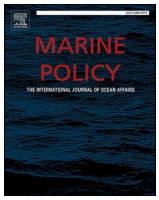
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Full length article

Remediating submerged marine munitions in European seas: Stakeholder priorities, requirements, perceived risks and constraints

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ABSTRACT

European coastal waters contain hundreds of thousands to millions of submerged munitions following World Wars I and II. This war legacy poses critical ecological, human health, economic, and security risks through accidental detonations and leakage of toxic substances from corroding munitions, underscoring the urgent need for remediation. We conducted a structured survey of knowledgeable stakeholders to identify their needs, constraints, and priorities for remediating submerged marine munitions. The largest proportion of respondents (50%) were affiliated with Germany-based organizations. Stakeholders reported high concern about the environmental, economic, and security-related impacts of submerged munitions and largely agreed that remediation would provide benefits across these domains. However, they also identified key concerns and barriers to remediation, including unclear institutional responsibilities; permit issuance and bureaucracy; inadequate risk assessment; remediation costs; and safety and security threats. Notably, none of the respondents in the present study preferred Blast in Place (BiP) as a remediation method, despite its historical prevalence, likely reflecting growing awareness of BiP's ecological and security/safety risks. These stakeholder insights provide a timely snapshot that may inform ongoing European policy initiatives, especially the development of the EU Oceans Pact (adopted in 2025) and the drafting of the forthcoming EU Ocean Act. The findings may also guide ongoing EU co-funded projects and the frameworks of regional institutions, such as HELCOM and OSPAR, toward a comprehensive strategy for safe and sustainable remediation of submerged munitions in European coastal waters.

1. Introduction

Until the 1970s, particularly in the decades following World Wars I and II, large quantities of military munitions were deliberately dumped at sea or remained on the seabed [1,2]. This has resulted in the widespread presence of submerged marine munitions, including intentionally dumped conventional munitions, munitions containing chemical warfare agents (CWAs), unexploded ordnance (UXO) and munitions associated with sunken military vessels or wrecks.

European coastal waters are among the most heavily affected, with the German sectors of the North Sea and Baltic Sea alone containing an estimated 1.6 million tonnes of conventional explosives [3,4]. Additionally, the total quantity of CWAs present in European waters is estimated at 75,500–189,000 tonnes [5].

This legacy presents significant environmental, human health and operational concerns. UXO primarily pose immediate risks to maritime safety, offshore infrastructure and navigation because of their potential for accidental detonation [1,6,7]. Corroding dumped conventional munitions and munitions containing CWAs pose chronic environmental and human health risks through the gradual release of hazardous substances such as TNT and sulfur mustard, which can exert genotoxic, carcinogenic and cytotoxic effects on marine biota and humans [8,9].

Climate-induced changes, including ocean warming and increasing storm intensity and frequency, are predicted to exacerbate these threats by accelerating the corrosion of already degraded munition casings [10]. Accelerated corrosion is expected to increase the release of hazardous constituents into marine ecosystems. However, the magnitude of the resulting ecological and human health consequences and risks remains uncertain [10,11]. These uncertainties underscore the need for a coordinated, large-scale risk assessment to support effective

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management and remediation across European coastal waters.

Given these growing concerns, risk assessment and remediation of submerged marine munitions have received substantial attention and support across Europe, including EU co-funded initiatives such as DAIMON I & II,[1] CONMAR II,[2] REMARCO,[3] and EROVMUS[4] [7,12,13]. Since 2023, the European Commission has recognized the need to develop a coherent framework to address the threats posed by UXO and chemical weapons at sea [14]. The framework promotes the monitoring and removal of UXO using innovative technologies with minimal environmental impact. At the policy level, the European Commission has initiated the European Ocean Pact to direct and guide new approaches for securing and protecting European marine environments [15].

Numerous studies have also enhanced our understanding of the environmental occurrence and ecological risks associated with submerged marine munitions [16–22]. GEOMAR et al. [13] emphasized that progress in remediating submerged marine munitions in European seas depends critically on broadening stakeholder engagement and integrating new and diverse perspectives into decision-making processes. This is critical, as munitions not only pose environmental but also economic, security and safety concerns. Hence, EU policies and strategies need to be better aligned to address the risks associated with submerged marine munitions.

Further, remediation approaches differ depending on the type of submerged munition and the risks they pose. For instance, UXO may threaten navigation, fisheries and offshore infrastructure, and are therefore typically managed through site-specific clearance operations, where removal or controlled disposal may be appropriate. In contrast, historically dumped conventional munitions and munitions containing CWAs often occur in designated dumping grounds, where remediation decisions require balancing long-term environmental risks, technical feasibility, worker safety, economic costs and the potential ecological impacts associated with disturbing corroding munitions [23,24]. Consequently, remediation strategies are typically evaluated on a site-specific basis and may differ according to national policies and management objectives [7].

