An empirical identification of a representative case of ship grounding in Swedish waters and estimation of resultant consequences

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Abstract

The study examines grounding risk in Swedish waters using a multi-source, exposure-based analytical framework integrating accident data from Transportstyrelsen with operational activity data that the Swedish National Road and Transport Research Institute, VTI calculated based on HELCOM's AIS-data and supplementary environmental and economic datasets. The analysis is based on 292 grounding incidents involving passenger ships, dry cargo ships and tankers over the period 2011-2023. Grounding frequency, exposure-normalised rates and consequence profiles are assessed to identify underlying risk patterns and representative scenarios. Results show that grounding incidents are concentrated in coastal and archipelagic areas and are dominated by passenger ships, which show consistently higher grounding rates relative to distance travelled, operational time and fleet size. Dry cargo ships display lower and more stable rates, indicating grounding occurrence proportional to operational exposure. While most incidents result in minor consequences, insurance data reveal increasing claim severity over time. Tanker groundings, although rare, represent the highest potential for severe environmental and economic impact. The findings demonstrate a difference between grounding frequency and consequence severity, highlighting the limitations of relying only on absolute accident counts. By integrating exposure-based metrics with consequence analysis, the study provides a strong assessment of grounding risk. The results support the need for differentiated risk management strategies targeting high-frequency operational risks in coastal waters and preparedness for low-probability, high-impact events in environmentally sensitive regions.

Keywords
ship grounding; maritime safety; risk assessment; risk management; risk analysis; exposure-normalised risk; Baltic Sea

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The study examines grounding risk in Swedish waters using a multi-source, exposure-based analytical framework integrating accident data from Transportstyrelsen with operational activity data that the Swedish National Road and Transport Research Institute, VTI calculated based on HELCOM's AIS-data and supplementary environmental and economic datasets. The analysis is based on 292 grounding incidents involving passenger ships, dry cargo ships and tankers over the period 2011-2023. Grounding frequency, exposure-normalised rates and consequence profiles are assessed to identify underlying risk patterns and representative scenarios. Results show that grounding incidents are concentrated in coastal and archipelagic areas and are dominated by passenger ships, which show consistently higher grounding rates relative to distance travelled, operational time and fleet size. Dry cargo ships display lower and more stable rates, indicating grounding occurrence proportional to operational exposure. While most incidents result in minor consequences, insurance data reveal increasing claim severity over time. Tanker groundings, although rare, represent the highest potential for severe environmental and economic impact. The findings demonstrate a difference between grounding frequency and consequence severity, highlighting the limitations of relying only on absolute accident counts. By integrating exposure-based metrics with consequence analysis, the study provides a strong assessment of grounding risk. The results support the need for differentiated risk management strategies targeting high-frequency operational risks in coastal waters and preparedness for low-probability, high-impact events in environmentally sensitive regions.

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1 Introduction

Ship grounding is among top types of marine accidents with serious consequences to ship and environment (Galić et al., 2022). Despite advances in electronic navigation systems, regulatory oversight and ship-traffic management, grounding incidents continue to occur across operational contexts and ship types (Pilatis et al., 2024). High-profile events such as the Amoco Cadiz (1978) (Gundlach et al., 1983), Exxon Valdez (1989) (Peterson et al., 2003) and Costa Concordia (2012) (Dankowski et al., 2014), illustrate the potential for serious ecological, human and economic consequences, while the Ever Given grounding in the Suez Canal (2021), highlighted how global maritime supply chains can be affected sans pollution (Qu et al., 2024).

Grounding is recognised as a complex socio-technical event arising from interactions between human performance, organisational structures and technological systems (Rasmussen, 1997; Reason, 1990). Foundational safety models, such as Swiss Cheese Model by Reason and Rasmussen's risk-management framework, emphasise how accidents emerge from layered system deficiencies rather than isolated operator failures (Rasmussen, 1997; Reason, 1990; Reason et al., 2006). Studies report that human and organisational factors are the most frequent contributors to grounding events (Dominguez-Péry et al., 2021; Hetherington et al., 2006; Wang & Fu, 2022). Ship characteristics are also linked to both occurrence and severity (Mazaheri et al., 2016; Mullai & Paulsson, 2011). Grounding-mechanics studies have further demonstrated that consequences depend on impact energy, hull design and seabed topology (Pedersen, 1995; Wang et al., 2002).

Studies in grounding-risk modelling have increasingly incorporated AIS-based exposure metrics to account for the influence of traffic density, navigational complexity and ship-specific operational profiles (Bye & Aalberg, 2018; Mazaheri et al., 2015; Valdez Banda et al., 2015). Studies in the Baltic Sea have highlighted the role of bathymetry, narrow fairways and seasonal ice conditions in shaping grounding probability (Valdez Banda et al., 2015). A point of divergence concerns regional grounding patterns. While several European monitoring sources suggest a general reduction in overall navigation-related accidents, Swedish national data show a less straightforward pattern; however, this pattern should be interpreted cautiously because observed increase may reflect improved reporting practices rather than a proportional increase in underlying accident occurrence (EMSA, 2024, 2025; Transportstyrelsen, 2024). This contrast motivates closer examination of grounding risks in Swedish waters.

Within this context, national-scale consequence analyses remain limited. Existing studies address consequence to ship, human and environment, they rarely integrate multi-source evidence into a unified national risk picture. This lack of integrated assessment is significant for Sweden, where shallow, archipelagic geography, high seasonal traffic and variable environmental conditions create unique navigational challenges.

This study responds to these gaps by providing an integrated, multi-dataset analysis of grounding occurrences in Swedish waters, and consequences, from 2011 to 2023. Drawing on data from Transportstyrelsen, EMCIP, VTI, HELCOM, IOPC Funds, ITOPF, NoMIS and Swedish

Club, the study examines grounding patterns, contributing factors, consequences to human, ship, environment and associated economic costs.

The insights derived contribute to the literature related to grounding-risk and inform targeted interventions in Swedish maritime safety governance.

The remainder of the paper is structured as follows. Section 2 describes the methods and materials. Section 3 presents and discusses the results. Section 4 introduces the representative accident scenarios and Section 5 offers conclusions.

2 Materials and methods

2.1 Materials

The study adopts a multi-source and exposure-based analytical framework to examine grounding risk in Swedish waters. The primary dataset consists of 535 groundings recorded between 2011 and 2024 and obtained from the Transportstyrelsen database. The distribution of ship types is presented in Figure 1. The dataset includes groundings within Swedish waters involving both, Swedish and foreign-flagged ships, and serves as the core basis for analysing grounding frequency, consequences and representative grounding scenarios. All records were translated from Swedish into English prior to analysis to ensure consistency in classification and interpretation.

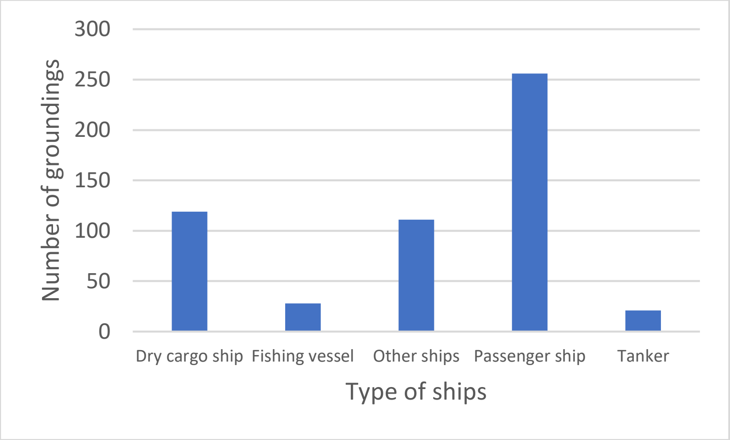


Figure 1: Distribution of ship groundings in Swedish waters by ship type: 2011-2024 (N = 535)

Source: Transportstyrelsen

For the remainder of the study, a harmonised set of 292 grounding incidents covering the period 2011-2023 was constructed to align with the availability of operational activity data that VTI (Swedish National Road and Transport Research Institute) calculated based on HELCOM's AIS-data (see Vierth, Johansson & Lind (2025)). The subset (Table 1) excludes near-miss incidents and is restricted to passenger ships, dry cargo ships and tankers. Passenger ships and dry cargo ships were selected because they are two most represented ship types in the grounding dataset, while tankers were additionally included due to their potential to cause severe environmental consequences, especially oil spill, in the event of grounding. This selection also ensures consistency between the accident and exposure datasets.

