures, management errors, negligence, and operational errors. It is important to mention that while the Brazilian authorities and shipping companies make efforts to implement legal criteria and regulatory standards correctly, many vessels still perform transport activities in the Amazon outside their legislation.

The ships' poor operating conditions can also be the cause of accidents in the Amazon region, as seen in Table 2. Errors in the transmission of navigational information, mechanical problems, and the poor structural condition or hydrodynamic performance of vessels are the factors producing greatest risks.

As discussed by [3,8], many shipbuilding techniques in the Amazon region are based on inherited knowledge, using empirical procedures to perform dynamic stability analyses and select adequate propulsion systems, rather than applying science-based knowledge and modern shipbuilding technologies. In many regions of the Brazilian Amazon, there is no advanced teaching, nor spread of knowledge in Naval Architecture and Marine Engineering education. The only universities offering undergraduate courses in these fields are in the cities of Belém and Manaus. The latter is relatively new, with specialized professors starting teaching in 2020 [42]. Another difficulty is related to inadequate communications, particularly in the more remote regions.

With respect to traffic and environmental risks, which are shown in Table 3, it is possible to highlight the channel conditions, which are very variable in the Amazon region, as seen in Appendix A.

Natural environment changes should also be considered since heavy rain and strong winds often pose a challenge on the Amazonian waterways. The vessels are commonly overloaded, disregarding the possibility of adverse events. Although inland navigation does not present wave environments as in the ocean, winds can cause unexpected waves that can affect the stability of overloaded vessels. Moreover, forest fires, which are significant environmental risks [43], can cause the accumulation of gases that may affect visibility.

Traffic conditions are also a topic of attention in inland navigation. High concentrations of vessels are common in several Amazon regions, as seen in [44]. Therefore, the poor steering and maneuvering capacity of traditional ships can be a possible cause of accidents.

4.1. Considerations in the Amazon Waterways

Besides the general risks that could contribute to marine accidents in the Amazon region, which were described in Tables 1–3, there are factors that are specific to the study area that need to be considered in initiatives to prevent regional ship accidents. Figure 11 shows some pictures to illustrate these factors, which are described in the following paragraphs.
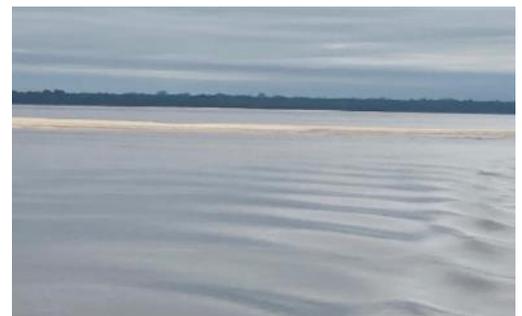
Preservation of the environment

(**a**)

Floating biomass (plants)

(**b**)

Floating biomass (trunks)

(**c**)

Lack of bathymetric knowledge

(**d**)

Figure 11. *Cont.*

Large banks in dry seasons
(**e**)

Lack of signalization
(**f**)

Forest fire emissions
(**g**)

Adverse environmental conditions
(**h**)

Lack of inspection
(**i**)

Illegal activities
(**j**)

Figure 11. Examples of factors that should be considered in marine accident prevention initiatives in the Amazon region: (**a**) Marine biodiversity: example of an Amazon dolphin known as "boto". (**b**) Floating vegetation obstructing the route of a barge. (**c**) A ship colliding with a tree trunk. (**d**) Dune in the middle of a river section caused by variation in water level and sediment transport. (**e**) Large and high banks appearing in the Amazon dry season. (**f**) A river section with lack of signalization for inland navigation. (**g**) Image taken at Rio Negro, Manaus, showing the poor visibility caused, in part, by forest fire emissions. (**h**) Floating structures being impacted by waves generated during a storm in the Amazon region. (**i**) Lack of inspection during unsafe cargo transfer between two ships. (**j**) Example of a police vessel of the "expresso" type commonly employed in some regions. Credits for the images: (**a**) Raíssa Kamezaki; (**b**,**c**) Ricardo de Almeida Sanches; (**d**,**f**,**i**,**j**) Jonatas Inácio Cordeiro; (**e**) Luis Barbosa; (**g**) Jassiel Fontes; (**h**) Kelton Sobral Moreira through Caroline Carvalho de Brito.