Moreover, decision-making should incorporate the perspectives of a broad and diverse range of stakeholders potentially affected by submerged marine munitions and their remediation activities, including blue economy industries, fishers, researchers, policymakers, local communities, tourism and recreational users. Such engagement facilitates the exchange of knowledge, experience and diverse perspectives to identify technical, operational and economic challenges, and research gaps requiring further investigation [25,26]. These insights support the development of feasible and efficient remediation strategies for submerged marine munitions in European coastal waters.

As part of the stakeholder engagement processes, we conducted a survey to identify stakeholder needs, perceived risks, operational constraints and priority concerns related to the remediation of submerged marine munitions. The survey provides a baseline for subsequent assessments aimed at understanding stakeholder perspectives on the risks and remediation of submerged marine munitions. The findings can support the co-design of strategies and frameworks for effective and responsible remediation of munitions in European seas. They can also contribute to discussions on the fifth priority of the European Ocean Pact and the associated Ocean Act by 2027. The fifth priority aims to develop a comprehensive strategy for the removal of UXO from European waters, starting with the Baltic and North Seas.

This paper presents the survey design and findings, discusses their implications for the remediation strategies, and concludes with recommendations for future research and stakeholder engagement.

2. Materials and methods

2.1. Survey design

This stakeholder survey was developed under the EU-funded project MMinE-SwEEPER (https://mminesweeper-munition.eu/), in collaboration with two other EU co-funded projects working on submerged marine munitions: MUNI-RISK (https://muni-risk.eu/) and MUNIMAP (https://interreg-baltic.eu/project/munimap/). An overarching goal of MMinE-SwEEPER is to facilitate stakeholder dialogue to identify and understand stakeholders' views and concerns regarding the potential risks posed by submerged marine munitions, as well as those associated with their clearance and remediation. For the present study, stakeholders were defined as individuals and organizations directly or indirectly affected by submerged marine munitions, including researchers, non-profit organizations (NPOs), and private, government, and security organizations.

Data were collected using a structured questionnaire comprising predominantly closed-ended questions, generating categorical and ordinal data suitable for statistical analysis [27]. The questionnaire represented the first stage of the stakeholder dialogue and was designed to map stakeholders' awareness, knowledge, perceptions, and concerns regarding submerged marine munitions across different activity sectors, including representatives of the economic and tourism sectors, industry, policymakers, researchers, and citizens. The questionnaire was administered using SurveyMonkey, a widely used online survey platform (https://www.surveymonkey.com/).

The draft questionnaire was developed by Aarhus University in collaboration with the HELCOM Secretariat, which jointly led the stakeholder dialogue activities within MMinE-SwEEPER. It was subsequently reviewed by all MMinE-SwEEPER project partners, particularly those involved in the stakeholder dialogue, as well as collaborators from the MUNI-RISK and MUNIMAP projects. This iterative review process ensured that the questionnaire addressed the objectives of the three projects while remaining relevant to the diverse stakeholder groups involved.

The final questionnaire comprised 18 questions (Q; Appendix A) structured into four thematic sections: (1) respondent profile and expertise in submerged marine munitions, (2) concerns related to potential effects of submerged marine munitions on the environment, economy, security and safety, (3) specific needs, limitations and reasons to remediate submerged marine munitions and (4) criteria to prioritize remediation sites.

The questionnaire comprised open-ended questions and two sets of 5-point Likert-scale items. The first scale ranged from: 1 = 'Not at all concerned', 2 = 'Slightly concerned', 3 = 'Somewhat concerned', 4 = 'Highly concerned', and 5 = 'Extremely concerned', to assess stakeholders' level of concern regarding submerged marine munitions. The second ranged from: 1 = 'Significant deterioration', 2 = 'Some deterioration', 3 = 'No effects', 4 = 'Some improvement', and 5 = 'Significant improvement' to evaluate stakeholders' perceptions of the expected environmental, social, and economic outcomes of remediation. Together, these Likert-scale questions provided insights into stakeholders' perceptions of submerged marine munitions, perceived remediation needs and the anticipated benefits or consequences of remediation.

The survey adopted a broad definition of submerged marine munitions without distinguishing between intentionally dumped conventional munitions, munitions containing CWAs, UXO and munitions associated with sunken military vessels or wrecks. This approach was intended to capture stakeholders' overall perceptions of submerged marine munitions in European seas. Consequently, respondents may have interpreted the term according to their professional background

[1] Decision Aid for Marine Munitions: Practical Application

[2] Concept for conventional Marine munition Remediation in the German North and Baltic Sea

[3] Remediation, Management, Monitoring and Cooperation addressing North Sea UXO

[4] Enhanced Remote Operated Vehicle interface for Munition Studies

and experience.

2.2. Survey area

The stakeholders represented organizations from 14 European coastal countries, bordering the Baltic, the Mediterranean, the Black Sea, and the Northeast Atlantic, as well as an organization from North America.

