

Article

An Approach to Calculating the Minimum Safety Distance Against the Potential Risks of Shipwrecks

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Abstract

From the perspective of sustainable marine environmental management, the threats posed by shipwrecks to navigation and the environment, as well as the difficulty of intervening in them, highlight the importance of a detailed risk assessment. Therefore, the safe management of wreck sites remains an ongoing study issue. However, international regulatory frameworks for maritime use have not established a direct distance standard for the possibility of interaction with wrecks. This study aims to contribute to the calculation of safety distances by examining safe management strategies against the potential risks of shipwrecks from a technical perspective. A mathematical approach was proposed for determining the minimum safety distance required, taking into account the position of the sunken ship on the seabed and the possibility of contact at anchor, which is relatively higher than at sea. This was applied in a risk assessment conducted using case studies of different conditions, and a set of risk measures was added, specifying the required safety distance for each risk. Then, scenarios with and without this intervention option were compared based on the ALARP principle. The results show that it is possible to reduce risk scores with less effort in situations where the response option with a safety margin is included.

Keywords: sustainable maritime governance; shipwreck; safety distance; safety zone; anchorage; risk assessment; marine protection; ecological buffer zone; environmental risks; maritime environmental compliance



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1. Introduction

It is estimated that millions of shipwrecks (~3 million) rest at the bottom of the world's seas. These ships pose hidden dangers beneath the sea and threaten other maritime activities because of the hazardous materials they may contain and their location on the seabed [1,2].

Shipwrecks caused by accidents, disasters, or abandonment and the hazardous materials in shipwrecks, such as fuel oil, cargo residues, and toxic substances, present a long-term risk of environmental contamination that can impact marine life and coastal communities for years [3]. Also, oil spills and petroleum products from wrecks at sea can cause serious biological damage, such as increased animal mortality, and negatively affect the health, growth, and reproduction of organisms in later years, due to long-term exposure to toxic substances and [4] ultimately disrupts the marine ecosystem.

From another perspective, shipwrecks are known to serve as suitable habitats for many marine species, and due to their structure, they have often acted as artificial reefs in various countries around the world [5]. These structures provide protection from predators,

serve as breeding grounds, and offer high food availability, thereby attracting a diverse range of organisms [6]. Fish often gather around shipwrecks, using them as habitats, which increases their populations and draws in commercial fishing. However, this can create risks, such as fishing equipment getting tangled in wrecks, which can cause economic losses and maritime accidents. Lost equipment and ghost nets can harm reef environments and wreck sites, posing serious problems for dive tourism [7].

Besides all these, shipwrecks can deteriorate over time due to factors such as navigational errors, corrosion, and physical damage from trawling or other human activities, which increases the possibility of leakage and the release of potentially hazardous materials. In addition to environmental and social issues, wrecks may also be found along shipping routes with high density of traffic or in nearby important anchorage areas, which could create extra navigational and operational challenges and risks for maritime activities and safety. In particular, anchoring in maritime operations demands extreme caution and is one of the most dangerous tasks due to the high risk of errors related to human and operational factors. Accidents can happen due to these errors during anchoring operations, such as oil spills on tankers and fires in deck and cargo compartments of cargo ships [8,9]. In maritime navigation, anchorage areas are designated locations planned by considering operational requirements and user needs to ensure ship and coastal safety.

Given the increasing maritime traffic, the effective and safe management of anchorage zones has become even more crucial. Since ship positioning, oceanographic conditions, and seabed features are key factors in planning these zones, existing studies mainly concentrate on these aspects [10–14]. Although some studies have evaluated the safety of anchorage areas [15–19], the correct position distances that should be taken against factors that may pose a risk in the interaction between these areas and wrecks have not been emphasized.

In this study, the safety distance that should be maintained as a precaution against the potential risks of shipwrecks is presented for situations where the possibility of contact, such as anchoring, is high. For this purpose, the area of the ship in these positions was examined, and a mathematical approach was proposed for determining the minimum required distance from the submerged ship's underwater position to the safety zone. First of all, from a stationary point at the origin of the shipwreck, a value has been provided for the equation created based on the size and anchoring limits of ships that have the potential to interact with it, as an additional precaution. The maritime traffic density, hydrometeorological conditions, and coastal spatial plans will constitute the additional safety margins that the maritime authority at the location of the wreck can specifically employ. This approach was then applied in a risk assessment conducted through various case studies with different hazard levels, types, and locations, and added to the set of risk prevention recommendations in the form of the safety distance required for each risk. Then, the situations with and without this intervention option were compared with the ALARP principle.

2. Safety Distance Criteria for Shipwrecks

In many international standards and codes, especially SOLAS (Safety of Life at Sea), warning systems, emergency procedures, mapping, and visual markings are mandatory when wrecks pose a threat to navigational safety [20,21]. Similarly, the ISM Code (International Safety Management Code) establishes management systems to ensure the safe operation of ships and minimize environmental risks. It requires ship operators to conduct risk assessments and create emergency procedures when planning navigation in areas at risk of shipwrecks [22]. Fuel and chemical leaks from shipwrecks are considered environmental risks under MARPOL (International Convention for the Prevention of Pollution from Ships) [23]. The Wreck Removal Convention (Nairobi, 2007), established

by the IMO (International Maritime Organization), addresses the removal of shipwrecks that endanger maritime safety [24]. UNCLOS (United Nations Convention on the Law of the Sea) is the global framework for utilizing marine areas and the protection of the marine environment [25]. UNESCO (United Nations Educational, Scientific and Cultural Organization) 2001 Convention on the Protection of Underwater Cultural Heritage; shipwrecks, particularly warships and historic merchant ships, are considered cultural heritage [26]. This convention prohibits the unauthorized excavation, destruction, or commercial exploitation of shipwrecks. IHO (International Hydrographic Organization) S-44 Standard—Hydrographic measurement accuracy specifies the accuracy criteria for sonar and lidar systems used to locate and map wrecks [27]. ISO (International Organization for Standardization) 19902—Design Standards for Offshore Structures; provides structural safety criteria for fixed or floating structures (e.g., buoy systems) to be constructed around wrecks [28]. It can serve as a reference, especially for warning systems and monitoring stations installed around wrecks.

However, all these maritime regulatory frameworks related to shipwrecks do not directly establish a distance standard, except for some general recommendations to ensure maritime safety when interacting with shipwrecks. And the fact that this distance has not been adequately studied so far has led to the emergence of certain risk factors in the marine environment or has hindered the easier and more economical prevention of an existing risk. Shipwrecks are considered “immovable hazards to maritime safety” in many local legal definitions. IMO regulations only recommend that local maritime authorities establish a “Prohibited Area” for shipwrecks within a certain distance, based on the ship’s size and the hydrographic features of the location. In this context, many qualitative factors are listed, but there is no quantitative measure that directly relates them to the safety distance.

Therefore, a lack of quantitative approaches that take the wreck’s location and position on the seabed as a starting point has been observed. For this, the depth of the wreck relative to the water surface, the area it covers underwater, and the characteristics of the vessel that might interact with the wreck should be taken into consideration. Furthermore, the risk values that define the wreck’s location, such as traffic density, physical environment (bathymetry, wind, currents, etc.), marine and coastal area plans (protection status, archaeological value, tourism, port facilities, etc.), should be reconstructed, and this approach should be used by authorities to more effectively establish minimum safe distances for the wreck.

Anchorage zones are one of the areas where maritime safety is most frequently studied. However, despite strict safety measures in these areas, the lack of intervention against shipwreck interactions is usually due to the fact that during site planning, the wreck is either not known at that moment or the accident that caused the wreck is discovered later. The anchoring circle radius calculation used in anchorage area planning offers a convenient mathematical approach for both ensuring the safety of these areas against shipwreck risk and for obtaining an upper safety limit value around the shipwreck. Based on this, an approach has been presented to establish a practical impact area generated by the structure of a hazardous shipwreck or obstacle itself. For the determination of this minimum safe zone, Equations (2) and (3) were formulated, respectively, and subsequently, by evaluating Equations (1)–(3), the minimum safe distance was presented as Equation (4).