First, preserving the uniquely valuable environment of the Amazon basin is vital (Figure 11a). The region has a great diversity of aquatic fauna, as seen in the database of aquatic fish species provided by [45]. Collisions between vessels and aquatic fauna do occasionally occur. For example, accidents between artisanal fisheries and cetaceans that occur on the Brazilian Coast and Central Amazon are the basis of a recent piece of research [19].

Secondly, interactions with floating biomass should be considered. The Amazon has almost a quarter of all the remaining rainforest of the planet [46], containing many dense vegetated subregions [47]. It is therefore very common that floating plants (Figure 11b) and trunks (Figure 11c) cause problems in the propulsion systems of vessels, or even impact and damage the hull of a vessel. For this reason, many vessels here install protection grills around the propeller to minimize interaction with biomass.

The climate of the Amazon basin features a wet and a dry season. Water levels are constantly measured at several monitoring stations, such as that at the Port of Manaus, on the Rio Negro, where monitoring has taken place since 1903 [48]. The graphs presented by [48] show the mean maximum and minimum water levels (~28 and ~17 m, respectively), with rainfall anomalies common, significantly affecting the water levels.

Every year, flooding and land erosion affect the flood plains in the Amazon Basin, causing ecological and sociological problems in the region [49]. These effects, added to the transport of sediments, can cause unexpected changes in the relief of the river bottom, formed during the dry season; see Figure 11d. In fact, in some regions, very large banks, several meters in height, are formed; see Figure 11e. Many of these banks do not exist in the wet season. Although there has been some topographic research done on the Amazon estuary [50], the largest in the world, as well as other parts of the Amazon [51], detailed bathymetries of all the Amazon rivers are still lacking.

As seen in Figure 1 and Appendix A, the Amazon waterways are complex in form, varying in shape and depth, and bordering an immense area of forest. This situation makes signalizing all the navigation routes difficult (Figure 11f). This is especially relevant at night when lighting signals to guide navigation can be crucial. Although rain and mist are common phenomena in the region, adequate visibility for navigation is even more complicated by concentrated forest fire emissions (Figure 11g), which are increasingly common here [52,53].

Although environmental conditions in the Amazon waterways are stable most of the time, with calm water, sunny days, and gentle winds, at times, adverse conditions occur. Typically, a combination of heavy rain with strong winds, called "*trombas d'água*", [54] tend to generate surface waves that can cause unexpected motion of vessels and other floating structures. Wind can also contribute to unexpected lateral forces on the high superstructure of the vessels, limiting their capacity to right themselves [55]. In waves, passenger vessels can be subject to different dynamic problems, including high accelerations [56], slamming (strong wave–hull interaction in the form of impact [29,57]), shipping water on the deck [58–61], and unexpected and unstable ship motion [62,63]. Some of these problems have been recorded with passenger vessels in the Amazon region, especially when they navigate close to the Amazon estuary, as documented in videos on the internet and social media (e.g., [64]).

Two main navigation areas, Area 1 and Area 2, defined in NORMAM-02/DCP [65], are found in the Amazon region. Area 1 has sheltered areas, such as lakes, bays, rivers, and channels, where there are waves with heights that do not present difficulties for vessels. On the other hand, in Area 2, there are partially sheltered areas, where waves with significant heights and/or adverse combinations of environmental agents are seen, such as wind, current, or tide, which can cause difficulties for the transit of vessels. Inland navigation in Area 2 within the Amazon region is described in the rules and procedures of the Ports Authority of Eastern Amazon (*CPAOR—Capitania dos Portos da Amazônia Oriental*) and the Inland Authority of Western Amazon (*CFAOC—Capitania Fluvial da Amazônia Ocidental*). Passenger vessels operating within the permitted navigation area, in Area 2 and regions close to the open sea, need to be subject to more detailed ship dynamics analyses (seakeeping and maneuvering).