Table 1: Distribution of grounding incidents in Swedish waters by ship type and severity: 2011 - 2023 (N = 292)

Source: Transportstyrelsen

Ship type	**Minor Accident**	**Serious accident**	**Total**
Dry cargo ship	46	20	66
Passenger ship	201	20	221
Tanker	4	1	5
Total	251	41	292

To account for variations in maritime activity in Swedish waters, operational data were calculated based on HELCOM's AIS-data. The calculation of the annual ship-kilometres sailed, ship-hours in operation and number of unique ships is described in Vierth, Johansson & Lind (2025). These data were integrated with the grounding dataset for the overlapping period 2011-2023 and serve as the denominator in the exposure-normalised framework, allowing grounding frequencies to be interpreted relative to traffic intensity rather than absolute counts. The inclusion of these data is essential to avoid bias arising from differences in fleet size and operational activity.

For comparative and contextual analysis at the European level, 1,404 grounding cases (2011-2024) were obtained from the European Marine Casualty Information Platform (EMCIP). To characterise environmental consequences, pollution incident records were obtained from HELCOM, while oil-spill statistics were sourced from International Tanker Owners Pollution Federation (ITOPF). Economic assessments were supported by aggregated marine insurance data from Nordic Marine Insurance Statistics (NoMIS) and Swedish Club. Together, the supplementary datasets extend the analysis beyond accident frequency to include environmental and economic dimensions of grounding risk.

In addition to quantitative analysis, the study also involved identification of representative grounding scenarios for Swedish waters which are derived from the distribution of grounding types, ship types and operational contexts. Scenario identification integrates grounding frequency, exposure-normalised risk metrics and consequence characteristics. This scenario-based approach complements statistical analysis by providing contextualised representations of grounding mechanisms and supports interpretation of risk patterns and consequence pathways.

2.2 Methodological framework

Figure 2 presents data integration framework illustrating how each data source contributes to the analytical components of the study. Transportstyrelsen database provides the core dataset of grounding incidents, forming the basis for grounding frequency, consequence analysis and serving as the numerator for exposure normalisation. Operational data calculated based on HELCOM's AIS-data provide measures of navigational activity which are used to derive exposure-adjusted grounding rates. EMCIP database is incorporated to support comparative analysis at the European level. Environmental consequence data from HELCOM and oil-spill statistics from ITOPF and IOPC Funds inform the assessment of environmental consequences. Economic consequence evaluation is supported by aggregated insurance data from NoMIS and Swedish Club. Together, these datasets enable a multi-dimensional analysis linking grounding occurrence, operational exposure and consequence severity.

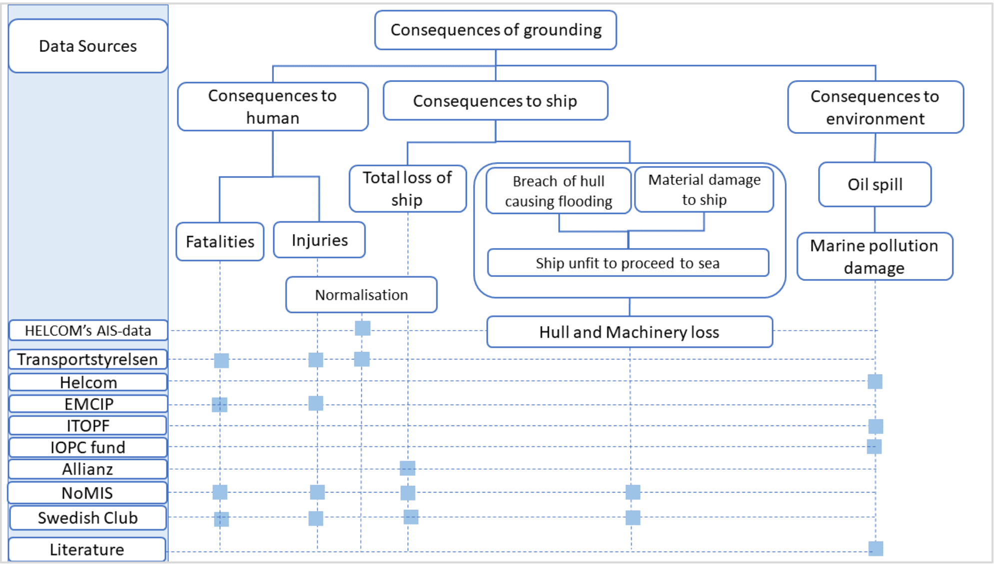


Figure 2: Conceptual framework for grounding consequence classification and respective data sources for consequence analysis.

2.3 Inclusion and exclusion criteria

To ensure methodological consistency and relevance, only groundings involving physical contact with the seabed were included. Near-miss incidents were excluded, as they do not represent realised accident consequences and are subject to reporting variability. The analysis focuses on passenger ships, dry cargo ships and tankers, selected due to their dominant representation in the dataset and their operational relevance. Other ship types were retained in the dataset but excluded from detailed analysis due to limited frequency. To ensure consistency between accident and activity data, activity data has been calculated per ship segment to match the segments used by Transportstyrelsen. Ship types that Transportstyrelsen classifies under “Other vessels” were excluded from the exposure-normalised analysis.

2.4 Exposure-normalised grounding rates

To enable exposure-normalised analysis, Transportstyrelsen’s grounding data and the calculated operational activity data were harmonised through a structured aggregation process. The distance sailed, hours of operation and number of unique ships in Swedish waters over a year has been calculated bottom-up by the ships’ IMO-number. To match the segments in Transportstyrelsen’s data activity, data has been aggregated using each ship’s IMO-number and corresponding Statcode 5 type classification. Passenger ships include, beside passenger ships, also passenger/general cargo ships, passenger/Ro-Ro cargo ships and cruise ships. Similarly, dry cargo ships in the accident data include beside ship types that are normally associated with dry cargo also container ships, bulk carriers, Ro-Ro cargo ships and refrigerated cargo ships. Tanker types were directly aligned. This harmonisation ensured consistency between the exposure data (denominator) and grounding data (numerator).

Following classification alignment, grounding counts were aggregated by ship type and year. Exposure variables were aggregated to the same ship groups and temporal resolution. The harmonised datasets were then merged based on common dimensions of year and ship type, ensuring structural consistency between grounding frequencies and exposure measures.

To account for variations in traffic intensity, grounding frequencies were normalised against groundings per 1 million kilometres sailed, groundings per 1 million hours in operation and groundings per 1,000 unique ships (Bye & Almklov, 2019).

Each exposure metric captures a different dimension of navigational activity. Distance-based measures reflect spatial exposure; time-based measures capture operational duration; and, fleet-based measures represent system participation. No single metric fully captures exposure; therefore, multiple measures are employed.

2.5 Limitations

AIS-based activity measures may be affected by transmission gaps, coverage limitations and differences in ship compliance. Furthermore, ship types are not directly comparable risk units. Differences in operational patterns, navigational environments and regulatory conditions may influence grounding rates independently of safety performance. Accordingly, exposure-normalised rates should be interpreted as relative indicators of risk rather than absolute probabilities. The assumption of proportionality between exposure and accident occurrence may not hold in all cases and results should therefore be interpreted with caution.

3 Results and discussion

3.1 Grounding characteristics and dataset patterns

The severity distribution show 86% of grounding incidents classified as minor and only 14% as serious (Figure 3). The presence of 14% serious accidents indicates that grounding events retain a meaningful potential for escalation. Therefore, there is need to interpret grounding risk not only through frequency but also through severity potential, particularly given that serious groundings are more likely to involve structural damage below the waterline, oil spill or serious economic losses.