The calculation of the anchoring circle radius is used to identify the maximum movement area of a vessel at anchor. The radius equations that define this circular area generally consider the ship’s length (L) and water depth (D), using the Pythagorean Theorem. Equation (1), which is one of these equations for the radius of the anchoring circle “ r_d ” [29],

$$r_d = L + \sqrt{(25\sqrt{D})^2 - D^2} \quad (1)$$

When planning a safe zone around the shipwreck location, it is important to know the horizontal and vertical areas covered by the wreck. Creating a cylinder that encompasses the volume from the largest dimensions of this fixed obstacle on the seabed allows for a more optimal circular zone on the surface for the same application area compared to rectangular shapes. In this case, the widest horizontal length of the obstacle will constitute the diameter of the cylinder base circle. The wreck, positioned in an irregular shape on the seabed shown in Figure 1, is assumed to form a virtual cylinder, with L_s (diameter of the cylinder) as the horizontal length and d_s (height of the cylinder) as the distance from the contact point with the seabed to the highest point of the wreck. The dimensional characteristics of submerged obstacles and wrecks vary depending on their structural situation and the water-column features in which they are located. Although parts of the wreck have collapsed, even 1–2 m pieces can pose significant hazards, especially if they correspond to critical structural components such as oil tanks or cargo holds. Therefore, the condition $d_s \geq 5$ m as the lower limit for the height of the obstacle is defined as a protective lower limit in terms of both measurement reliability and operational safety. In cases where the actual height of the wreck or part of it is below 5 m or cannot be verified by measurement, a conservative approach is assumed to be $d_s = 5$ m. The following criteria were considered in determining this lower limit: Operational depth ranges of anchorage areas or areas where anchorage can be made, port approach, and waiting areas [12,13], Minimum oil spill amount that could create an environmental hazard (International Tanker Owners Pollution Federation (ITOPF) categorizes spills as small scale if less than 7 tonnes) [30], and the dimensions of potentially polluting structures, especially oil tanks and cargo compartments [20], non-hazardous but historically significant or immovable wrecks and scattered debris [31] and uncertainties in measurement and hydrographic survey in shallow waters [27].

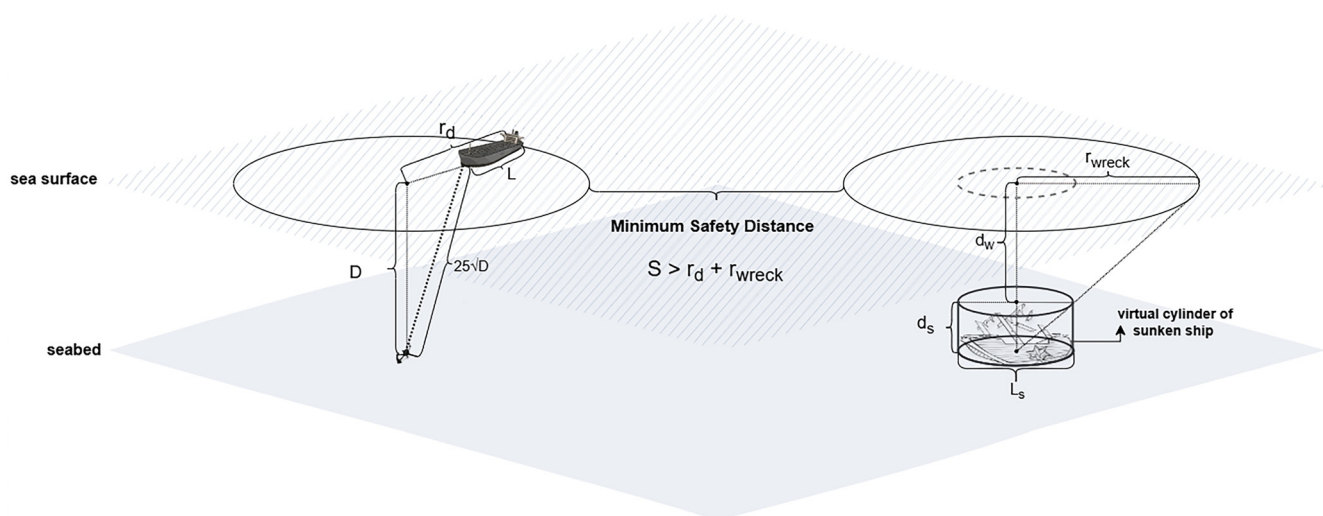


Figure 1. The ship, its anchor chains and their location relative to the wreck.

The radius of the circle formed by this cylinder above the water column using Thales's theorem is called r_{wreck} , and the distance from the water surface to d_s is called d_w . Using the parallel relationship of these defined points, the aim is to determine the length values, and in this context, Thales's theorem, which enables establishing a ratio, is utilized. When basic proportionality is applied to an object with this structure, the ratio of d_s to d_w in Equation (2) and the ratio of $L_s/2$ to r_{wreck} in Equation (3) emerge:

$$\frac{d_s}{d_s + d_w} = \frac{L_s/2}{r_{wreck}} \quad (2)$$

$$r_{wreck} = \frac{L_s(d_s + d_w)}{2d_s} \quad (3)$$

This equation only provides the radius of the minimum safe zone created by the fixed obstacle. However, when determining the safety distance, the circle of a vessel anchoring near this area should also be considered. The movement of this vessel's chain during anchoring could pose a risk of damage to the anchoring operation or the wreck. Therefore, to determine the practically applicable minimum safe distance “*S*,” Equation (4) should be applied as follows:

$$S > r_d + r_{wreck} \quad (4)$$

Accordingly, the minimum “*S*” should be composed of the r_d of the ship that will be anchored around the wreck, the r_{wreck} of the shipwreck. The r_{wreck} created by the wreck varies depending on d_w . As d_w decreases, meaning the obstacle approaches the surface, r_{wreck} decreases, or when the obstacle is fully visible and above the surface, the probability of detection increases (clear precautions and markings), and thus r_{wreck} equals the diameter of the virtual cylinder. As d_w increases, meaning the obstacle is deeper, r_{wreck} increases. Of course, shallow and deep wrecks pose different types of risks; shallow wrecks generally pose navigational hazards, while deep wrecks are more associated with environmental and structural risks. In this context, just as a collision with a surface wreck poses a significant hazard, contact of a relatively deeper wreck with an external force such as an anchor is also dangerous. Furthermore, structural deterioration and the leakage of hazardous materials onto the seabed can disrupt habitat and pose serious environmental risks. In fact, in maritime, the active depth range, where anthropogenic and hydrometeorological influences are evident, represents areas such as anchorage areas with a maximum depth of 100 m, where the possibility of interaction is high.

Of course, due to the irregular sinking of the sunken ship, in most cases, its position on the seabed cannot be known without a technical examination. However, when safety is a concern, it is always necessary to consider the largest dimensions. In other words, the ship's length and depth are not actually dimensions determined by the ship's structural form, but rather the verticality and horizontality of the seabed. In this case, the ‘safety distance’ *S*, which varies along with the maximum possible d_s of the cylinder, the maximum possible length of the sunken ship L_s , and other factors to be added later, is schematically shown in Figure 1 along with the ship, the anchor chains, and their positions relative to the wreck.

For the formation of a safe zone in wrecked areas, the formulation developed up to this point in the study, which is based on parameters such as water depth and ship length, is expected to represent a deterministic approach. However, errors and uncertainties arising in maritime operations, primarily human factors, require consideration of multiple interacting sources in calculations like those in this study. Additionally, the most important parameter for identifying a sunken ship—the coordinates—may be subject to deviations and errors in measurement, verification, and the devices used to obtain them, necessitating an uncertainty analysis for safety margins. In a specific real case where all parameters are known, there are many established analysis methods applicable to maritime operations. In such cases, measurement uncertainties are used to analyze noise and deviations using filtering systems and algorithms (e.g., Kalman filters, Monte Carlo simulation, and statistical methods), and random errors are reduced by averaging [32–34]. Similarly, environmental modeling techniques are used to numerically model the atmospheric and topographic effects around the shipwreck area, and the margin of error is tested. In cases where in situ measurements of wrecks are possible, measurement accuracy (relative confidence ellipses) is increased by calibrating measuring devices (positioning systems, sonar, echosounder) and using reference points (e.g., fixed buoys or known depths). However, studies that address shipwreck areas, such as this study, may contain data that are often uncertain

or cannot be remeasured. In such uncertain environments, instead of probabilistic analyses, which are also included in this study, Deterministic safety margins and intervention strategies for risk factors are defined with a case-based approach. This method, which is widely used in engineering and enables practical management decision making, addresses uncertainties not statistically but through fixed safety margins, providing applicable and precautionary guidance.