2.3. Stakeholders identification and selection

The Horizon Europe-funded MMinE-SwEEPER project identified and compiled a roster of stakeholders whose expertise lies in submerged marine munitions risks. The roster includes identified professionals from HELCOM, NATO and JPI Ocean communities, as well as other specialists whose activities intersect with marine munitions. These specialists are acknowledged by the 19 partners of the MMinE-SwEEPER project, although they may not be actively involved in munition remediation and risk assessment. The roster represents diverse disciplines and sectors, including research, private industry, governance (environmental institutions, policy, security, and safety entities), and non-profit organizations (NPOs).

2.4. Data collection

The questionnaire was emailed to 107 individuals identified and listed on the stakeholder roster. It was also distributed to potential respondents through the project's communication channels, including LinkedIn, the MMinE-SwEEPER newsletter and the Kiel Munition Clearance Week (KMCW) website, between February and August 2025. At the close of the survey (31 August 2025), the completed questionnaires were analyzed using the analytical tools embedded in SurveyMonkey, Microsoft Excel, and R-studio.

2.5. Data analysis

All statistical analyses and data visualizations were performed using R-Studio (version 4.5.1; [28]). Descriptive statistics for the Likert scale items were summarized using frequency distributions, proportions, medians and interquartile ranges (IQR), depending on the questionnaire item. A chi-square goodness-of-fit test with Bonferroni-adjusted p-values was used to assess whether there was a significant difference in the stakeholder response across the concern levels for Q7. An ordinal logistic regression model was used to analyse the association between stakeholder concern levels, their organizations' involvement in the munition-related activities, and their representative sectors. For the repeated-measures Likert-scale items (Q8–Q10 and Q13–Q16), significant differences in stakeholder responses across categories were evaluated using the nonparametric Friedman test. Statistical significance was set at $p < 0.05$. When the Friedman test indicated significant differences, pairwise comparisons were conducted using Conover's post-hoc test with appropriate p-value adjustment. To assess the degree of agreement in stakeholder concern levels, Kendall's coefficient of concordance (W), was calculated for each Friedman analysis. Values for W range from 0 to 1, where 0 indicates no agreement, 0.0–0.1 very weak agreement, 0.1–0.3 weak agreement, 0.3–0.5 moderate agreement, > 0.5 strong agreement, and 1 perfect agreement. A cumulative link mixed-effect model (CLMM) with random effects was fitted to account for clustering or repeated measures [29] and to examine differences in stakeholder concern levels across sectors (Q8–Q10 and Q13–Q16). The association between stakeholder sector and selected key aspects requiring further information before remediation (Q12) was examined using Fisher's exact test with Monte Carlo simulations.

3. Results

A total of 52 stakeholders (hereafter, respondents) fully completed the questionnaire out of 81 participants. Most responses were received through the project's communication channels (websites and LinkedIn), and all respondents confirmed authorization to represent their organizations. The detailed survey results are provided in the following sections.

3.1. Location and organization profile of respondents (Q1–Q6)

Most respondents were from organizations based in the Baltic Sea countries (Fig. 1; Q1), with the largest proportion from Germany (DE; 50%), followed by Poland (PL; 12%) and Estonia (EE; 8%). There was one respondent from a Canadian organization.

Overall, 75% of the organizations reported to be actively working on submerged marine munitions, often in collaboration with others, while 25% were not actively working on submerged marine munitions but indicated relevant knowledge of the topic (Fig. 2; Q3 & Q5). Three of the organizations that responded to not being actively working on marine munitions collaborated with other organizations engaged in the topic.

In terms of the different sectors, the highest proportion of response from organizations directly involved in the munition topic were from the research sector (41%), followed by private (31%), governance (18%), NPOs (8%) and security sectors (3%) (Fig. 2). The highest response from the organizations not directly involved but knowledgeable on the munition topic were from the private sector (39%) followed by research (31%), governance (23%) and NPOs (8%) sectors.

3.2. Respondents' Concern levels about the impacts of submerged marine munitions on the environment, economy, security and safety (Q7–Q10)

The respondents indicated varying levels of concern about munitions in European seas (Fig. 3; Q7). Overall, the largest proportion reported being *highly concerned* (42%), followed by *extremely concerned* (33%), *somewhat concerned* (17%) and *slightly concerned* (6%). Only one respondent (2%) indicated being *not at all concerned*. This respondent indicated that munitions do not affect their organization. Overall difference in concern levels was statistically significant (χ^2 (4, N = 52) = 31.1, $p < 0.001$). Pairwise comparisons with Bonferroni adjustment showed that the proportions of stakeholders who indicated being *highly* or *extremely concerned* were significantly higher than those indicating being *slightly* or *not at all concerned*. However, no significant difference was observed between the *highly* and *extremely concerned* stakeholders, nor between the *slightly* and *not at all concerned* stakeholders (Fig. 3; Q7).