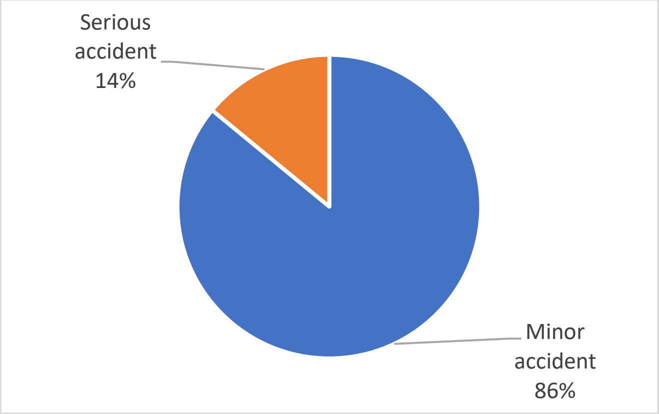
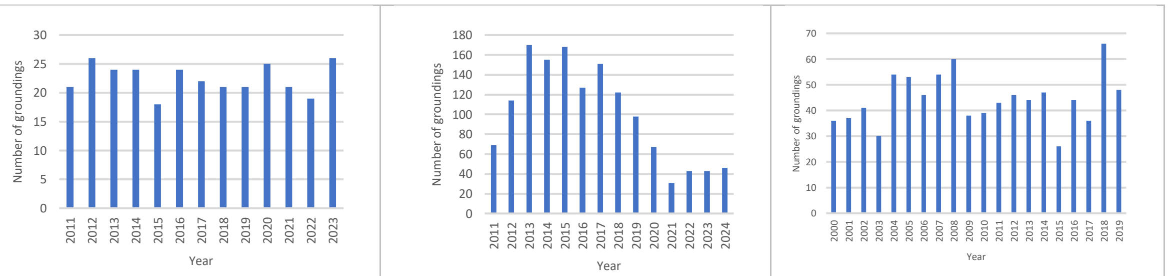


Figure 3: Distribution of Grounding Accidents by Severity in Swedish waters (2011-2023, N = 292)

Source: Transportstyrelsen

The temporal distribution of grounding incidents reveals a relatively stable trend in Swedish waters (Figure 4a) which indicates that grounding occurrence is tied to routine operational activity rather than shifts in safety performance. At the regional scale, both Baltic Sea (Figure 4c) and European datasets (Figure 4b) show similar variability. Baltic Sea shows fluctuations with no sustained decline which suggests that grounding risk remains stable despite regulatory and technological improvements.



(a) Groundings in Swedish waters involving passenger ships, dry cargo ships and tankers: 2011-2023 (N= 292)

Source: Transportstyrelsen

(b) Groundings in European waters: 2011-2024 (N=1404)

Source: EMCIP

(c) Groundings in the Baltic Sea: 2000-2019 (N = 888)

Source: HELCOM

Figure 4. Annual distribution of ship grounding accidents in Swedish waters, Baltic Sea and European waters

The distribution of grounding incidents by operational status indicates a dominance of powered groundings, which account for majority of cases compared to drift-related incidents. This pattern suggests that most grounding events occur while ships are actively navigating rather than drifting, highlighting the central role of human decision-making, manoeuvring and navigational control in grounding risk. This aligns with ITOPF data, which identify powered groundings as a leading cause of spills exceeding seven tonnes and with structural-mechanics research showing that hard bottom contact during powered manoeuvres produces significant hull stresses and elevated breach probability (ITOPF, 2025).

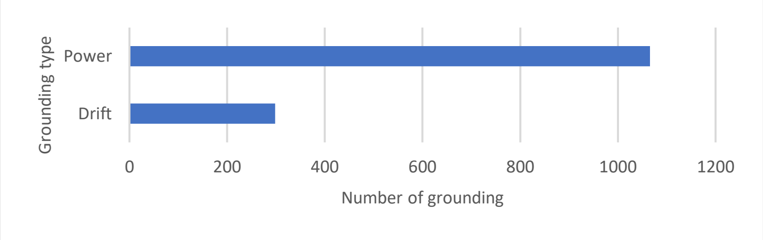


Figure 5: Ship’s underway status at the time of grounding: 2011-2024 (N = 1,364)

Source: EMCIP

3.2 Seasonal and operational patterns

Temporal distribution of groundings demonstrates a seasonal pattern, with a marked increase during the summer months (Figure 6). This trend is consistent with heightened maritime activity in Swedish waters during the summer period, driven by increased passenger transport and recreational navigation (Figure 8b). The concentration of groundings during this period suggests that traffic density and operational complexity, particularly in confined and archipelagic environments, are key determinants of grounding occurrence. Distribution of wind speed at the time of grounding (Figure 7) indicates that the majority of incidents occur under moderate wind conditions suggesting that adverse weather is not the primary driver of grounding events. Instead, the findings point to the predominance of operational and human factors in grounding occurrence under otherwise manageable environmental conditions.

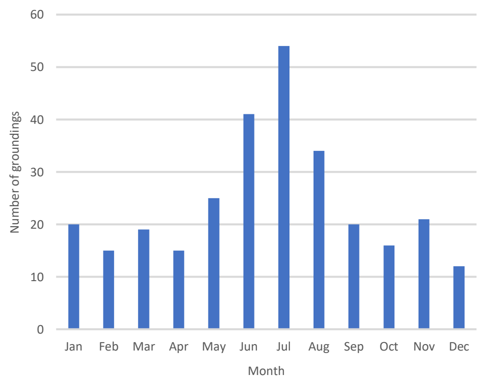


Figure 6: Month-wise distribution of ship grounding in Swedish waters: 2011-2023 (N=292)

Source: Transportstyrelsen

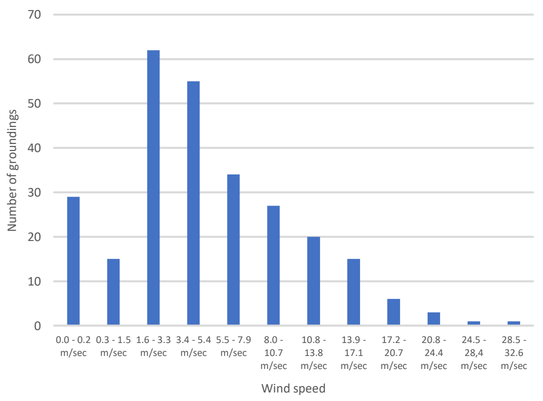
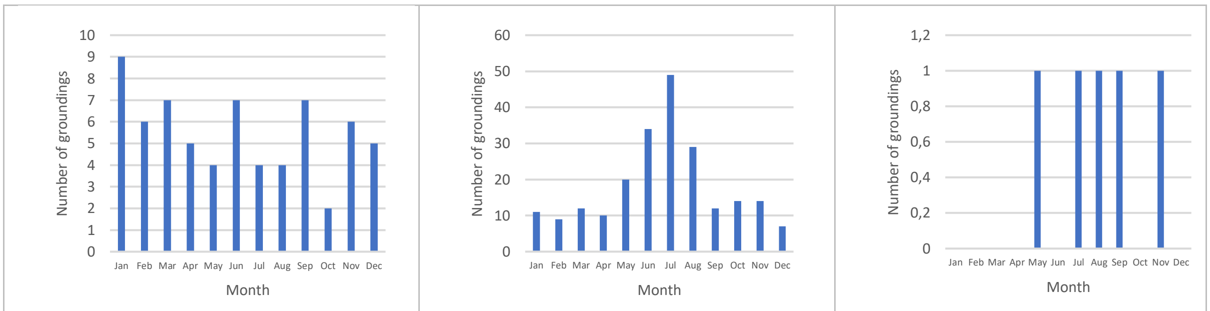


Figure 7: Distribution of average wind speed at the time of ship grounding in Swedish waters: 2011-2023 (N=268)

Source: Transportstyrelsen



(a) Dry cargo ships (N = 66)

(b) Passenger ships (N = 221)

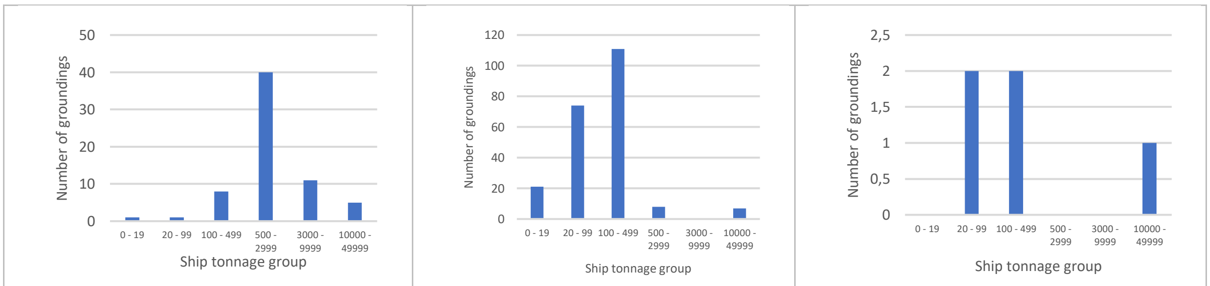
(c) Tankers (N = 5)

Figure 8: Seasonal distribution of ship groundings in Swedish waters: 2011 -2023 (N = 292)

Source: Transportstyrelsen

3.3 Ship characteristics

Distribution of grounding incidents by ship tonnage reveals distinct patterns across ship types, reflecting differences in operational profiles and exposure (Figure 9). Passenger ships show concentration in 100-499 GT range, which accounts for the majority of grounding cases. Dry cargo ships display a different distribution, with grounding incidents concentrated in the 500-2999 GT range. These ships operate under more standardised navigational conditions compared to passenger ships but may still encounter grounding risks during port approaches and departures. In contrast, tanker groundings are limited in number and do not show a clear distribution pattern, which reflects their low representation in the dataset.