Secondly, it is known that many factors are qualitatively involved in risk assessments that address situations where wrecks may interact with shipping. However, these factors that should be included in the safety distance need to be more accurately determined to provide a quantitative value. Recalculate the risk values that define the wreck's surroundings and include factors that might influence the safety distance based on its proximity to anchorage areas and maritime traffic. Because this analysis will guide maritime decision makers to establish gradual safety zones as an effective precaution and intervention against risks from shipwrecks. For shipwrecks that are not removed and pose a risk, key factors such as traffic density, physical environment (like bottom structure, bathymetry, wind, currents, etc.) and coastal area planning (such as protection status, archaeological value, tourism, port facilities, etc.) have a greater impact on navigation more than other factors, and it is more possible to provide a concrete distance inference is possible for navigational safety.

Calculating a route width for maritime traffic density is often challenging. The traffic line depends on many variables, such as vessel type, density, and environmental conditions. However, international maritime standards include recommended distances for narrow passages, traffic separation schemes, and port approach channels [35]. All of these widths are increased by local authorities to ensure safe passage in turning and maneuvering areas. In this context, the factors determining the maximum route width are when the TSS (Traffic Separation Scheme) is the widest two-lane and the largest separation zone. Wrecks located within this wide range are within risk limits that could affect the position of a moving or anchored vessel. Therefore, in these areas, identifying the density of maritime traffic will require dynamic planning that affects the distance at various levels.

Hydrometeorological and physical conditions affecting ships are critical to navigational safety and operational efficiency. Of these factors, meteorological and oceanographic factors constitute calculable portion of the environmental impact dimensions. Risk factors, such as wind and current strength and direction, wave height, and wave period, decrease maneuverability, making anchoring operations more difficult and increasing the risk of anchor dragging. During sudden wind changes, the chain tension increases, and the anchor can lift off the ground. It is not possible to provide a fixed standard for anchors dragging behavior in a dynamic marine environment. However, all these hydrometeorological factors also have a quantitative equivalent in ship operation. As these conditions worsen, the operational decision is to increase the length of the anchor chain. The length of the chain is the most critical factor for safe anchoring. Generally, the length of the anchor chain deployed should be 5 to 10 times the water depth [36]. If the length of the chain is insufficient, the anchor may not set properly on the seabed, and dragging is likely to occur under strong wind and wave conditions.

Marine and coastal spatial planning involves the spatial organization of various marine activities, including fishing, energy, transportation, tourism, and nature conservation, as well as decisions regarding coastal reclamation, construction, protection, and use. Spatial planning maps for many countries are published internationally through UNESCO Marine Spatial Planning global program. This allows decision-makers to monitor current and potential activities in marine and coastal areas. Planning becomes critical due to heavy maritime traffic, shipwrecks, and infrastructure risks in areas where tourism, diving, fishing,

ecological protection sites, underwater cables, and cultural heritage locations overlap on ship anchorage zones and routes. According to the spatial planning of sea and coastal areas, the anchorage area, route width, and safety distance length to wrecks should be redefined in environmentally sensitive zones and regions where they overlap with shipping routes.

As a result, traffic density, hydrometeorological conditions, and spatial plans of marine areas are significant factors that may affect the safety distance of the risk values defining the shipwreck environment according to the anchorage areas and marine traffic. Table 1 lists these factors and their potential impact on the safety distance.

Table 1. Quantitative values for the safe distance of wrecks from anchorage areas and navigation routes.

Risk Factor	Evaluation	Safety Distance Recommendation
maritime traffic density	Existence of waterways such as channels, passages, traffic separation schemes and port approach channels	The route width should be re-evaluated depending on the ship type and size. (For traffic widths of $1000 + 200$ m, a safety distance of <700 m) [37]
hydrometeorological conditions	Providing wind, current, wave and bathymetric data	Provide nowcasting weather, wind, current, and wave forecast models. (1 shackle-27.5 m) for each hour of exposure in winds of 6 Beaufort and above) [38]
Marine and coastal spatial planning	Determination of factors that may pose a threat to ship safety and protect the environment from activities in marine and coastal areas.	Complete information on waterway components should be supplied by the nearest coastal authority and published as spatial maps. (The ability to shift within $+/-$ distances with AIS-supported route optimization and location information) [39]

Additionally, there are operational steps that users can take when faced with these factors. Therefore, it is possible to consider the distance in risk factors in relation to the distance-proximity relationship, and this potential will be incorporated into the formula in Equation (4), providing an opportunity for safer planning for maritime authorities. In this study, the risk factors, which are considered in three general categories that can be most quantitative, will have an additional dimension beyond the maximum chain length. For this dimension, the specific characteristics of the wreck's location (for instance, dynamic sea areas with constant strong winds or currents) must also be added as a value in the safety distance formula. Accordingly, this additional value, which represents these quantitative parameters to obtain the safest distance even in the worst-case scenario in the marine environment, is called "K";

$$S > r_d + r_{wreck} + K \quad (5)$$

The new formula will be as shown in Equation (5). All the elements examined here are inferences aimed at estimating the safest distances a ship should maintain from wrecks, except under extreme conditions. The risks that a wreck creates in the marine environment are not limited to ships alone. However, being located in a safer area in relation to wrecks often means preventing dangers before they escalate into threats. The goal is to enhance the precautionary measures by conducting a risk assessment based on real-life cases using these assumptions.

3. Case Study

To validate the newly defined safety distance regarding the risks posed by shipwrecks to maritime transportation, in this study, three separate shipwreck cases of different types and locations are presented. The wreck investigated is the St. Vincent-flagged general cargo ship M/V Ulla, which sank while at anchor 1.3 miles off the Port of Iskenderun in the Iskenderun Bay, the Mediterranean side of Türkiye on 6 September 2004. The M/V Ulla ship, built in 1969, with a deadweight tonnage of 3650 DWT and dimensions of 95.93 m (length overall) by 13.7 m (beam), sank while carrying 2200 tons of chemical waste [40].

The position of the wreck, which is approximately 40 m deep, has been analyzed in relation to the seabed, including its location, loads, bow-stern boundary, and living area regions. It has been determined that the ballast tanks, which maintain the balance of the ship, are taking in water, causing the ship to lean 20 degrees to the starboard side and some of the ship's plating to lose its properties; there is severe corrosion and decay, and the cargo is taking in water from the cargo manifold, becoming solidified and heavier. Therefore, it has been determined that waste removal and disposal activities carried out after the sinking date were not successful [41]. Currently, official authorities are continuing decision-making processes regarding the legal status and intervention related to the sinking.

The other is a warship named HMS Majestic belonging to the United Kingdom Navy, which was torpedoed and sunk by a submarine attack on 27 May 1915, during World War I. It is located at the entrance of the Çanakkale Strait, 0.30 miles from the nearest land. The HMS Majestic measures 118 m in length (LOA) and 23 m in width (B). The wreck contains numerous unexploded shells of various sizes and cable-shaped gunpowder capable of burning underwater [31]. The wreck is listed as part of the Gallipoli underwater historical heritage and has been explored multiple times. At a depth of approximately 23 m, the wreck has lost its firing mechanisms but largely retains its shape. The ship is located in waters with a high level of maritime traffic in the Çanakkale Strait, the western entrance of the Turkish Straits System, and the surrounding area contains many remnants of underwater military ammunition [42].

Another sunken vessel is the Moldova-flagged dry cargo ship M/V Yukka. On 12 August 2012, a fire broke out on the ship, leading to the evacuation of the crew and the unloading of the feldspar cargo. The ship was towed to the port in Ereğli District, Zonguldak (Black Sea), and began taking on water from the stern [40]. As a result, it was pulled out of the port with tugboats and sank about 2 miles offshore in the Güllüç shipyard area. M/V Yukka has a deadweight tonnage of 3353 DWT and measures 114 m (LOA) and 13.2 m (B). During the sinking, the incident was documented, and although the fire damaged the engine room and living quarters, the overall shape of the ship was largely preserved. The dangerous cargo on board was unloaded during the evacuation before the sinking, but no survey or salvage operations were carried out afterward [43]. The ship was intended to be moved as far away as possible from the shipyard and port areas, but unfortunately, it could not be moved out of the high-traffic zone.