Finally, there are barriers to the application of maritime regulations in inland Amazonian navigation. Although the Brazilian Navy and municipal authorities carry out extensive campaigns to restrict potentially dangerous activities, the sheer size of the region makes it difficult to cover all the navigation areas (e.g., Figure 11i), putting at risk the safety of

vessels and people. Examples include races between vessels, the unlawful transport of fuels and cargo, risky maneuvers, unstable distribution of weight in vessels, operation in unsuitable areas (e.g., in the presence of waves). Drug transportation [66,67] and other illegal transport activities [68,69], including pirate attacks [70], are still a great concern in the Amazon waterways. Although local authorities employ high-speed vessels to combat these issues and to provide salvage and rescue activities (e.g., Figure 11j), the sheer size of the region makes them crucial challenges to be faced.

5. Preventative Measures to Reduce Passenger Ship Accidents in the Amazon

Passenger ship accidents can occur in different modes of operation, either in port or when navigating in restricted, or unrestricted, waters. From the data consulted, it is seen that in the Amazon region many ship accidents can occur because of negligence (human factors), a lack of navigational aids, and weather conditions. Ventikos et al. [71] performed a review of navigational accidents in adverse weather conditions, concluding that, in these situations, accidents are related to insufficient power and poor maneuverability of the vessels. These can be exacerbated by the vessel characteristics, namely, ships designed according to traditional means, rather than using technical and certified procedures [3,72].

Furthermore, it is well known that excess loads and poor distribution of weight (passengers and/or cargo) are common practice in river transport in the Amazon, particularly in remote regions where legislation is difficult to apply. Many ships work without fulfilling the minimum technical requirements, and it is possible that ship owners do not have hydrostatic information nor stability analyses of their vessels. They may assume that environmental conditions will not affect the performance of their vessels, and therefore, the vessels are not prepared for unexpected dangerous situations caused by adverse conditions.

Although shipbuilding and repair activities are not new in the Amazon region, research, development, and extension activities using Naval Architecture and Marine Engineering concepts are lacking. For example, in the state of Amazonas, the undergraduate course in this area, founded in 2013 in the capital Manaus, is relatively recent. There has been little scientific innovation in the Amazonian naval industry in recent years. It is hoped that applied research in Naval Architecture and Marine Engineering, and the participation of government and industry, will contribute to the divulgation of recommendations and good practices to help stakeholders and decision makers. The implementation of recent international standards from the IMO will also prevent passenger ship accidents.

Based on the research performed and the current situation of navigation in the Brazilian Amazon, Figure 12 shows some suggestions to reduce the number and severity of passenger ship accidents in the region. Each suggestion is described as follows:

- *Reinforce education and training*: Wróbel [73] emphasizes that human error is significantly related to maritime safety. In this framework, education and training initiatives to improve the ability of crews to act correctly in emergencies are needed, as stated by [74]. Studies to evaluate the effects of safety knowledge, training, and management of the operational safety of vessels are required, as proposed in [75]. Fu et al. [76] suggested that research related to risk decisions in accident scenarios is also needed.
- *Continuous verification*: Periodic activities to verify and certify the technical capabilities of the crew, as well as the integrity and operation conditions of the ship are recommended [74]. The experience of safety management on ships in other regions of the world, such as in [77] in Asia, should be considered.
- *Strengthening regulations in naval processes*: Initiatives to promote the application of technical guidelines and regulations with relevance to the naval sector, including shipbuilding, repair, and navigation activities are needed. It is important that the naval industry in the Amazon region be updated with respect to the new regulations from the IMO. For example, the new IMO Second Generation Intact Stability Criteria should be implemented to plan safer navigation in the navigational Area 2, where waves and winds create risks. Petacco and Gualeni [78] and Petacco et al. [79] present a general overview and examples of the application of this criteria.