(a) Dry cargo ships (N=66)

(b) Passenger ships (N=221)

(c) Tankers (N = 5)

Figure 9: Characteristics of ships involved in groundings in Swedish waters distributed by ship tonnage group: 2021 -2023 (N = 292)

Source: Transportstyrelsen

Figure 10 shows that grounding incidents are heavily concentrated among ships with relatively small beam widths within 0-10.9 m range. This aligns closely with the earlier finding that passenger ships and smaller dry cargo ships dominate grounding occurrences, as these ship classes typically fall within these dimensional ranges and operate intensively in confined coastal and archipelagic waters. A similar pattern is observed for ship draft (Figure 11), where majority of grounding incidents involve ships with draft below 5 m. The low representation of deep-draft ships suggests that grounding risk in Swedish waters is primarily associated with operations in shallow and constrained environments rather than open sea.

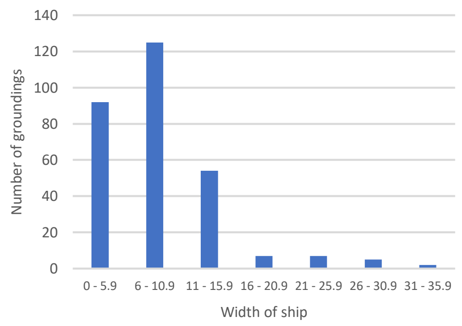


Figure 10: Maximum width of ships grounded in Swedish waters: 2011-2023 (N=292)

Source: Transportstyrelsen

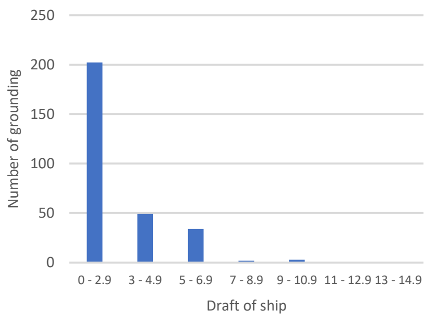


Figure 11: Draft of ships grounded in Swedish waters: 2011-2023 (N=292)

Source: Transportstyrelsen

Global distribution of grounding-related insurance claims by ship type (Figure 12) reveals a different pattern compared to Swedish dataset, highlighting the importance of scale and fleet composition in grounding risk assessment. Bulk carriers account for the largest share of claims (44%), followed by container ships (32%), with tankers contributing 11%.

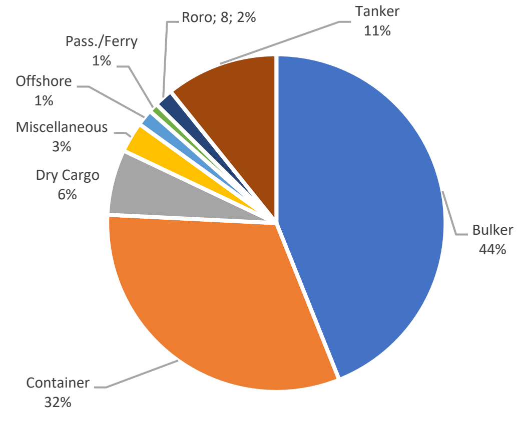


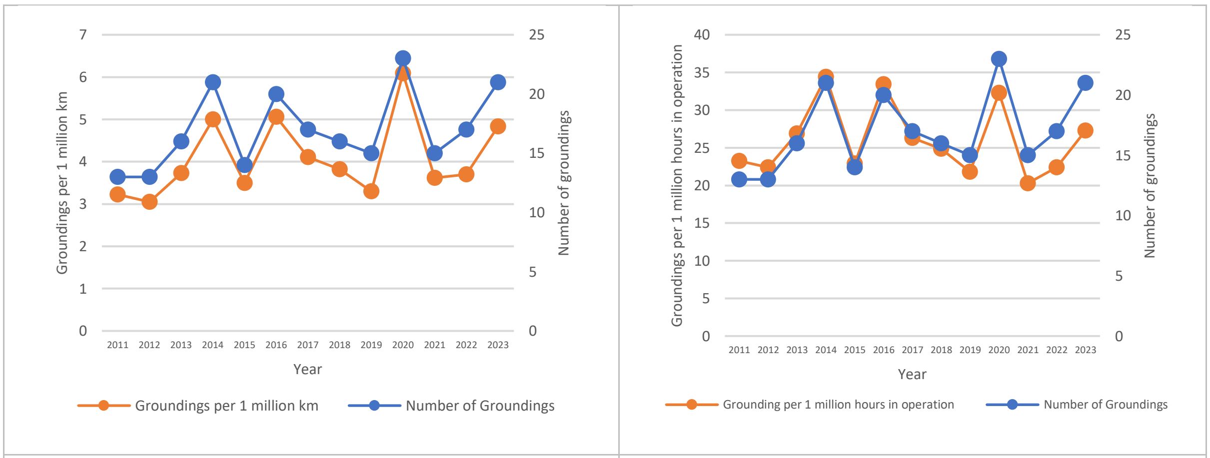
Figure 12: Distribution of global grounding claim numbers per ship type: 2011 - 2024 (N = 446)

Source: Swedish Club

3.4 Grounding trends

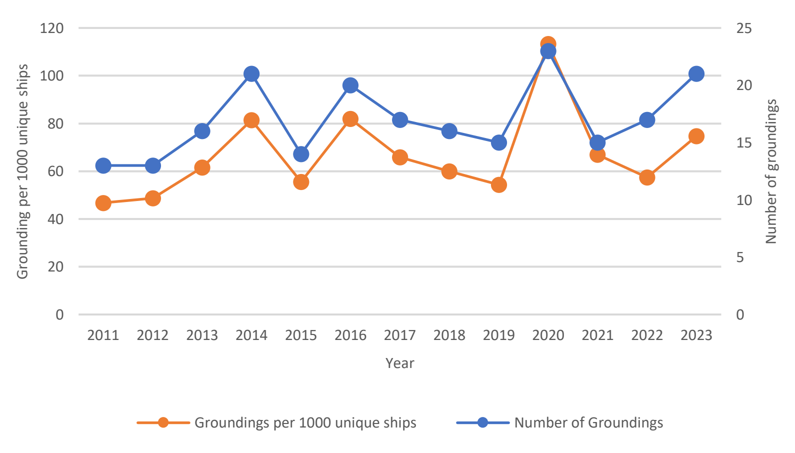
3.4.1 Grounding trends among passenger ships

Exposure-normalised trends for passenger ships (Figure 13) provide a representation of grounding risk than absolute frequencies alone by accounting for variations in operational activity. Across all three metrics, the grounding rates show moderate interannual variability but no clear long-term increasing or decreasing trend. This indicates that grounding risk among passenger ships in Swedish waters is relatively stable over time and structurally linked to their operational profile rather than driven by temporal changes in safety performance. Distance-normalised rates (Figure 13a) fluctuate within a relatively narrow range, with observable peaks around 2014, 2016 and 2020. A similar pattern is observed in time-normalised rates (Figure 13b), where grounding rates per million operational hours show short-term variability but remain broadly consistent across the study period. Fleet-normalised rates (Figure 13c) further highlight the sensitivity of grounding risk to changes in fleet composition and utilisation. The pronounced peak observed around 2020 indicates a temporary increase in groundings relative to the number of passenger ships, which may reflect changes in traffic patterns or operational concentration. When interpreted alongside previous results on seasonality, ship size and operational context, the findings confirm that grounding risk for passenger ships is primarily driven by high-frequency operations in constrained environments, with exposure rather than ship characteristics alone acting as the dominant determinant.