3.1. Definition of Study Area and Region

The location of the wreck is situated very close to the settlement areas, as shown in Figure 2. The Iskenderun Bay covers an area of approximately 2275 km² in the northeastern corner of the Eastern Mediterranean [44]. It is one of the five main port regions in Turkey and has a very extensive hinterland, positioned along many trade routes. According to data from 2020 to 2024, the average number of ships arriving in the region is 4256, while the number of vessels arriving until the first half of 2025 is 2135 [45]. Therefore, the site of the shipwreck is located at a point where ships frequently pass through. The M/V Ulla wreck is located within the administrative boundaries of the Iskenderun Port

Authority. Additionally, as indicated by the location marked in Figure 2, it is adjacent to the first anchorage area within the port's administrative zone. The first anchorage area is designated for ships carrying hazardous materials [46].

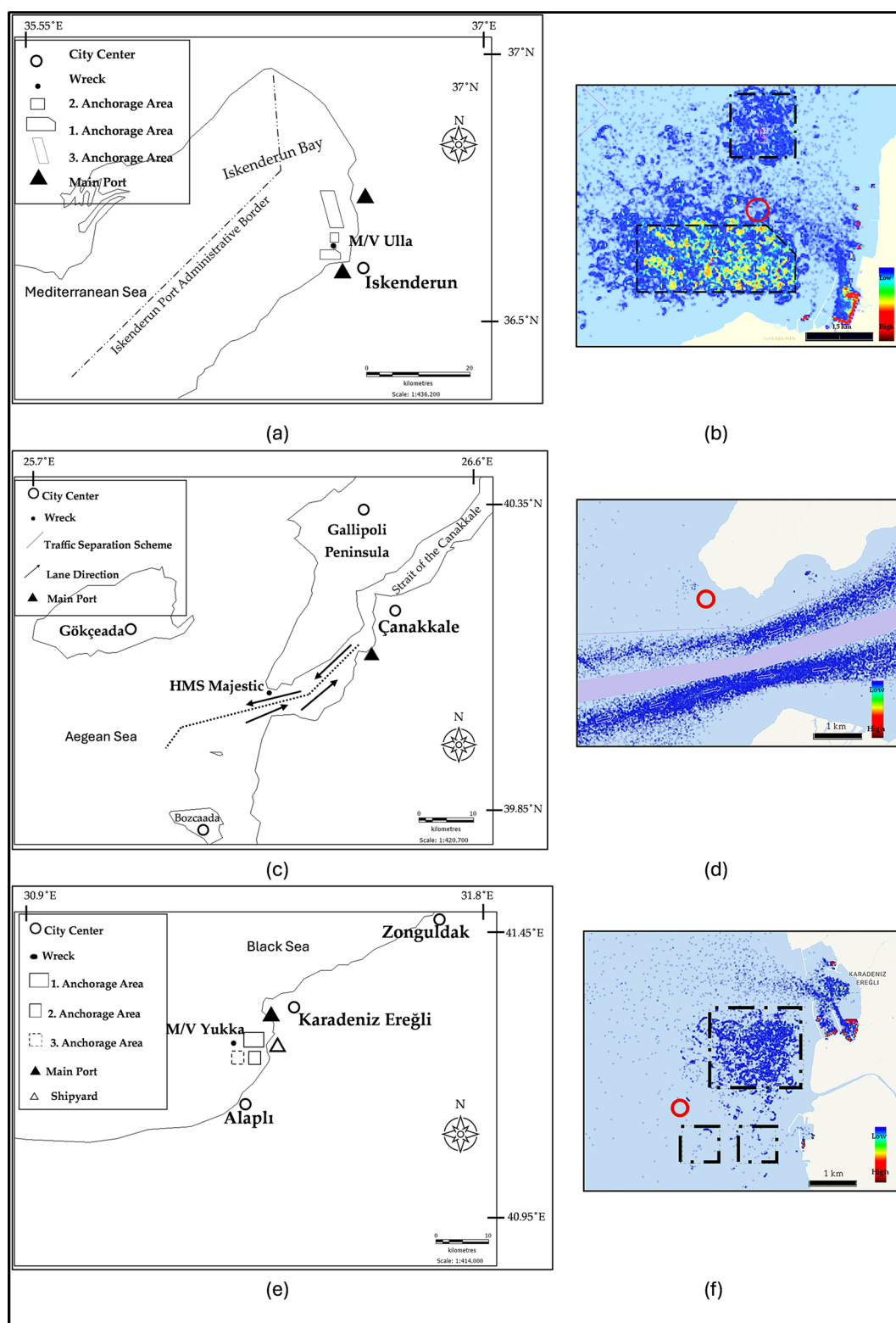


Figure 2. Wreck Locations and ship density map in their areas in 2024: (a) M/V Ulla in the Iskenderun Bay; (b) Ship density around M/V Ulla; (c) HMS Majestic in Strait of Canakkale; (d) Ship density around HMS Majestic; (e) M/V Yukka off the coast of Karadeniz Ereğli; (f) Ship density around M/V Yukka.

Zonguldak is located in the western Black Sea Region of Türkiye. Its location on the Black Sea coast and its connection to Ankara and the Central Anatolian hinterland make it an important logistics center. Karadeniz Ereğli Port, located near the M/V Yukka ship, is one of Türkiye's largest and most active ports for cargo such as coal, metal, and steel. It is a strategic point, especially for heavy industry and bulk cargo transportation [47]. According to data from 2020 to 2024, the average number of ships arriving in the port region is 750, while the number of vessels arriving until the first half of 2025 is 297 [45].

The Çanakkale Strait is an important part of the Turkish Straits System, connecting the Mediterranean to the Black Sea via the Sea of Marmara and the Strait of Istanbul. And HMS Majestic is located right at the entrance to the Aegean Sea through the Strait. Maritime traffic in the Turkish Straits is extremely busy due to commercial vessels, coastal shipping, fishing boats, and local passages. This congestion further complicates navigational safety, especially with the transport of oil, LNG, LPG, chemicals, and other hazardous materials [48]. According to data from 2006 to 2024, an annual average of 45,237 vessels passed through the Çanakkale Strait, 6233 of which had a LOA longer than 200 m. Additionally, 2569 chemical tankers, 121 LNG tankers, and 714 LPG tankers passed through the Çanakkale Strait. Also, the number of vessels arriving until the first half of 2025 is 21,607 [45].

3.2. Risk Assessment

The risk factors targeting the wrecks are not limited to physical hazards; they also present a highly layered structure involving environmental, cultural, economic, and governance dimensions. In this study, the risk levels of the sample shipwrecks were analyzed from a technical perspective, and sustainable recommendations were proposed for each risk. The safety distances required for the wreck to address these risks were assessed and incorporated into the recommendations for maritime management and other decision-makers. Then, the system evaluated the priorities of the interventions in line with the ALARP (As low as reasonably practicable) principles, giving risk scores and effort-economy values, and as a result, an ALARP was established based on the impact-benefit outcomes.

The relative risk assessment approach for sunken ships proposed by [49] involves a rough risk evaluation based on available data, key risks, and potential impacts, leading to the classification of risks. The general approach used to identify the risks posed by a sunken ship was developed according to the methodology outlined by [49–51] through stages for task prioritization, outcome, and risk prioritization. Subsequently, the general, environmental, and economic risk assessment criteria for sunken ships [51] were reviewed and adapted for this study. To develop the risk scores, the studies by [52,53] were examined.

From the additional quantities listed in Table 1, the maritime traffic data of the region was obtained from the port authority [45] and analyzed, while annual sea and weather data were provided by the national meteorology center [54]. The wreck and the facilities around the wreck area, land use, and coastal structures were obtained from the Ministry of Environment, Urbanization, and Climate Change [55] and examined with their legal statuses. This information was used to assess the legal compliance of intervention strategies. This multi-source data collection approach aimed to enhance both the technical accuracy and social acceptability of the decision support system. All collected data were systematically transferred to a digital environment and integrated into analysis modules.

The M/V Ulla wreck is at a depth of 40 m, its structural condition and hull integrity are preserved, but the cargo compartment poses a potential risk of chemical leakage due to corrosion. According to the map of the wreck's surroundings shown in Figure 2, the wreck is approximately 1.30 nautical miles from the İskenderun Port entrance. The wreck is located 0.19 miles from the designated 1st anchorage area for hazardous materials vessels,

0.66 miles from the 2nd anchorage area, and 1.34 nautical miles from settlements where various fishing, tourism, and recreational activities are carried out at multiple locations. When the integrated coastal area plan of the region is examined, it is understood that the wreck is within the boundaries of the plan's working area, and that it is in a region with low risk in terms of climate change, sea level rise, tsunamis, and ground conditions, but it is located within the boundaries of the first-degree earthquake zone [55,56]. When the spatial plans were examined, it was understood that the shipwreck was sufficiently far from the nearest marine protected area, archaeological site, and underwater artifacts [55]. The region is under the influence of the temperate Mediterranean climate and transportation is possible throughout the year, including the winter months [54]. Additionally, as seen in Figure 2, the ship traffic density map, even in the known wreck area where the local authorities have declared a 200 m prohibited area [46], vessel activity has been observed [57]. Although these are generally small boats, it is clear that the wreck poses various risks, primarily related to navigation safety, among other concerns.