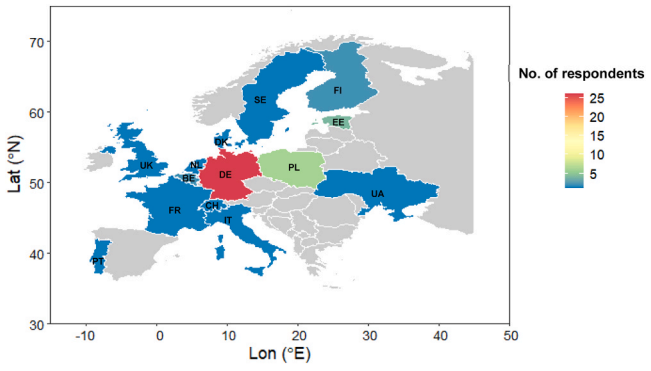


Fig. 1. Geographical distribution of respondents in Europe (Q1). Countries represented include Portugal (PT), France (FR), Switzerland (CH), Italy (IT), Germany (DE), Belgium (BE), Netherlands (NL), United Kingdom (UK), Denmark (DK), Poland (PL), Ukraine (UA), Sweden (SE), Estonia (EE) and Finland (FI). Countries shown in grey colour represent no participation. One Canadian respondent was also recorded but is not shown in the figure.

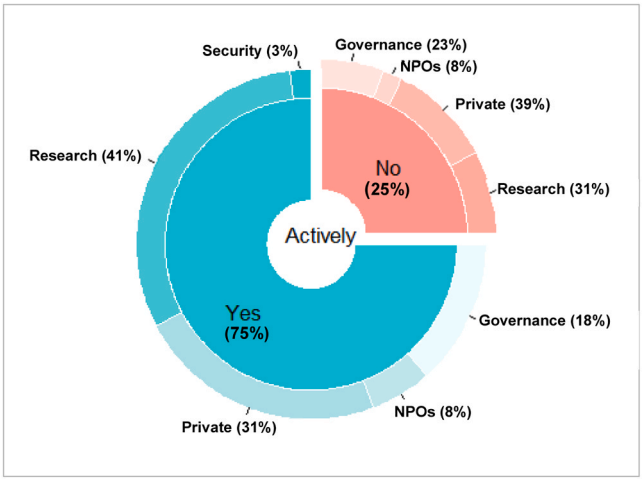


Fig. 2. Respondents organizational sector (Q3) and whether they are actively working on submerged marine munitions (Q5).

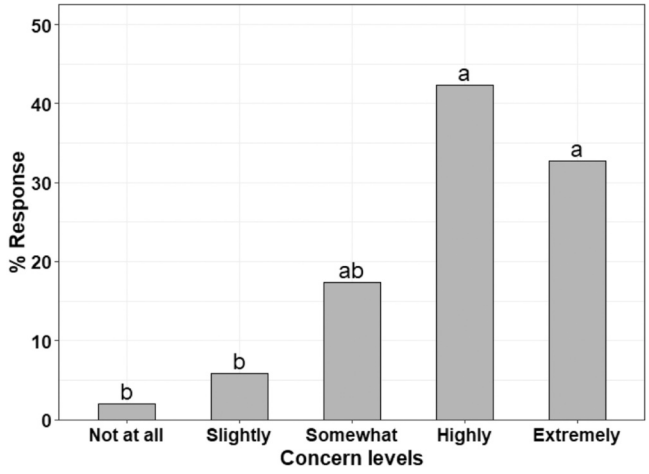


Fig. 3. Respondents' concern levels about munitions submerged in European seas (Q7). Bars that do not share the same alphabet are significantly different.

Respondents who worked on the munition topic tended to report higher levels of concern than those who did not. However, the difference was not statistically significant (ordinal logistic regression: $\beta = 0.83$, $p = 0.17$; Fisher's exact test $p = 0.40$). Respondents' comments on why they selected concern levels are provided in Table 1s.

Similar to their overall concerns about munitions in the sea, the respondents generally indicated *high* to *extreme concern levels* about the impact of submerged marine munitions across the environmental, economic and security-related categories (Fig. 4A–C). Concern levels varied across the categories. For environmental impact categories (Fig. 4A; Q8), the respondents indicated *high* to *extreme concern levels* for almost all categories (48–73%), except for marine birds, for which only 37% indicated *high* to *extreme concern levels* and 42% indicated that they were *slightly* to *not at all concerned*. The median and IQR concern levels for each category are provided in Table 2s.

The Friedman test showed a significant difference ($p < 0.001$, $W = 0.7$) in concern levels among environmental categories. Within the marine organism groups, Conover's pairwise comparison test showed that concern for marine birds was significantly lower than for marine mammals and fish, and concern for fish was significantly higher than for marine mammals. Although concern for benthic biota was greater than for pelagic biota, and concern for sediment was greater than for water pollution, these differences were not statistically significant.