(a) Distance-normalised grounding rates

(b) Time-normalised grounding rates



(c) Fleet-normalised grounding rates

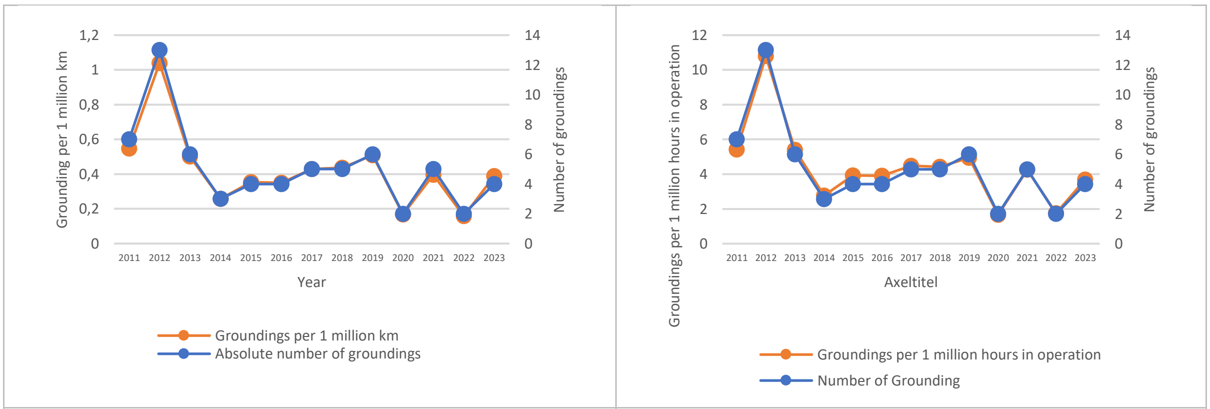
Figure 13: Trends in passenger ship grounding frequency and exposure-normalised grounding rates in Swedish waters: 2011 - 2023 (N = 292)

Source: VTI calculations based on HELCOM's AIS-data; Transportstyrelsen

3.4.2 Collision trends among dry cargo ships

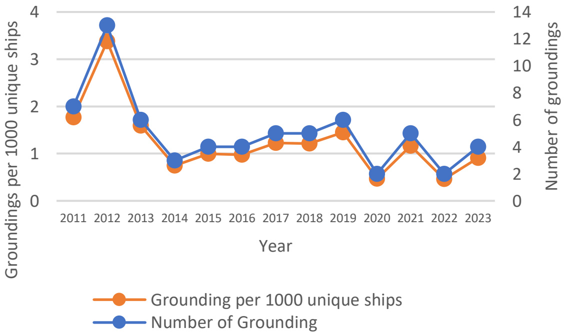
The grounding trends for dry cargo ships (Figure 14) show a relatively stable pattern over time, with limited interannual variability once exposure is accounted for. In contrast to passenger ships, the alignment between absolute groundings and exposure-normalised rates is notably strong across all three metrics, indicating that grounding occurrence for dry cargo ships is proportional to operational activity. This suggests that, unlike passenger ships, dry cargo grounding risk is less influenced by operational complexity and more closely reflects underlying traffic exposure. Time-normalised rates (Figure 14b) closely track the absolute number of groundings, with a peak observed around 2012 followed by a decline and subsequent stabilisation at lower levels which indicates that high grounding frequency in the early part of the period is largely explained by higher operational intensity rather than an increase in risk. Similarly, fleet-normalised rates (Figure 14c) show a peak in 2012, followed by relatively low and stable values, suggesting that grounding risk per ship has remained limited and consistent over time. The absence of large fluctuations in the later years reinforces the interpretation of a stable risk profile.

The consistency across distance-, time- and fleet-normalised measures indicates that grounding risk for dry cargo ships in Swedish waters is stable and largely exposure-driven. When interpreted alongside earlier findings on ship characteristics and operational context, the results suggest that dry cargo ships operate under more standardised navigational conditions with lower variability in risk compared to passenger ships. This reinforces the broader conclusion that grounding risk in Swedish waters is differentiated by ship type, with passenger ships showing higher sensitivity to operational conditions, while dry cargo ships display a more proportional relationship between activity and accident occurrence.



(a) Distance-normalised grounding rates

(b) Time-normalised grounding rates



(c) Fleet-normalised grounding rates

Figure 14: Trends in dry cargo ship grounding frequency and exposure-normalised grounding rates based on distance, operational time and fleet size in Swedish waters, 2011-2023 (N = 292)

Source: VTI calculations based on HELCOM's AIS-data; Transportstyrelsen

3.4.3 Groundings per 1 million km: passenger ships, dry cargo ships

The distance-normalised grounding rates (Figure 15) reveal a difference between passenger ships and dry cargo ships, reinforcing earlier findings on ship-specific risk profiles. Passenger ships consistently show higher grounding rates per million kilometres sailed, typically ranging between approximately 3 and 6 groundings, whereas dry cargo ships remain below 1 grounding per million kilometres throughout the study period. This difference indicates that the higher grounding frequency observed for passenger ships is not only a function of greater activity, but reflects a higher risk per unit distance travelled. Trend shows interannual variability for passenger ships, with peaks around 2014, 2016 and 2020. When interpreted in conjunction with previous results on ship characteristics, seasonality and operational context, the findings confirm that grounding risk in Swedish waters is differentiated by ship type. Passenger ships, operating more in coastal and archipelagic environments, show higher risk per unit distance due to constrained navigation and frequent manoeuvring. Dry cargo ships, by comparison, operate under more standardised conditions, resulting in a lower and more stable risk profile. This distinction underscores the importance of exposure-normalised metrics in identifying underlying risk patterns that are not apparent from absolute frequencies alone.

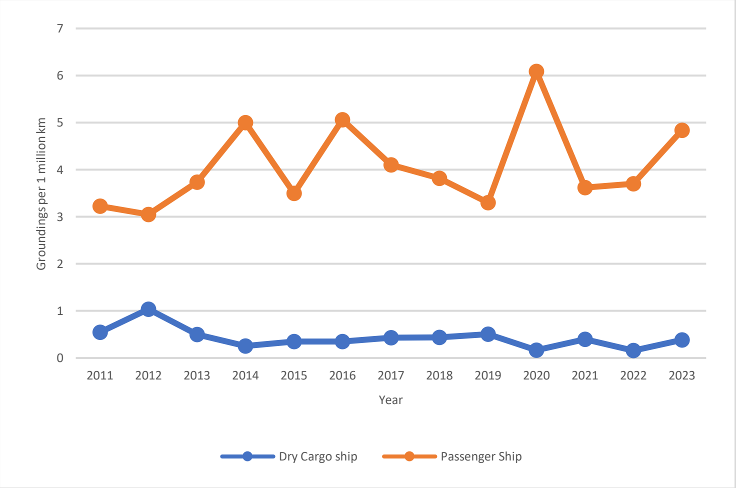


Figure 15: Passenger and dry cargo ship groundings per 1 million km: 2011 -2023 (N = 292)

Source: VTI calculations based on HELCOM's AIS-data; Transportstyrelsen

3.4.4 Groundings per 1 million hours in operation: passenger ships, dry cargo ships

Time-normalised grounding rates (Figure 16) reinforce the structural differences in risk profiles between passenger ships and dry cargo ships identified in previous analyses. Passenger ships consistently show higher grounding rates per million operational hours, ranging between approximately 20 and 35 incidents, whereas dry cargo ships remain at lower levels, generally below 10 and often closer to 5 incidents per million hours. This persistent gap indicates that the grounding frequency associated with passenger ships is not solely attributable to higher activity levels but reflects a higher likelihood of grounding during active navigation.

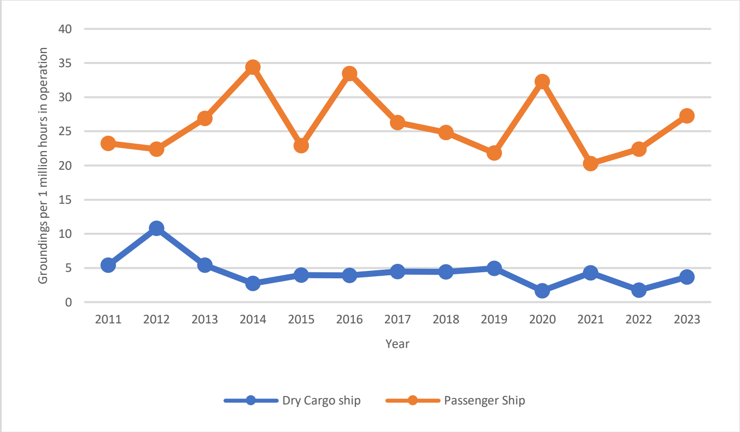


Figure 16: Passenger and dry cargo ship groundings per 1 million hours in operation: 2011 -2023 (N = 292)

Source: VTI calculations based on HELCOM's AIS-data; Transportstyrelsen

3.4.5 Groundings per 1,000 unique ships: passenger ships, dry cargo ships

Fleet-normalised grounding rates (Figure 17) further substantiate the difference in risk profiles between passenger ships and dry cargo ships, while also revealing greater sensitivity to variations in fleet size and utilisation. Passenger ships consistently show higher grounding rates per 1,000 unique ships, with values fluctuating between approximately 50 and over 110 groundings per 1,000 ships. The peak observed around 2020 represents an increase relative to the fleet, indicating a temporary concentration of grounding events that is not fully explained by exposure in distance or time terms alone. In contrast, dry cargo ships maintain low and stable grounding rates when normalised by fleet size, with values remaining close to zero throughout the study period.