The HMS Majestic wreck has sunk from a depth of 18 m to 23 m due to gradual burial by sand. Although it largely retains its structural form, significant corrosion is observed. On it, there are numerous unexploded shells from World War I and gunpowder in the form of cables with underwater burning properties, posing an explosion risk [42]. According to the map of the wreck area shown in Figure 2, the wreck is located south of the TSS, which has quite busy maritime traffic at the southern entrance of the Çanakkale Strait. The Gallipoli Peninsula is a region of historical significance where many tourism and recreational activities, such as diving, are carried out at multiple points, and it is also an area where many underwater wars ammunition remnants are found around the wreck [31]. When the integrated coastal area plan of the region was examined, it was understood that the shipwreck was located within the borders of the Çanakkale Wars Gallipoli historical area protection zone and therefore it was in the area where it was among the archaeological and underwater artifacts. It is understood to be in a low-risk area in terms of climate change, sea level rise, tsunamis, and ground conditions [55]. The region is under the influence of the Marmara transitional climate, exhibits characteristics of a transition between the continental Black Sea and Mediterranean climates, and access is available year-round [54]. Although the shipwreck is within the boundaries of the Gelibolu historical site protection zone, it poses a risk to life and property due to the presence of many war munitions on and around the shipwreck and its status as a diving and sightseeing spot.

The M/V Yukka wreck is approximately 58 m deep, and the ship's shape is largely preserved [43]. The cargo on board has been unloaded, but it is estimated that there is a small amount of fuel remaining. The wreck is 2.5 miles from the port of Ereğli, which is the main port of the largest iron and steel industry region in the Black Sea, and 2 miles from the nearest land, the shipyard area. As shown in Figure 2, it is 0.16 miles from the anchoring area designated for military ships numbered 3. When examining the integrated coastal area plan of the region, it is understood that the wreck is located near the industrial zone boundaries, in a low-risk area in terms of climate change, sea level rise, tsunamis, and ground conditions [58]. The region is under the influence of the Black Sea climate and experiences rainfall in all seasons. Although there is an increase in wind and wave heights during winter months, transportation is generally possible throughout the year [54]. While the wreck appears relatively safer in terms of depth, the lack of a complete survey and its proximity to a heavily industrialized and shipyard area pose risks for navigation safety.

The multidimensional risks of the wrecks are evaluated using the parameters of hazard severity and occurrence probability through a matrix method. This approach is structured to provide data to the core modules of the decision support system. Hazard definitions, organized according to probability and consequence levels, are prepared to

encompass environmental, safety, cultural, and economic dimensions. The basic risk score for the wreck is calculated by multiplying the probability and impact components within a traditional risk analysis framework. In probability–consequence-based hazard definitions for the wrecked ship, each parameter is scored between 1 (low) and 5 (high), and the total risk score is normalized to enable comparison. These values are listed in Table 2 along with explanations and precautions. Additionally, considering the region’s dense maritime traffic and its unique geopolitical, historical, and ecological features, the safety distance established for the wreck shapes this matrix into an interdisciplinary framework that can be used in technical analyses.

Table 2. Risk Matrix created according to the new safety distance for sea transportation and anchorage areas of sunken ships.

Risk Code	Risk Category	Potential Hazard	Probability (1–5)	Severity (1–5)	Risk Score	Explanation/Precaution	Safety Distance Recommendation
RC1	Navigation risk	Collision with or close passage to the wreck, creating an obstacle to the ships’ route and threatening the ship traffic	4	3	12	Removal of the wreck, partial removal, definition of the new safety distance, warning structures, AIS warning systems, mapping, radar integration, and integrated data sharing.	≥ 300 m
			3	5	15		≥ 400 m
			3	3	9		≥ 250 m
RC2	Anchoring risk	Contact with the wreck or structural collapse when anchoring	5	5	25	Replanning of anchorage zones, removal of the wreck, warning structures, sonar scanning, additional pilot support	≥ 500 m
			2	5	10		≥ 250 m
			5	3	15		≥ 400 m
RC3	Structural deterioration and leakage risk	With the collapse of the wreck, metal and chemical leakage spread to the anchorage area and route.	3	5	15	Removal of the wreck, removal of hazardous materials, creation of a buffer zone around the wreck, regular scanning and neutralization by expert teams.	≥ 400 m
			5	2	10		≥ 300 m
			1	2	2		≥ 50 m
RC4	Fishing and other economic risks	Entanglement of nets with the wreck, equipment loss, and damage to fishing activities	4	3	12	The redefinition of fishing zones, installation of warning signs, removal of the wreck, suggestions for alternative activities, and development of sustainable fishing plans should be implemented.	≥ 300 m
			2	4	8		≥ 100 m
			2	3	6		≥ 50 m
RC5	Ecological and other environmental risks	Chemical leaks and habitat degradation for marine life, damaging the sensitive marine ecosystem	3	5	15	Removal of the wreck, Partial removal, Regular leak monitoring systems, emergency response plans required, Restoration compatible with protected areas, or controlled wreck management	≥ 350 m
			3	4	12		≥ 250 m
			2	2	4		≥ 50 m

Table 2. Cont.

Risk Code	Risk Category	Potential Hazard	Probability (1–5)	Severity (1–5)	Risk Score	Explanation/Precaution	Safety Distance Recommendation
RC6	Life safety, diving safety risk	The local residents, divers, and tourists being exposed to chemicals due to structural deterioration	2	5	10	Removal of the wreck, removal of hazardous materials, pre-dive structural analysis; restriction of access to risky areas, separation of diving routes and transportation routes.	≥250 m
			5	5	25		≥500 m
			1	2	2		≥50 m
RC7	Legal risks	Uncertainty of ownership and international disputes, uncertainty about intervention rights around the wreck	2	3	6	Legal inventory studies; international maritime law consultancy and international coordination.	≥100 m
			3	5	15		≥200 m
			3	2	6		≥100 m
RC8	Visual/radar confusion	The wreck is disrupting radar signals or signals are being misinterpreted.	2	3	6	Partial removal, radar calibration, wreck marking systems.	≥100 m
			2	3	6		≥100 m
			5	4	20		≥400 m
RC9	Cultural and tourism risks	Damage to historical artifacts, damage to tourism activities	3	3	9	Protecting the surrounding monuments, developing sustainable tourism plans, impact analysis and alternative activity suggestions.	≥300 m
			5	5	25		≥500 m
			1	2	2		≥50 m

One of the most significant concerns regarding shipwrecks, as seen in Figure 2, is the risk they pose to surrounding maritime activities. The chains and anchors of nearby ships are at risk of hitting the M/V Ulla, which is known to still contain chemical waste. Similarly, the ship, which was in the region since 2000 and sank in 2004, could experience structural deterioration due to factors such as corrosion or the collapse of the shipwreck, potentially spreading chemical leaks to nearby ships, anchorage areas, and routes. This scenario would damage the region's marine ecosystem and lead to habitat degradation for marine species. Hazardous materials left over from the war around HMS Majestic pose a threat to both ships passing through the busy and constant traffic of the Çanakkale Strait and to the safety of life due to diving activities conducted on and around it. The shipwreck has experienced significant corrosion over the past 110 years, leading to serious deterioration [31]. The wreck of M/V Yukka is located quite close to the industrial and shipyard area, and the lack of a thorough survey after sinking introduces some uncertainties. The sinking was recorded at the time, and the sinking position occurred at a steep angle [43]. However, its exact position on the seabed is unknown, and although the bathymetric map of the point is known to be 58 m, the underwater dimensions of the wreck are not recorded, so precise calculations cannot be made. Considering the nearby ship traffic, especially the proximity to the anchorage area for military ships, it also poses a significant navigational risk for submarines. Additionally, it is known that there is a small amount of fuel remaining in the ship [43].