Across the economic impacts categories, the majority of respondents indicated being *highly* to *extremely concerned* (40–75%) (Fig. 4B; Q9). The Friedman test showed a significant difference in concern levels ($p < 0.001$, $W = 0.6$). Conover's pairwise comparison test further showed that the concern about aquaculture impacts was significantly lower than for all other economic categories. Additionally, concerns regarding the seabed industry and infrastructure were greater than for blue sustainable economy development and maritime activities.

Similar to economic concerns, most of the respondents indicated being *highly to extremely concerned* (35–67%) (Fig. 4C; Q10) about the impact of submerged marine munitions on security and safety, except for marine police, where most indicated being *slightly* to *not at all concerned* (37%). The Friedman test showed a significant difference in concern levels across the security categories ($p < 0.001$, $W = 0.7$). Conover's pairwise comparison test showed that the concern for marine police security was significantly lower than for civil and infrastructure security. Also, the concern level about the security impacts on infrastructure was higher than for both occupational and marine police security. The CLMM indicated that the respondents' sector was not a statistically significant predictor of their concern level across all categories (all $p > 0.05$).

3.3. Remediation of submerged marine munitions (Q11)

To evaluate the general perspective and perceived institutional capacity for remediating submerged munitions, the survey examined whether the current knowledge is enough to initiate remediation. The majority (62%) of respondents indicated there is sufficient knowledge and tools to initiate remediation actions, while 38% disagreed (data not shown). The responses varied depending on the location of the organization (Fig. 5; Q11). Among Central European organizations (Germany and Poland), which accounted for the highest survey participation, approximately two-thirds of respondents indicated that sufficient tools and knowledge were available, while one-third disagreed. Responses from Western (United Kingdom, Switzerland, Netherlands, France and Belgium), Eastern (Ukraine), Northern (Sweden, Finland, Estonia and Denmark) European and international (Canada) organizations were more variable; however, these patterns are based on small sample sizes and should be interpreted with caution.

3.4. Aspects requiring further information (Q12)

The respondents identified *responsibilities, permits issuances and bureaucracy* (56%) as the most important aspects needing further information to initiate remediation (Fig. 6; Q12). This was followed by *risk assessment* (50%), *available remediation technologies and methodologies* (50%) and *environmental risks* (48%). The Fisher's exact test showed no statistically significant association between the respondents' organizational sector and the selected aspects that need further information to initiate remediation (p-value > 0.05). Other aspects specified as needing further information, as well as the percentage selection based on the organizational sectors, are provided in Table 3s and Fig. 1s, respectively.

3.5. Impacts of remediating munitions on the Environment, Economy, and Security and Safety (Q13–Q15)

Overall, the respondents indicated that remediation of submerged marine munitions would positively impact the environment, economy, and security and safety (Fig. 7 A–C; Table 3s). Regarding environmental impact, 52–55% of respondents indicated that they anticipate *some* to *significant improvements* across the different categories (Fig. 7A; Q13). The Friedman test showed no significant difference ($p = 0.8$, $W = 0.9$) in the concern level across the different environmental categories ($p = 0.8$). The CLMM indicated that the respondents' sector was not a statistically significant predictor of their concern level across all categories (all $p > 0.05$).