- *Enhancing legislation on maritime activities*: Increasing control in the ports of the states, and internal and external ship inspection, including operations, are recommended [74]. The study and implementation of updated maritime regulations in ship design, ship-building, and navigation should be considered.

- *Encouraging scientific and technological development*: Research and development activities to improve various ship technologies are vital. Scientific and technological assessment of stability, mechanical systems, and maneuvering (steering and control) issues are also lacking. An example of scientific application would be the study of the behavior of vessels subjected to severe beam wind [80], which would require advanced simulation methods and experimental data for validating their results, as shown by [55,81,82]. Simulation methods based in Computational Fluid Dynamics (CFD) should be employed to analyze accidents related to flooding, fire and explosions, and oil spills, as demonstrated by Zhang et al. [83], Xie et al. [84], and Tkalich [85], respectively. On the other hand, structural analyses, using tools such as Finite Element Methods (FEM), could be employed to investigate collision and grounding accidents, as proposed by Martinez et al. [86] and Prabowo et al. [87], respectively.

- *Seeking more government support*: To promote and strengthen the support of the government in terms of funds for passenger accident prevention [74,88], including outreach and dissemination activities through regional media are needed. The role of social media is important in disseminating information, as suggested by [89], to prevent environmental incidents.

- *Stimulating the interest of owners and industry*: To invest in improving ship safety as well as the safety perception by the shipping companies and owners [74]. The dissemination of information related to possible social and environmental impacts caused by passenger ship accidents may cause stakeholders to prioritize safety and security issues in transportation [90].

- *Using new technologies*: Planning strategies to implement recent technologies, such as those from 4.0 Industry, to prevent accidents, as proposed very recently by [91], are important options. Sepheri et al. [91] presented the use of *Cyber-physical systems*, *Augmented Reality and Digitalization*, *Internet of Things*, *Big Data*, and *Cloud Computing* to prevent navigational accidents. Based on the 4.0 technologies framework, concepts such as *Shipping 4.0* [92,93], *Ports 4.0* [94], *Maritime 4.0* [95], and *Machine Learning* approaches to improve the sustainability of ship design and operations [96] are being considered in marine applications. Finally, the use of renewable energy sources to provide signalization or communication through autonomous floating, anchored, or fixed devices could reduce accident risks in navigation. Some uses of solar and hydrokinetic energies, which are available in the Amazon, were discussed by [3,97–100]. For example, it is possible to mention autonomous and sustainable auxiliary devices like autonomous buoys that are being developed for environmental monitoring, as in [101–103]. Underwater exploration using manned and unmanned robots, such as those presented in [104–108], are also options to increase knowledge of the underwater environment and learn more about land changes in navigation areas.
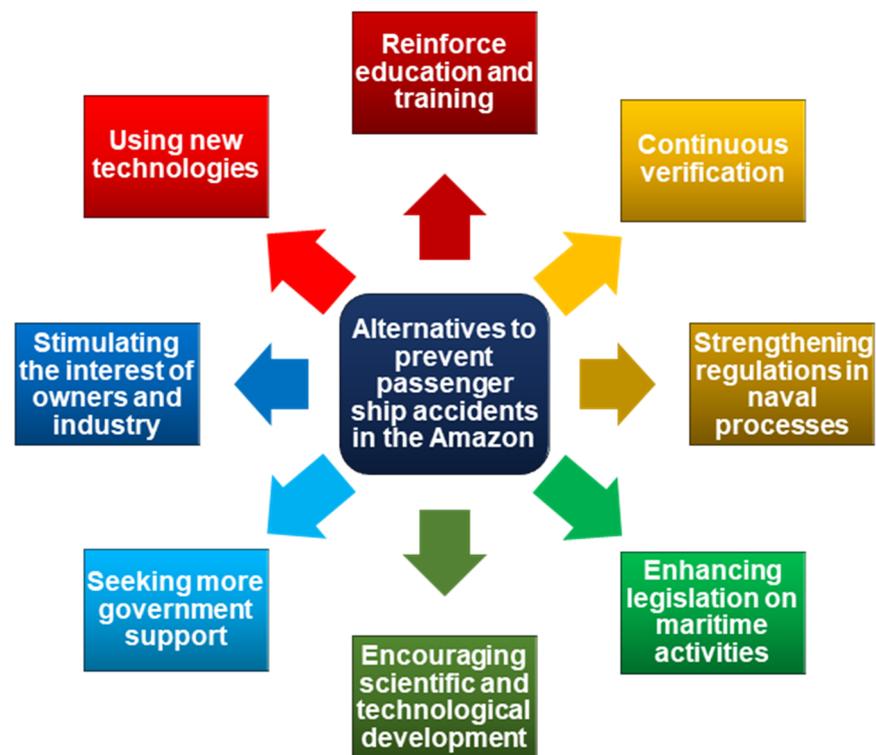
Figure 12. Alternatives proposed to minimize the occurrence of passenger transport accidents with vessels in the Amazon region.