Fishing activities around these three wrecks carry safety, environmental, and economic risks due to net entanglement in wrecks, equipment loss, shrinking fishing grounds, and species migration. Regarding life safety, areas with heavy maritime traffic may hinder

search and rescue operations by limiting emergency response capabilities. On the other hand, in sunken ships with limited visibility, the risk of losing direction, getting trapped, or gas poisoning is a serious danger primarily for divers, tourists, and researchers. Damage to tourism potential poses both economic and social risks. Additionally, underwater historical artifacts may also be damaged. The protection status of wrecks can create legal disputes over ownership and intervention rights. Also, incorrect adjustment of safety zones threatens data and information security, leading to errors in mapping navigation systems. Lack of technical, historical, or environmental data on the wreck may undermine the risk analysis.

All these risk factors are assigned to potential hazards, probability-severity, and risk scores in Table 2. The explanation and precaution columns are designed to assist the maritime management's decision support system. In the last column, the recommended distance is indicated using the safety distance formula in Formula (5). For this purpose, two separate L values were taken according to the size of the largest ship in the region and the average size of the ships arriving in the region. The formula was then run with D values, using the region's bathymetry map for examination. The length of the largest ships arriving in the M/V Ulla wreck region and anchoring in the anchorage area 1350 m away from the wreck was 300 m, and the average length of ships arriving in the region was 200 m. The deepest point in anchorage area 1 is 42 m in the northern part near the wreck, and the shallowest is 19 m in the southern part. To calculate from the wreck's origin and to consider the high drafts of these ships (and a 10% safety margin), $D = 42$ was taken. The values of the virtual cylinder formed by the M/V Ulla underwater are $L_s = 95$, $D_{\text{wreck}} = 40$ m (total depth of the wreck), $d_s = 16$, and $d_w = 24$. When these values are substituted into Formula (5), $S > 575 + K$ is found for the largest vessels and $S > 475 + K$ for the average vessels. The average length of ships passing through the HMS Majestic wreck area is taken as 200 m. There is a southbound traffic lane approximately 600 m near the wreck, and continuous traffic exists. $D = 36$ was taken as the general bathymetry of the wreck area in all weather and sea conditions that caused these ships to drift to the wreck area. The values of the virtual cylinder created by HMS Majestic underwater are $L_s = 118$, $D_{\text{wreck}} = 23$ m, $d_s = 6$, and $d_w = 17$. When these values are substituted into Formula (5), for medium-sized ships, $S > 575 + K$. The length of the largest ships anchoring in the M/V Yukka wreck area and near the debris at the 3rd anchoring zone, which is 250 m away, is 270 m, while the average length of ships arriving in the area is 180 m. The deepest point of the 3rd anchoring zone is 58 m at the northern edge near the wreck, and the shallowest point is 42 m at the southern edge. Considering the origin of the wreck, D is taken as 58 m. The values of the virtual cylinder created by M/V Yukka underwater are $L_s = 114$, $D_{\text{wreck}} = 60$ m, $d_s = 20\text{--}30$, and $d_w = 40\text{--}30$. When these values are substituted into Formula (5), for the largest ships, $S > 630\text{--}570 + K$ and for medium-sized ships, $S > 560\text{--}480 + K$.

The additional safety distance K is an optional addition to other measures taken by the authority, depending on the characteristics of the specific location of the wreck and the possibilities of the area allowing for this planning. For the K values explained in Section 2, the Coastline Bathymetric and Oceanographic Measurements Expert Assessment Reports of these three wrecks were first examined [58–60]. Then, information about sea and weather conditions was analyzed, and it was intended to explain how a K , whether necessary or not, can be determined. The M/V Ulla is located in Iskenderun Bay, where the average annual wind speed is approximately 2.5–4.5 m/s [54]. Although tornado formation is frequently observed in the southern part of the bay, no negative feedback regarding navigation safety has been reported. During winter months, except for stormy days, the average wave height is 1 m [60]. The seabed structure mostly consists of mixed sediments (sand, mud, gravel) on muddy and sandy bottoms [61]. Although northerly

and northwesterly winds increase wave height in the area of the HMS Majestic wreck, the annual average wave height is approximately 0.8 m, and the wind speed is around 2–4 m/s [48]. The area around Seddülbahir, where the wreck is located, extends from the Gallipoli Peninsula and contains both hard rocks and sedimentary ground [59]. When examining the hydrometeorological conditions of the M/V Yukka shipwreck area, it has been understood that the region experiences rip currents, but these are not a significant factor for navigation. During the winter months, aside from stormy days, the average wave height is 1 m [58]. Although the average wind speed in the area is 5 m/s from the south, northern winter storms reaching Beaufort 7–8 (50–74 m/s) have been quite common in recent years [54]. The seabed is generally covered with sedimentary deposits transported from rivers [62].

To consider this value for the M/V Ulla and HMS Majestic, the additional distance risk factors in Table 1 indicate that hydrometeorological conditions are within regional norms, extreme conditions are quite rare and generally have a regular pattern. In the M/V Yukka area, although the hydrometeorological conditions are generally suitable for navigation, the increase in extreme conditions in recent years and the occurrence of two sinking incidents in the last five years indicate that additional safety measures are necessary [63]. This is an inference that additional precautions should be taken for the sunken ship.

Marine traffic density in the area of M/V Ulla and HMS Majestic makes increasing the safety distance crucial. The M/V Yukka location is relatively more secluded. When examining the integrated coastal zone management and spatial plans for these three shipwrecks, it is necessary to create a safety zone by planning the largest possible area near the tourism, port and industrial facilities. The maritime authority's initiative should be to keep the S value as high as possible, considering both the width of the maritime traffic lanes and the density of ships. However, as in many narrow passages and channels, the M/V Ulla wreck (with its proximity to the port entrance) and HMS Majestic (at the entrance to the strait) also poses an obstacle to maximum area utilization. Therefore, the formula has recommended a principle of minimum safety distance for the minimum precaution that must be taken in this case study.

As seen from the ship density map, active vessel traffic in the area still poses a risk. Similarly, considering all the risks in Table 2 and the chemical waste still present inside the sunken ship, distance recommendations have been developed for each risk factor. Although the area around the HMS Majestic wreck is a protected area, the safety distance should be at the maximum Strait conditions due to other historical and dangerous wrecks in the vicinity. Furthermore, the southern part of the Strait entrance is relatively safer for a potential expansion decision. The M/V Yukka wreck site, like the M/V Ulla, is adjacent to the anchorage area (military and commercial), but area usage is not as restrictive as the Bay. However, it poses numerous navigational threats, including adjacent submarines, and is located at the intersection of industrial cargo movement. Additionally, cases resulting in sinking due to hydrometeorological conditions are vital for ensuring navigation safety in this area. While numerous studies on ship drift have been conducted in the literature, it is certain that the ships in the M/V Yukka wreck area could drift by more than 250 m under these conditions, based on the diverse data in [16,17,64–66] that allows for different distance inferences. In this case, considering an additional measure of +250 m allowed by the field condition for the K value, the result is obtained as $S > 900$ m. In Table 2, all risks analyzed in this study are generated for three cases and are specified separately for M/V Ulla, HMS Majestic and M/V Yukka in the Probability, Severity, Risk Score and Distance Recommendation columns, respectively.

In addition to all these risk factors for shipwrecks, these factors also have many additional risks that can be quite diversified. Some of these additional risks and the indirect

risks that may arise from intervention strategies are evaluated through subsequent risk analysis in Table 3. Besides environmental and ecological risks, for instance, the M/V Ulla wreckage has created artificial habitats for invasive species in the region, such as lionfish [67]. The displacement or collapse of the wreck can disrupt the seabed structure and affect the biota. Old paint and coatings on the ship may break down over time, leading to microplastic pollution [68]. Additionally, potential ecosystem disturbances caused by the redistribution of sediment during the surface cleaning of the wreck are addressed within this scope. This analysis was conducted in an integrated manner with scenario simulations.

Table 3. Subsequent Risk Assessment and Risk Mitigation.