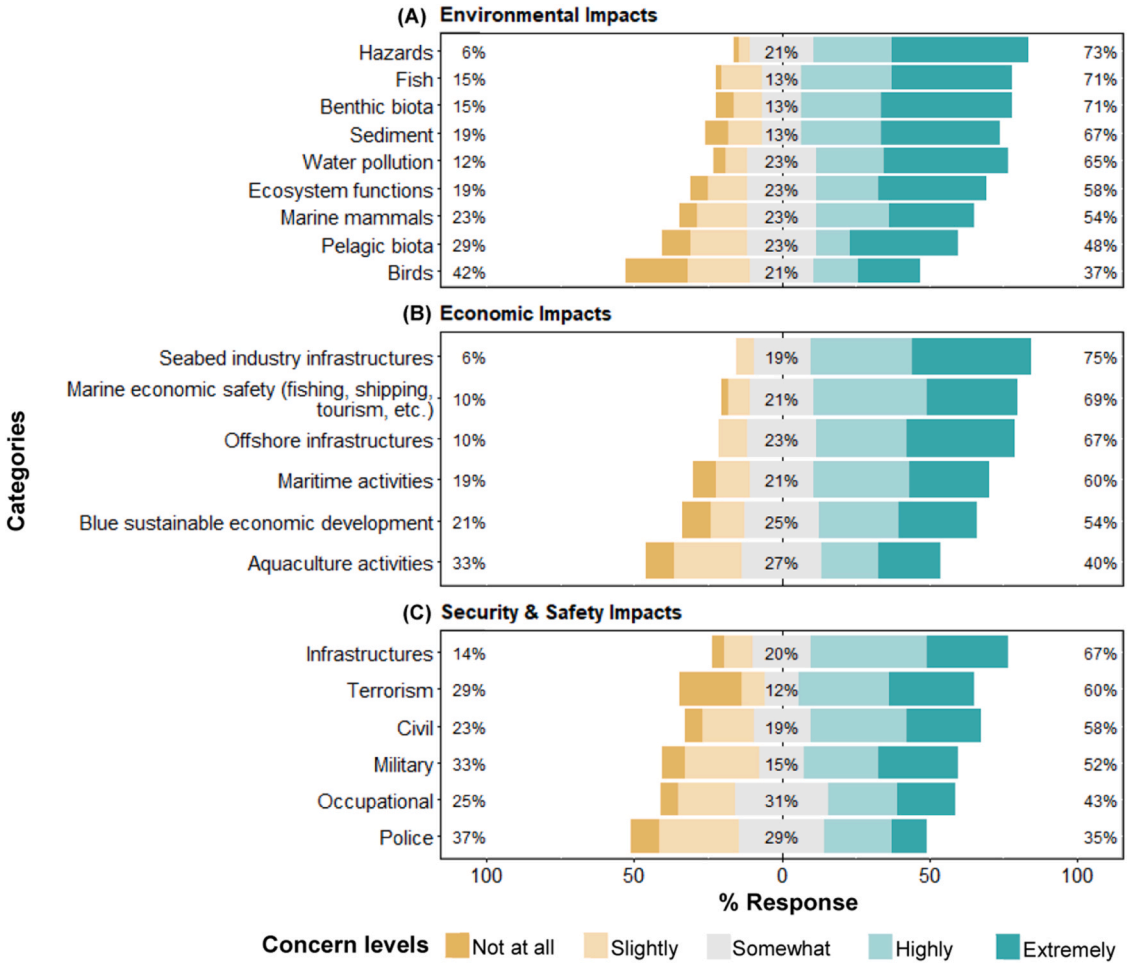


Fig. 4. Diverging stacked bar chart of respondents' concern levels about the impact of submerged marine munitions on the environmental (A; Q8), economic (B; Q9), and security and safety (C; Q10) categories. The responses are arranged to centre with *somewhat concerned* as a neutral response.

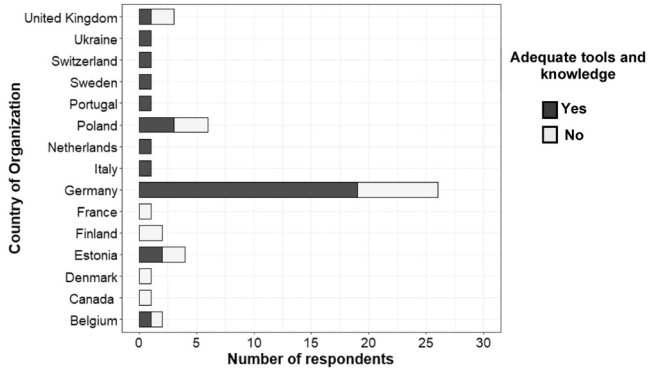


Fig. 5. Respondents' perception of the availability of adequate tools and knowledge to initiate remediation actions by the country of organization (Q11).

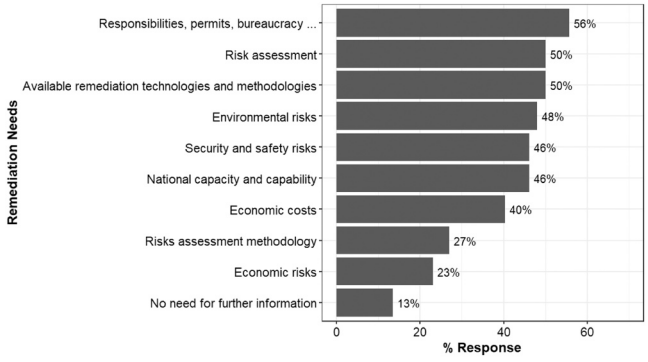


Fig. 6. Distribution of the key aspects requiring further information before proceeding with remediation activities (Q12).

The median and IQR concern level for each category is provided in Table 4s.

A similar pattern was observed for economic impacts (Fig. 7B; Q14) and security and safety impacts (Fig. 7C; Q15), with 40–65% and 45–67% of stakeholders indicating *some* to *significant improvements*, respectively. The Friedman test showed significant differences in concern levels for the economic ($p = 0.002$, $W = 0.6$) and security and safety ($p < 0.001$, $W = 0.7$) categories. For the economic impact categories, Convor's pairwise comparison showed that the improvement level for offshore sustainable industry development (cabling, offshore wind farms, etc.) is greater than the public economy (public cost of remediation). For the security and safety impact categories, Convor's pairwise comparison indicated that improvements in ethics and well-being issues will be greater than in geopolitical and military security.