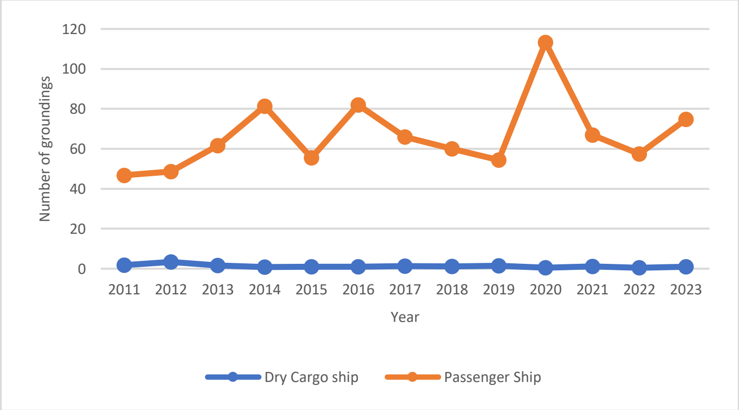


Figure 17: Passenger and dry cargo ship groundings per 1,000 unique ships: 2011-2023 (N = 292)

Source: VTI calculations based on HELCOM's AIS-data; Transportstyrelsen

3.5 Economic consequences of grounding

3.5.1 Consequence distribution and escalation potential of grounding incidents

Distribution of reported consequences associated with grounding incidents (Figure 18) indicates that severe consequences are relatively few. Among the recorded cases, leakage and spill-related incidents represent the most prominent consequence types. The occurrence of leakage and spill events, although limited in number, is particularly significant given their potential to escalate into environmental damage, especially in sensitive coastal and archipelagic ecosystems. The presence of these types confirms that grounding incidents can evolve into multi-dimensional events affecting ship integrity, human safety and the environment.

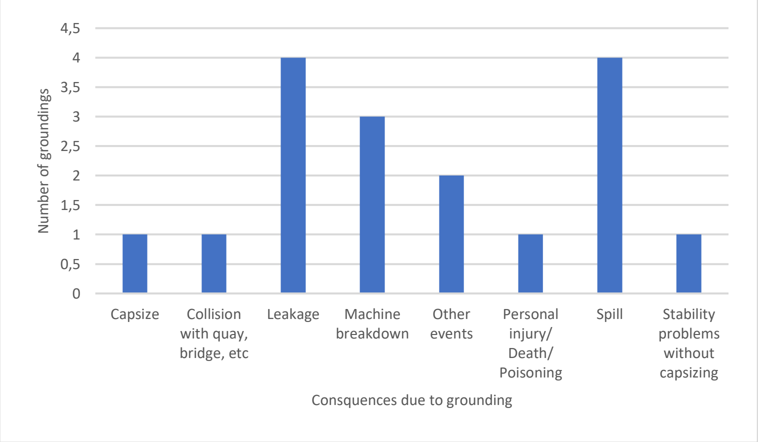


Figure 18: Distribution of reported consequences associated with grounding incidents in Swedish waters: 2011 -2023 (N = 17)

Source: Transportstyrelsen

3.5.2 Consequences to ship

Global ship-loss statistics show that grounding events are severe (Allianz, 2025). Between 2015 and 2024, a total of 110 ships over 100 GT were lost due to grounding, an annual average of eleven total losses (Figure 19). Losses peaked in 2015 and 2016, with 19 and 22 ships respectively, before declining sharply after 2020. Despite this reduction, grounding remains a persistent contributor to global total losses.

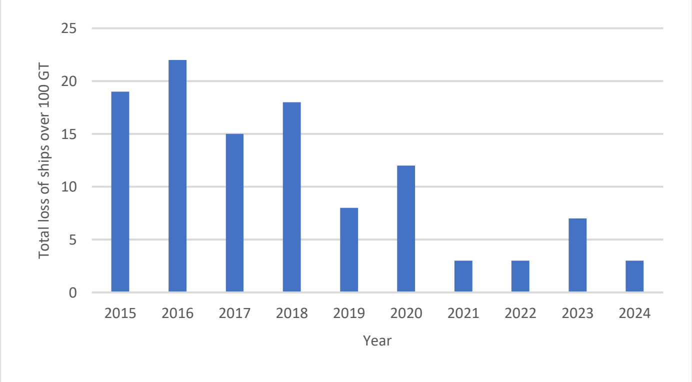


Figure 19: Annual distribution of total loss of ships over 100 GT: 2015-2024 (N = 110)

Source: Allianz

Marine-insurance data provide a complementary view of the broader economic consequences. NoMIS Ocean Hull records indicate that grounding accounted for 621.6 USD million total hull-claim value between 2019 and 2023 and 76.3 USD million claim value in 2024 (NoMIS, n.d.).

The cost per gross ton for grounding-related claims fluctuated between USD 1.30 and 2.09 during 2015-2024 (Figure 20), while the average claim cost for all hull claims rose from USD 242,999 in 2015 to over USD 320,000 in 2024 (Figure 21). When minor claims are excluded, the average claim cost for grounding-related cases exceeding USD 10,000 peaked over USD 559,000 in 2023 (Figure 22).

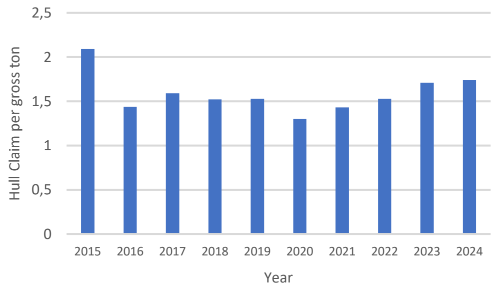


Figure 20: Ocean Hull Claim per gross ton by accident year: 2015-2024 (USD/GT)

Source: NoMIS

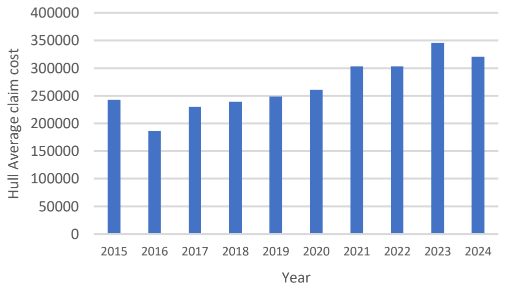


Figure 21: Ocean Hull Average claim cost by accident year: 2015-2024 (USD)

Source: NoMIS

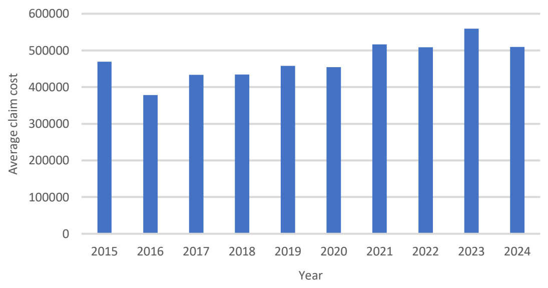


Figure 22: Ocean Hull Average claim cost of all claims >10,000 USD excluding total losses by accident year: 2015-2024

Source: NoMIS

Variations in claim values across ship types are more substantial than variations across ship ages. Age-group analysis for 2019-2024 shows only limited differences in average claim magnitude (Figure 23), suggesting that older ships do not necessarily suffer more severe grounding consequences. In contrast, ship-type analysis (Figure 24) indicates that passenger ships incur the highest per-ship claim costs, while supply ships show the highest cost per gross ton. Cargo ships show high claim per gross ton. These differences highlight that grounding severity is more closely linked to ship function.