Risk Factors	Possible Sequential Risks	Mitigation Strategy
Chemical leakage	Acceleration of the spill during the response; temporary displacement of marine organisms	Controlled liquid evacuation from debris, installation of barrier systems
Structural collapse/ metal corrosion	Disruption of the seabed structure; alteration of diving routes	Controlled liquid discharge from the wreck, installation of barrier systems
Navigation obstacle	Alternative routes also increase traffic density	Mapping the wreck with new safety zones and integration into maritime warning systems
Ecosystem degradation	Shift of fishing activities to other regions; local economic impacts Disruption of natural species balance; increased intervention costs	Protection Zone Declaration, according to the new safety zone, fishing is prohibited around the sunken ship, biological monitoring and species control programs around the shipwreck
Damage to historical and cultural assets	Decline in tourism revenues; access restrictions for local residents	Changes in diving limits, digital archiving and virtual tour systems
Legal uncertainty and ownership issues	The prolongation of the intervention process; misinformation in the public opinion	International archive research and diplomatic negotiations
Tourism and fishing impact	Unplanned tourists use, increased pressure on the ecosystem Increase in access costs; exclusion of amateur divers	Integration of new tourist diving zones, reorganization of fishing zones, trained diving teams, sonar-supported navigation systems
Lack of data and misleading mapping	Data security risk; misuse of sensitive information	Detailed Lidar and sonar-based seabed mapping projects

Risk mitigation can always lead to new risks. Therefore, subsequent risk analysis should be an integral part of response plans. These tables also provide decision-makers with a broader perspective on risk and response.

3.3. Decision Support Function with ALARP

In this section, the multidimensional risk assessment regarding the shipwrecks is structured to determine new safety distance and intervention priorities and to produce a decision support function for maritime authorities and other stakeholders. Following the risk analyses presented in the previous section, the ALARP principle was utilized to strengthen the assessment using the risk matrix and to identify improvement and precaution priorities. This method helps reduce risks to acceptable levels and determine management strategies [69,70]. Accordingly, the amount of risk and the effort involved should be balanced. With the presence of concrete and operational interventions in this study, effort represents both monetary cost and impact represents benefit. ALARP was applied for both the current situation and the safety distance proposed in this study.

The analysis in Table 4 aimed to assess the environmental, cultural, and navigational safety risks of the shipwreck and bring the intervention level to a “reasonably reduced”

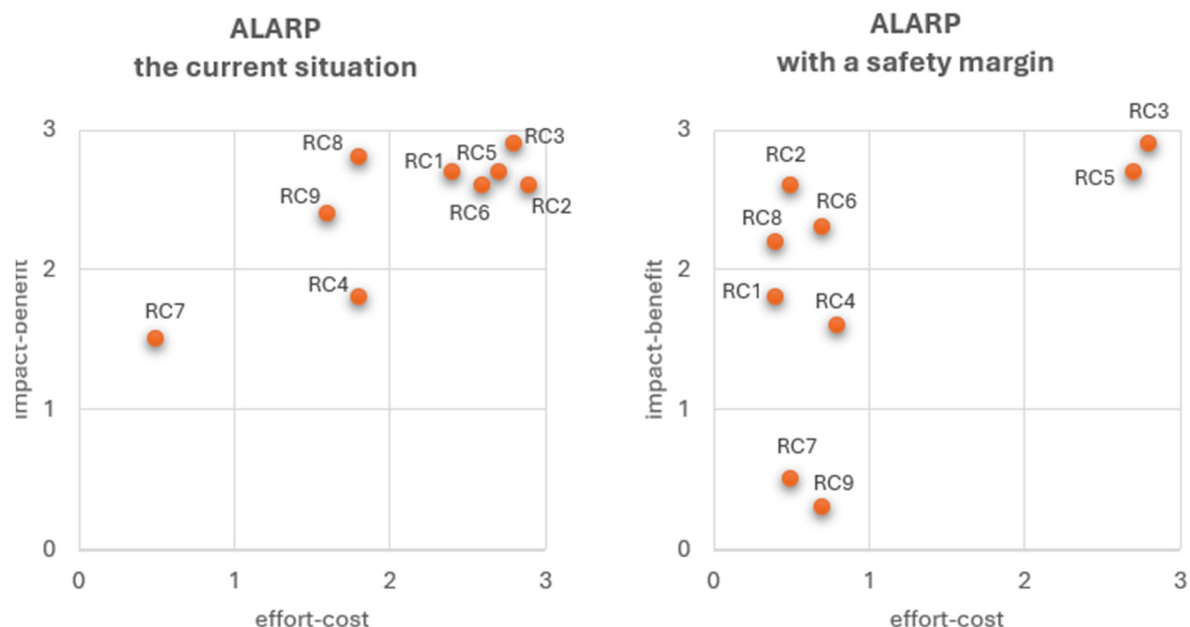
level. For this purpose, the regulatory rules mentioned at the beginning of Section 2, and the risk scores derived from the risk assessment in Section 3, were taken into consideration. Regulatory rules related to navigational safety (RC1, RC2, RC4, RC3, RC6, RC8) are primarily addressed by the management, marking, and informational directives of the ISM, SOLAS, and IALA codes [20,22,71]. In such cases, an effective safety management system should be established and operated for ship and marine operations through the implementation of the ISM Safety Management System (SMS). Furthermore, all three Codes provide pollution prevention procedures to minimize the environmental impact of wrecks. Before operating in wreck areas, comprehensive risk assessments should be conducted, hazards should be identified, and appropriate precautions should be taken. Crew and relevant personnel should be regularly trained in the risks and safety procedures associated with wrecks. In order to manage the risks posed by wrecks to maritime traffic and ensure safety, IALA sets standards for the rapid and effective marking of wrecks in its O-133 recommendation (Emergency Wreck Marking Buoy) [71]. It also recommends assessing the hazard status of wrecks, conducting risk analyses, and making appropriate marking decisions to protect navigation safety. For environmental risks (RC5, RC3, RC4, RC9), MARPOL 73/78 focuses on the protection of the marine environment related to wrecks [23]. In particular, to reduce the environmental impact of shipwrecks, it is recommended to take pollution prevention measures, prevent the leakage of fuel and hazardous substances, and prepare and implement emergency response plans. Within this scope, international standards and procedures have been established to prevent the spread of oil, chemicals, and other hazardous substances into the sea following ship accidents. MARPOL encourages the development of effective pollution control and response mechanisms to minimize the environmental damage caused by shipwrecks. In this context, many packages of measures are emerging, including ecological mapping and seasonal restrictions. For structural intervention (RC3, RC7, RC5), ISO 19901-1 provides operational recommendations regarding wrecks and underwater obstacles, emphasizing the importance of accurately assessing meteorological and oceanic conditions [28]. Considering metocean data in areas where wrecks are located is critical for structural safety and managing environmental impacts. The Wreck Removal Convention (Nairobi International Convention on the Removal of Wrecks) provides an international legal framework for the rapid and effective removal of wrecks that pose risks to maritime safety, property safety, and the environment [24]. Reporting shipwrecks, hazard assessment, removal obligations, international cooperation, and environmental protection are among the fundamental principles emphasized in this context. Cultural Heritage and Social Impacts (RC9, RC6, RC3, RC5, RC7), the 2001 UNESCO Convention provides an international framework for the protection of wrecks older than 100 years and underwater cultural heritage [26]. This convention aims to prevent the looting and destruction of wrecks and to promote scientific research and ethical excavation practices. It also makes suggestions for the preservation and sustainable management of the cultural and historical values of the shipwrecks. UNCLOS contains detailed recommendations regarding environmental protection and pollution prevention obligations regarding shipwrecks [25]. Accordingly, contracting states are obligated to take all necessary measures to protect the marine environment and prevent pollution, use best available methods, conduct environmental impact assessments, and ensure information sharing. For Mapping, Monitoring, and Communication risks (RC8, RC1, RC2, RC6), fundamental principles are emphasized, such as conducting a risk assessment to ensure locational quality and accuracy in accordance with ISM and especially IHO S-44, establishing communication protocols, ensuring secure data management and sharing, and ensuring personnel training and certification [27].

Table 4. ALARP Integration: Standard-Based Risk Module.

Risk Factors	Risk Score			ALARP Current Situation		ALARP Safety Margin	
	M/V Ulla	HMS Majestic	M/V Yukka	Effort/Cost	Impact/Benefit	Effort/Cost	Impact/Benefit
RC1	12	15	9	High	High	Low	Moderate
RC2	25	10	15	High	High	Low	High
RC3	15	10	2	High	High	High	High
RC4	12	8	6	Moderate	Moderate	Low	Moderate
RC5	15	12	4	High	High	High	High
RC6	10	25	2	High	High	Low	High
RC7	6	15	6	Low	Moderate	Low	Low
RC8	6	6	20	Moderate	High	Low	High
RC9	9	25	2	Moderate	High	Low	Low

To this end, the risk codes identified in Table 2 were graded according to their respective response packages. In this way, the priorities of the interventions were evaluated according to the risk scores in the module and as a result, ALARP was created, which offers the impact and benefits in terms of effort-cost value.