3.6. *Respondents' concerns regarding the impact of remediation activities across environmental, economic, governance, and security and safety categories (Q16)*

The responses varied across the categories considered to be affected

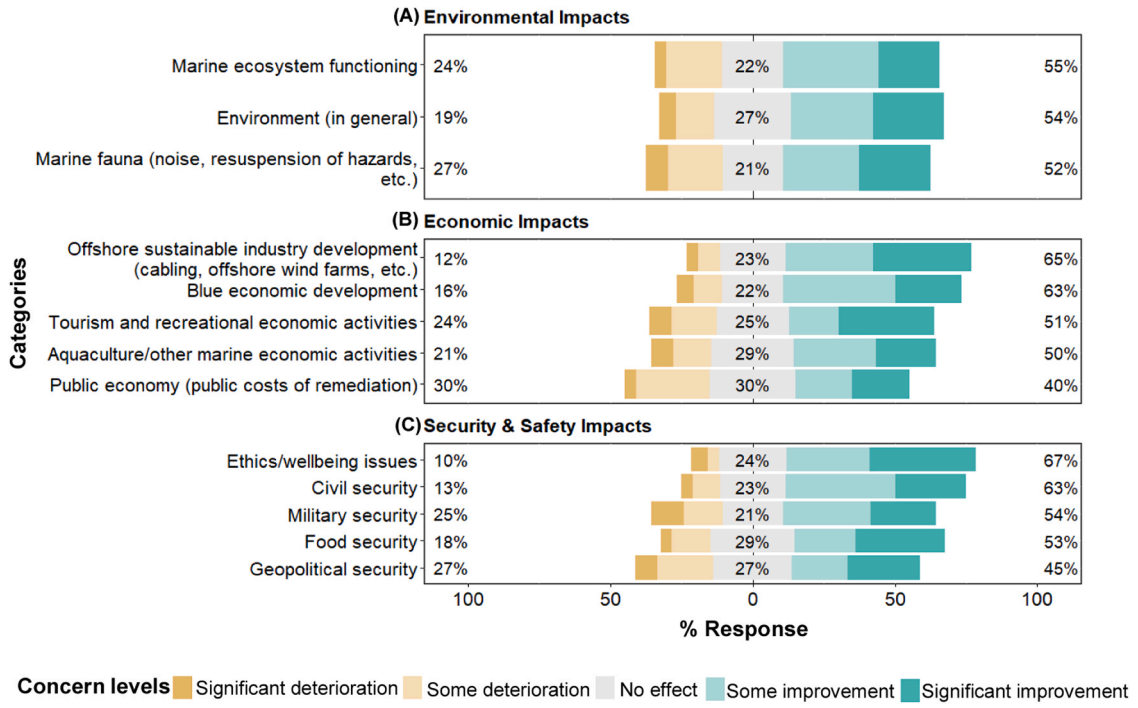


Fig. 7. Diverging stacked bar chart of respondents' concern levels on the impact of remediating submerged marine munitions on the environmental (A; Q13), economic (B; Q14), and security and safety (C; Q15) categories. The responses are arranged to centre *somewhat concerned* as a neutral response.

by remediation activities (Fig. 8; Q16).

The highest concern level was for remediation cost, with 66% of the respondents being *highly* to *extremely concerned*. Comparable levels of concern were observed for coordination between different authorities in the same state and regional/national capability and capacity to remediate (62 and 64% respectively), followed by safety and security risk of remediation actions (58%). The lowest proportions of *high* to *extreme concern* levels were observed for geopolitical situation, efficiency of current remediation methodology and ecosystem function (46% each) (Fig. 8). The Friedman test indicated a significant overall difference in responses across the categories ($\chi^2(10) = 26.39$, $p = 0.003$). However, the magnitude of this effect was small ($W = 0.053$), indicating low agreement in respondents' concern levels. Consistent with this, Conover's post-hoc pairwise comparisons with the Holm adjustment did not