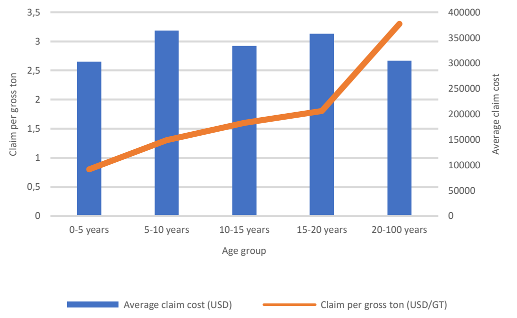


Figure 23: Ocean Hull Claim per gross ton and average claim cost by age group for accident year 2019-2024

Source: NoMIS

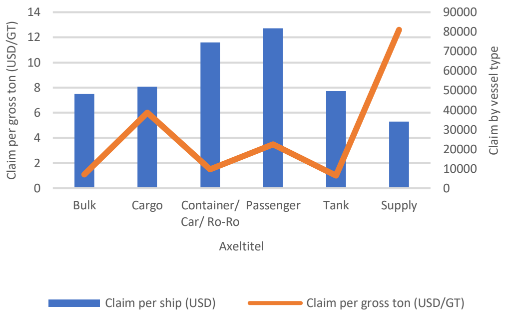


Figure 24: Ocean Hull Claim by ship type, per ship and per gross ton, average claim for accident year 2019-2024

Source: NoMIS

3.5.3 Consequences to humans

In this study, valuation of consequences to humans follows the current Swedish transport cost benefit analysis framework. ASEK provides nationally endorsed unit values for fatalities and injuries expressed as societal costs, incorporating risk valuation (Value of a Statistical Life), healthcare expenditure and loss of production. These unit values replace earlier estimates derived from older contingent valuation studies that are no longer consistent with Swedish appraisal practice (Hultkrantz & Svensson, 2012; Persson et al., 2001).

Table 2 summarises the ASEK 8.0 accident valuation for deaths and injury severity levels in road traffic for 2019 and 2045 price levels. These values are used in the present study to contextualise the potential societal impact of grounding related casualties in Swedish waters. Although Swedish grounding incidents resulted in zero fatality and 16 injuries (7 crew and 9 passengers) during 2011-2023, ASEK framework for road traffic demonstrates that even a single high severity casualty event would generate substantial welfare losses from a societal perspective when the unit values recommended for road traffic are applied.

In this study, ASEK unit values are not used to compute aggregate monetary losses or expected annual costs. Instead, they serve as severity reference values to support consequence-based risk interpretation. Given the low frequency of fatalities and serious injuries in Swedish grounding incidents, direct monetisation would provide limited analytical value. However, groundings are characterised by escalation potential where rare human causalities may coincide with severe ship damage or environmental harm. ASEK framework for road traffic, therefore provides consistent societal benchmark for evaluating potential magnitude of human consequences in representative grounding scenarios and for informing coastal state risk management decisions.

Table 2: Societal valuation of deaths and injuries in road traffic in Swedish transport CBA

(Includes risk valuation, healthcare costs and lost production)

Source: ASEK 8.0 (2024),

	2019 (USD)	2045 (USD)
Death	5828680	7844100
Very seriously injured	2085820	2758470
Seriously, exclude very seriously injured	1379950	1854600
Serious injured	1616780	2166780
Not seriously injured	81840	109340

To complement the societal valuation, aggregated injury claim data from the Swedish Club are used to illustrate private financial exposure associated with personal injury in grounding incidents. Swedish Club data for 2013 -2017 indicate average injury-claim costs ranging from USD 29,000 - 47,000 for lower-value claims and USD 44,500 - 67,500 for higher-value claims (Figure 25).

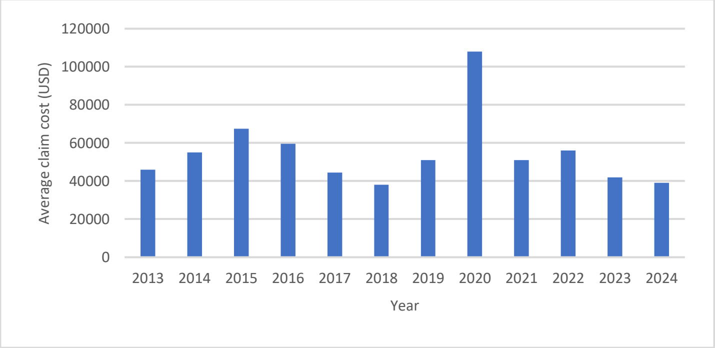


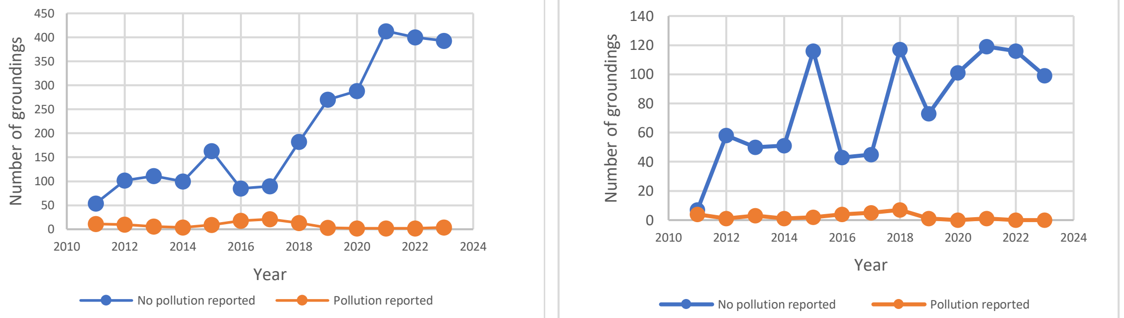
Figure 25: Average claim cost for injury, 2013-2024

Source: Swedish Club

It is important to note that ASEK injury valuations for road safety are not directly comparable to Swedish Club injury claims because ASEK values represent societal welfare losses and include valuation, healthcare costs and productivity losses while maritime insurance claims reflect realised compensation and liability costs borne by shipowners within the scope of insurance coverage. In this study, the two valuation approaches are treated as complementary rather than equivalent which captures different dimensions of consequences of ship groundings.

3.5.4 Consequences to the environment

Groundings also generate environmental liabilities, through pollution damages. Grounding incidents in Swedish waters between 2011 and 2023 resulted in a cumulative total of 240 tonnes of spilled oil. In a broader context, EMSA documented 602 pollution events across Europe between 2014 and 2023 (EMSA, 2024), while HELCOM recorded 204 ship-related pollution cases in the Baltic Sea from 2000 to 2019. Global ITOPF statistics indicate that tanker spills amounted to roughly 190,000 tonnes during 2011-2024 (Figure 26) (ITOPF, 2025).

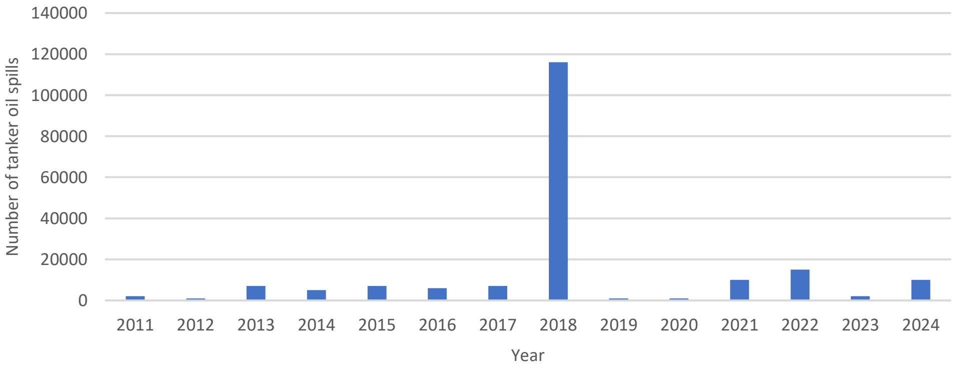


(a) Baltic Sea spills

Source: HELCOM

(b) Swedish waters' spills

Source: HELCOM



(c) Global tanker oil spills

Source: ITOPF

Figure 26: Trends in tanker oil spills (2011-2024)

Although Sweden's annual spill volumes are modest relative to global figures, the semi-enclosed and ecologically sensitive character of the Baltic Sea means that even moderate spills can generate high costs.