6. Social Relevance

Some of the most relevant social problems in the Brazilian Amazon are related to access to clean water, illiteracy, violence, and limited opportunities to obtain a better life with respect to the rest of the country [109]. The prevention of passenger ship accidents in the Amazon region is of great relevance to reducing transport inequalities and to increasing sustainability in communities with different levels of economic and social vulnerability. Several cities in the Amazon region are disconnected from the rest of Brazil by highways [40,110], and some cities remain completely flooded during half of the year, in the wet season, as in the case of Anamã, in the State of Amazonas [111]. This situation causes people of different communities to need to conduct daily activities using vessels, since air transport is not economically nor technically viable in several regions. These vessel activities are related to fishing [112], transport for scholar activities [3,113], local and long-distance transport, etc., in which different problems, such as catastrophic accidents (e.g., shipwrecks), serious injuries like "*escalpelamentos*" (head scalpel [25]), river level rise vulnerability [114], and the lack of accessibility of people to transport vessels [115], are even found.

Thus, the reduction of accidents in passenger transportation is important in contributing to the sustainable future of the habitants of the Amazon. Related initiatives to prevent accidents could contribute not only to the good health and well-being of Amazonian people, defined as the third sustainability objective of the United Nations, but also to other goals, such as quality of education, decent work and economic growth, reduced inequalities, and sustainable cities and communities [116–119].

Technological and economic changes have caused several social impacts in the Amazon region. Some examples are cited by [120], such as the construction of the Trans-Amazonian Highway in 1974, the increase in the price of agricultural products, the implementation of hydroelectric plants, mining activities, and port-related activities. This suggests that new accident prevention projects including the implementation of new technologies or devices, such as those for improving navigation activities, should be evaluated considering the social inequalities in different Amazon regions. Social resilience and studies on the

vulnerability of people to changes (as done by [121]) should be considered in accident prevention and transportation [122] projects.

Finally, it is important to mention a that there are diverse indigenous communities distributed in the Amazon, as presented by [123]. According to Brazil's Constitution, their customs, languages, social organization, creeds, traditions, and the lands they traditionally occupy should be recognized. Whereas above-ground property belongs to the indigenous community, water resources and minerals belong to the state. These resources could be extracted or dammed after consultation with the indigenous communities [124]. This is an important factor that should be considered in possible initiatives related to accident prevention in preserved areas, mainly when the use of land or water resources will be necessary for deploying devices or technologies.