Figure 3 shows the X-Y graph of the ALARP model, including the ALARP generated in Table 4, and the safety distance response proposed in the study. The three values for each risk factor, with “best,” “medium,” and “worst” scenarios (Low = 1, Medium = 2, High = 3), are shown on the X-axis as the effort-cost, and on the Y-axis, it is shown as a point based on the impact-benefit score as the effect of risk reduction. Accordingly, the ALARP area in the second graph provides the most ideal intervention zone for risks such as RC2, RC6, RC8, and RC1, which involve high reduction effects and low/moderate costs.

**Figure 3.** ALARP model according to effort-cost impact-benefit.

The decision support system developed as part of the application analyzed the multidimensional risks associated with these three shipwrecks and determined intervention priorities. The findings were classified using quantitative risk scores. According to the risk

scoring results, pronounced risk differences were observed among the risks and were used as the baseline data for intervention prioritization. The ALARP module provides decision-makers with a critical decision-making principle that shows possible developments and intervention options.

4. Discussion

Perhaps the most complex objective in reducing the environmental impact of maritime transport within sustainable maritime management is shipwreck management. The multi-layered technical, legal, and ecological risks of shipwrecks, the socio-political challenges, and the often-multidisciplinary working conditions are the biggest obstacles to developing conceptual applications [72–74]. For the authority, the location and size of the wreck, the cause of the sinking, environmental conditions (currents, depth, seabed structure), and environmental risks directly impact response methods. The responsibility of the wreck and the obligation to remove it can create various legal uncertainties and gray areas in international law [75]. Conflicts between international and local regulations often occur. Additionally, the cost and technical intervention complexity can cause significant decision-making difficulties in this environment with multiple stakeholder participants [76].

Therefore, developing a common approach to shipwreck cases, which often have very different histories, has been quite difficult and remains incomplete. In this study, the issue of safe management of the wreck area, which is one of these shortcomings, was primarily addressed with a technical approach and it was aimed to contribute to the calculation of safety distances. For this purpose, a mathematical approach was proposed to find the minimum safe zone by taking into account the possible contact line of the shipwreck, which is a fixed obstacle. Anchoring operations, which have a higher probability of contact than navigation, are also included in this calculation. Finally, physical conditions have been added as an additional value that allows the maritime authority to more easily quantify among the many factors that may affect safety in the maritime environment. For this purpose, the $S > r_d + r_{wreck} + K$ formula has been suggested for determining the minimum safety distance that should be maintained in this study, and this suggestion has been applied in detail to three sunken cases that still pose various risks today.

In fact, in such a situation, the decision-making organization is always expected to define the largest area as an avoidance zone. However, as is known, maritime activities are more active near land, other ships, and facilities rather than in open seas. In fact, even a sunken ship often experiences its sinking fate in these dense areas while functioning as part of such a busy region. Therefore, it will be necessary to realistically increase precautionary measures to manage the wreck without disrupting maritime activities. The authorities should manage the universe affected by the threat in the relevant region with systematic and gradual zones and communicate this to users using the most quantitative and tangible values possible.

The most important actions taken in this regard include stricter enforcement of obligations under the MARPOL 73/78 Convention and tightening inspections related to waste import and export within the framework of the Basel Convention. The most concrete measure taken by the local maritime authority in the M/V Ulla shipwreck was the declaration of a 200 m restricted zone based on the potential for dissolution and spread of the chemical. However, the distance between the wreck and the nearby anchorage area 1 is only 350 m. It is recommended that this distance be increased to at least $S > 575$ m, which meets all the safety distance limits listed in Table 2, especially for navigational safety. This result provides a relatively more reasonable and quickly implemented recommendation for many high-risk wrecks. HMS Majestic, which is located at the entrance to the Strait despite being in the protected area and still carrying explosive material, should receive the maximum

safety margin possible under these conditions, $S > 575$. The southern branch of the Strait entrance is relatively safer, so the historical area protection strip should be extended to this distance. A basic distance criterion of $S > 560$ has been proposed for M/V Yukka, which has not yet been explored in situ and therefore its position on the seabed is still uncertain. M/V Yukka also provides an example of the application of the additional distance 'K' in the formula, with its risky hydrometeorological conditions for navigational safety. Because weather and sea conditions in the area around the M/V Yukka wreck can cause ships to drift, it is almost mandatory to add a distance of over 250 m to the minimum safety distance. In this case, with the added K value, $S > 800$ is found as a measurement allowed by the area. In addition, while the findings reveal the system's decision-making capacity, they also highlight some important points of discussion. As seen in risks RC1, RC2, RC4, RC6, and RC8, a set of measures with a safety margin, in addition to existing intervention measures, indicated a lower effort-cost level. This situation shows that in the current situation, where the shipwreck has not yet been removed from Iskenderun Bay, the safety margin integrated into the decision function makes it possible to produce more practical decisions. In this way, it will be possible to make improvements and reduce risk scores with less effort.

This finding shows that intervention decisions should be made dynamically and by considering subsequent effects, and that relying solely on technical parameters in environmental risk analyses may limit decision quality.

One limitation of the study is the lack of use of social data such as local perception and analysis techniques that facilitate stakeholder participation. Additionally, the performance of the proposed system has not been tested in large case data applications. The significant lack of dimensional and positional information regarding sunken ships is also evident here as the most important challenge in theoretical studies of marine areas. In these areas, detailed data and field feasibility studies should be conducted, followed by re-measurements, sensor calibration work, and field-based uncertainty measurements to establish sensitivity and confidence criteria. Safe management and environmental sustainability of wrecks should therefore encourage more field work with authority-supported practices.

5. Conclusions

Shipwrecks are a serious concern in maritime safety, threatening the environment, navigational safety, and the economy. International regulatory frameworks for maritime use, such as the IMO, have not established a direct distance standard for potential interactions with shipwrecks, other than some general recommendations for ensuring maritime safety. The lack of sufficient research on this topic has prevented the emergence of certain risk factors in the marine environment or the easier and more economical mitigation of existing risks. This study aims to determine the necessary safety distances against potential risks in wreck areas, using a situation such as anchoring, where the probability of contact with wrecks is high. For this purpose, the area and chain movement created by the ship in these positions were examined, and a mathematical approach was proposed for determining the minimum safety distance required. This approach allows the maritime authority to add additional safety margins, when necessary, based on traffic density, hydrometeorological conditions, and coastal spatial plans. The proposed approach was studied with shipwreck cases located at three different critical points and applied to a risk assessment. Then, a sustainable recommendation was presented for each risk and the safety distances required by maritime management to ensure these risks were included in the recommendations.

The risk factors related to the sunken ship present a highly layered structure in terms of environmental, cultural, and economic dimensions. For this reason, the priorities of the interventions were evaluated according to the risk scores in the module, and as a result, ALARP was created, which offers the impact and benefits in terms of effort-cost value. As a

result, the potential impacts and benefits were identified. The safety margin demonstrated that in situations where intervention options are available, it is possible to reduce risk scores with less effort. Therefore, it can be said that the application of case analysis yielded successful results in terms of technical accuracy, economic acceptability, and concretizing decision-making processes. As a result, in any case where there is no definite action, such as the removal of the wrecks, it is clear that establishing an appropriate safety zone is among the quickest technical and practical decisions the authorities can take, primarily for environmental protection and the safety of life and property.

For shipwrecks, risk assessment and its integration into the decision support system has shown that data-driven analysis will enable risks to be managed in a more transparent and solution-oriented manner. With the formula presented in the study, these boundaries can be more clearly determined and managed in safe area management and spatial planning. The system can support strategic decision-making processes for both public institutions and academic research by generating warnings and recommending response strategies when critical thresholds are exceeded. The method in this study can be expanded and applied to other strategic maritime areas. The system's predictive ability can be increased by monitoring the long-term effects of risks and applying it to a sunken ship in the field. More inclusive environmental governance should be supported through integrated scenario analyses such as the IPCC SSPs, which include themes such as cultural heritage, ecotourism and maritime safety. At this point, dynamic calculations can be modeled in which the pollution risk and safe area can change accordingly, in parallel with the temporal changes of the wrecks as a result of corrosion and other structural deterioration. In the future, the system's adaptive decision-making ability can be improved with artificial intelligence-supported learning modules, and map-based risk distribution components can be integrated.

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