Historical spill data provide useful cost benchmarks. The Nakhodka (1997), Erika (1999) and Solar I (2006) incidents resulted in clean-up costs of USD 14,190/tonne, USD 16,337/tonne and USD 20,724/tonne, respectively (ITOPF, 2025). These cases demonstrate how shoreline complexity, ecological vulnerability and local context influence clean-up expenditures. For the Baltic Sea, regionally calibrated clean-up costs of approximately USD 13,000/tonne suggest that even small spills can lead to liabilities in the millions of dollars (Vanem et al., 2008). Insurance data are consistent with this picture because in 2019, the Swedish Club reported an average pollution damage claim cost of USD 282,000, despite a relatively low claim frequency of 0.02. Overall, the environmental consequences of grounding represent the highest potential financial exposure, particularly when shoreline contamination, long-term ecological impacts and compensation mechanisms are taken into account.

4 Representative grounding scenarios for risk management

4.1 Most likely grounding scenario

The most likely grounding scenario in Swedish waters involves passenger ships grounding while operating under power in coastal and archipelagic waters (Figure 27). Passenger ships constitute the dominant ship type in the grounding dataset and, importantly, they also show consistently higher grounding rates than dry cargo ships across all three exposure measures.

Spatial analysis shows high concentration of incidents in the Stockholm archipelago (Figure 28), with additional clustering in other archipelagic and coastal traffic areas. Passenger ship groundings are concentrated in 100 – 499 GT range and occurrence peaks during the summer months, when traffic density is highest. At the same time, most incidents occur under moderate wind conditions, indicating that extreme weather is not the principal driver. The scenario reflects a high-frequency, operationally driven risk pattern, where grounding likelihood is shaped primarily by route structure, traffic intensity and manoeuvring complexity. Although the majority of these events are classified as minor, their recurrence indicates persistent exposure to navigational risk in specific coastal corridors.

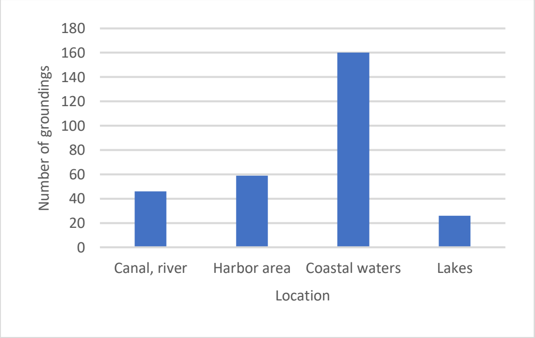


Figure 27: Location of groundings in Swedish waters: 2011 -2023 (N = 291)

Source: Transportstyrelsen

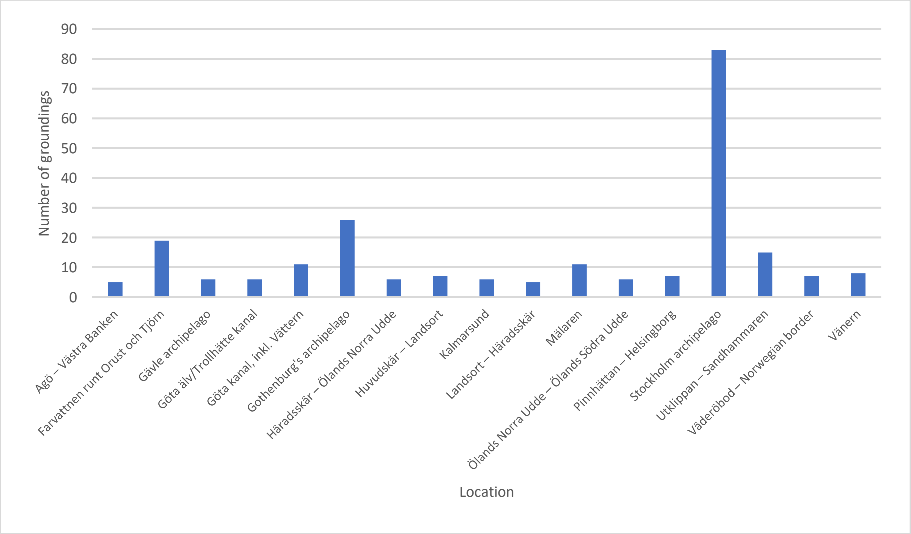


Figure 28: National area of groundings in Swedish waters: 2011 -2023 (N = 234)

(Locations with less than 5 groundings are excluded to make the graph more visible)

Source: Transportstyrelsen

4.2 Second most likely grounding scenario

The second most likely grounding scenario in Swedish waters involves dry cargo ships operating under power in coastal and port-approach environments. Dry cargo grounding incidents occur in coastal waters and port approaches. However, compared to passenger ships, dry cargo ships are more strongly associated with port-entry and cargo-handling corridors, reflecting their operational role in freight transport and terminal access.

Dry cargo groundings are predominantly concentrated within the 500-2999 GT range, indicating that medium-sized ships constitute the primary risk group. Seasonal patterns are less pronounced than for passenger ships, suggesting a more uniform distribution of operations throughout the year.

In terms of consequences, most dry cargo grounding incidents are classified as minor, similar to passenger ships. However, the structural configuration and loading conditions of dry cargo ships introduce variability in damage consequences, particularly in cases involving bottom contact or grounding at speed. While the environmental risk is generally lower than for tankers, the potential for cargo-related impacts and localised damage remains relevant.

4.3 High-consequence, low-frequency grounding scenario for tankers

The high-consequence, low-frequency grounding scenario in Swedish waters is associated with tanker ships grounding under power in coastal or environmentally sensitive areas. This scenario is defined not by frequency, but by its disproportionate potential for severe environmental and economic consequences. Tankers constitute only a small fraction of the grounding dataset, with very limited recorded incidents and are therefore not statistically dominant in either absolute or exposure-normalised terms. However, their inclusion is essential within a risk management framework due to the magnitude of potential consequences in the event of hull breach and cargo release.

From an exposure perspective, tanker grounding rates cannot be robustly generalised due to the small sample size, but available evidence suggests that their occurrence is relatively rare compared to passenger and dry cargo ships. This low frequency reflects stricter regulatory controls, specialised operational procedures and routing measures typically applied to tanker traffic. Nevertheless, when grounding does occur, the consequences are structurally different. Unlike the predominantly minor consequences observed for other ship types, tanker groundings carry a high likelihood of escalation into pollution incidents, structural damage below the waterline and large-scale economic loss, particularly in cases involving loaded ships.

5 Policy implications for grounding risk management

Grounding risk in Swedish waters is primarily shaped by operational exposure within a developed maritime system, requiring targeted optimisation rather than structural reform. Passenger vessels, which show the highest exposure-normalised risk, necessitate strengthened preventive measures in coastal and archipelagic areas to reduce workload during routine operations. For dry cargo vessels, grounding occurrence is largely proportional to exposure and concentrated in port approaches, indicating that risk mitigation should focus on maintaining reliable navigational infrastructure.

Tanker groundings, while rare, represent the greatest environmental and economic risk, requiring emphasis on consequence mitigation through routing measures, mandatory pilotage, escort operations and strengthened spill response capacity, particularly in the Baltic Sea. More broadly, the findings highlight the importance of integrating AIS-based exposure metrics into policy frameworks, as absolute frequencies alone do not adequately capture risk in high-traffic environments. The spatial clustering of incidents further supports geographically targeted interventions, reinforcing the need for a differentiated approach aligned with vessel type, operational context and consequence potential.

6 Conclusions

The study examined grounding risk in Swedish waters using a multi-source, exposure-based analytical framework integrating accident data, operational activity metrics and consequence datasets. The results show that grounding incidents are dominated by passenger vessels and are concentrated in coastal and archipelagic environments characterised by high traffic density and navigational complexity. Although most incidents are minor, exposure-normalised analysis demonstrates that passenger ships exhibit higher grounding rates relative to operational activity. In contrast, grounding occurrence for dry cargo vessels is largely proportional to exposure, reflecting a more stable and operationally consistent risk profile. Tanker groundings, while rare, represent the highest potential for environmental and economic consequence. At the same time, increasing claim severity indicates that the economic consequences of grounding are becoming more significant, even for non-catastrophic events. These findings highlight the limitations of relying on absolute frequencies and emphasise the importance of integrating exposure-based and consequence-oriented metrics. Therefore, grounding risk in Swedish waters reflects a combination of high-frequency, low-consequence operational events and low-frequency, high-impact scenarios, supporting the need for differentiated risk management strategies addressing both routine navigation in coastal areas and preparedness for severe events in sensitive Baltic environments.

Author Contributions

Conceptualization, methodology, validation, formal analysis: A.H. & C.T.; Data curation, writing—original draft preparation: C. T.; Resources, writing—review and editing, visualization, supervision, project administration: A.H; writing—review, project administration: J-U. S – H & I. V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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