7. Conclusions

From the research described above, the following suggestions are made:

The integrated review presented in this paper can be used by stakeholders and decision makers, including government agencies, ship owners, transport companies, and engineers to improve vessels and operations related to passenger transport in the Amazon waterways. This is important in order to reduce transport inequalities, as well as to contribute to human development and sustainability in communities with high levels of economic and social vulnerability.

Passenger ship accidents are often related to human factors, ship conditions, and human and environmental factors. Therefore, research and development, as well as extension activities on these topics should be performed. In addition, there are particularities of the Amazon region that should be considered in order to prevent such accidents; these are described as follows:

- As an ecosystem, the Amazon is one of the most biodiverse places on earth; thus, preventing the interference of navigation from aquatic animals or floating plants that can cause unexpected collisions is required.
- The water levels in the Amazon waterways vary during the year, so improving bathymetric knowledge for the dry and wet seasons, to avoid grounding, is required.
- The Amazon is the world's biggest rainforest, so it is difficult to signalize all the waterways. Efforts to provide better signalization are required for safer navigation.
- Adverse environmental conditions in the Amazon, including the occurrence of rain, wind, and waves, could contribute to the occurrence of accidents and should be accounted for in ship design and regulation activities.
- Irregular vessels still operate in remote regions of Amazon waterways, so the enforcement of maritime legislation in remote regions must be strengthened, and illegal activities must be eradicated. Moreover, inspection activities related to navigation accident prevention should be increased and improved, and more government participation in accident prevention projects are demanded.
- Scientific research related to Naval Architecture and Marine Engineering topics is still scarce in the Brazilian Amazon. Therefore, scientific knowledge and education activities related to navigational and safety procedures for ship owners, shipping companies, crew, and passengers should be encouraged. Moreover, national, and international collaborations are required to strengthen research and development activities in Safety and Naval Architecture and Marine Engineering aspects. Initiatives are also needed in order to implement technical procedures, both in existing maritime regulations and research into new technologies, such as those from 4.0 Industry.
- Millions of people who live in the Amazon use the rivers as their main means of transport; thus, social aspects should be considered in accident prevention initiatives, involving the social inequalities of different Amazonian communities, as well as their resilience and vulnerability to changes.

In the present study, some topics were presented in a general manner to propose an integrated framework, providing useful references. Moreover, the statistics of accidents

analyzed were based on reports of registered cases in the Brazilian Naval districts (NDs). Further research should be done to quantify the occurrence of accidents in the Amazon region considering other sources of information. Moreover, research should be done to identify and document real causes of marine accidents in the Amazon region through technical visits and interviews.

Author Contributions: Conceptualization, J.V.H.F.; methodology, J.V.H.F.; software, J.V.H.F. and P.R.R.d.A.; validation, J.V.H.F. and P.R.R.d.A.; formal analysis, J.V.H.F., P.R.R.d.A., H.W.S.M., R.S. and I.D.H.; investigation, J.V.H.F., P.R.R.d.A., H.W.S.M., R.A.S. and I.D.H.; resources, J.V.H.F.; data curation, J.V.H.F. and P.R.R.d.A.; writing—original draft preparation, J.V.H.F., P.R.R.d.A., H.W.S.M. and I.D.H.; writing—review and editing, J.V.H.F., C.A.R., P.T.T.E., E.M., S.M. and R.S.; visualization, J.V.H.F., P.R.R.d.A. and R.A.S.; supervision, J.V.H.F.; project administration, J.V.H.F.; funding acquisition, J.V.H.F. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

This appendix presents some pictures that demonstrate the complexity of the waterway systems in the Amazon region (Figure A1). In the region, it is possible to find the interaction of rivers with different characteristics (color, chemical components, acidity; Figure A1a), groups of islands whose elevation may change in wet and dry seasons (Figure A1b), and sinuous rivers with complex curves (Figure A1c).
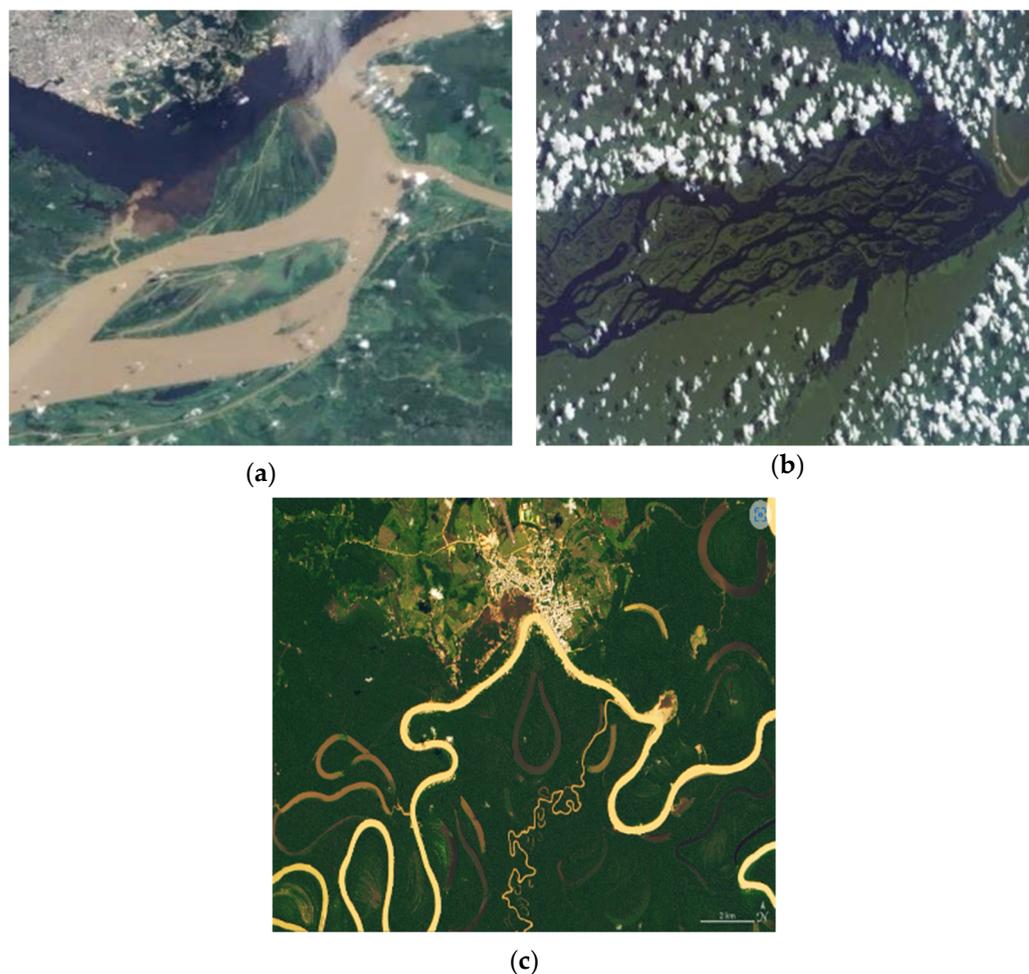
(a)

(b)

(c)

Figure A1. The complex Amazon waterways: (**a**) Interaction between Negro and Solimoes Rivers near Manaus, capital of Amazonas state (image taken on 17 July 2009) [125]. (**b**) Digital image taken from space showing an area of many islands in the Rio Negro (Black River), in the Central Amazon, a region considered a long "archipelago", upstream Manaus (not shown in the figure). While the archipelago is about 120 km in total length, the image shows only the middle section (data acquired on 1 January 2018) [126]. (**c**) Meanders in the Juruá river, one of the most sinuous rivers in the Amazon Basin (image taken on 27 May 2019) [127]. Source of images (**a**–**c**) is Catalog of NASA (National Aeronautics and Space Administration; https://visibleearth.nasa.gov/images, Accessed on 29 July 2022).

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