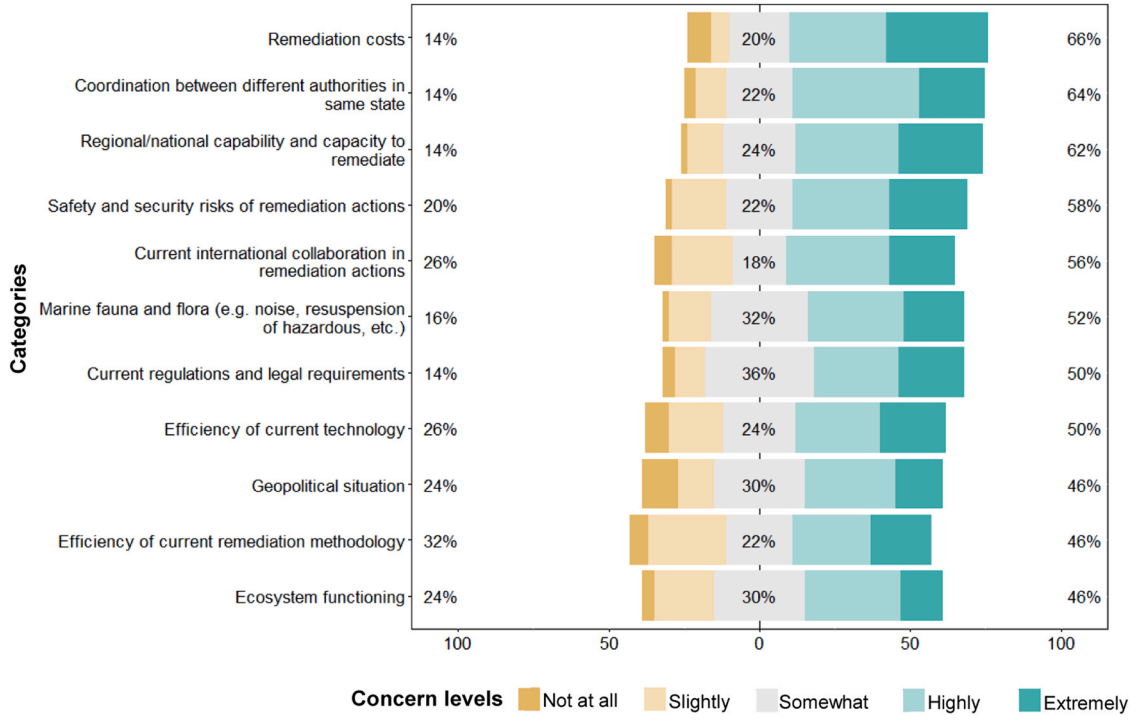


Fig. 8. Diverging stacked bar chart of respondents' concern level on the effects of submerged marine munition remediation activities across the environmental, economic, governance, and security and safety categories (Q16). The responses are arranged to centre *somewhat concerned* as a neutral response.

identify any statistically significant differences among the individual categories. The CLMM indicated that the respondents' sector was not a statistically significant predictor of their concern levels ($p > 0.05$). The median and IQR concern levels for each category are provided in Table 6s.

3.7. Whether, how and what to remediate (Q17 & Q18): methodology and prioritization criteria

In response to Q17, which examined whether remediation of submerged marine munitions should be undertaken at present or in future following the resolution of the identified gaps, all respondents, except one, agreed that remediation should be undertaken (data not shown). Regarding the remediation methods/approaches to prioritize, 51% of the respondents indicated

that remediation approaches and methods should be tailored to the specific conditions of each site and case (Fig. 9).

In addition to tailoring remediation methods to the site and case, 35% of stakeholders identified the removal of munitions as the most preferred method. This was followed by on-land disposal and on-site destruction other than Blast in Place (BiP), with 6% each. None of the stakeholders opted for BiP as an appropriate remediation method (Fig. 9). Two "other" methods indicated by the respondents were "prevent stripping equipment" for mines and the "use of platforms for destroying munitions".

Regarding the criteria to be addressed for prioritizing remediation sites (Fig. 10; Q18), munition occurrence was selected by the most respondents (73%), followed by residue concentration (60%) and security risks (52%). The stakeholders' comments on other criteria are provided in Table 6s.

4. Discussion

The present study aimed to identify stakeholder needs, perceived risks, operational constraints and priority concerns related to the remediation of submerged marine munitions in European waters. The presence of submerged munitions poses critical environmental, economic and security concerns for most European coastal states [10,12,13,30]. These concerns are increasingly recognized not only as legacy contamination issues but also as broader marine governance challenges. Despite multilateral goals and coordinated actions relative to the management and potential remediation of submerged munitions in the Baltic Sea, national efforts to remediate vary considerably across the EU [7,12,31]. Remediation is often ad hoc and driven by specific incidents or infrastructure clearance needs [12]. The disparity in remediation efforts may be due to variations in the legal framework and policy focus, funding availability, expertise level, and quality and dissemination of

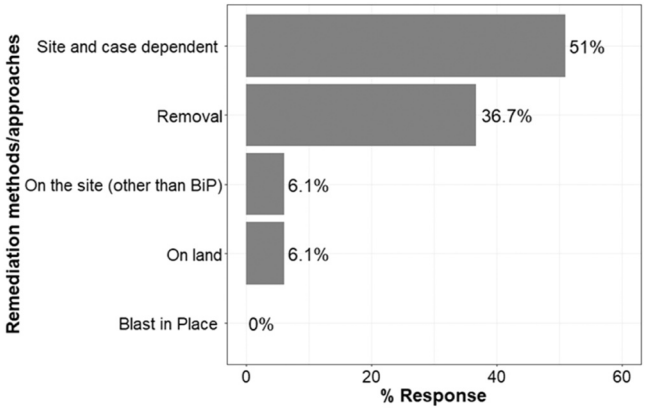


Fig. 9. Respondents' perspectives on methods/approaches to prioritize during remediation. BiP stands for Blast in Place (Q17).

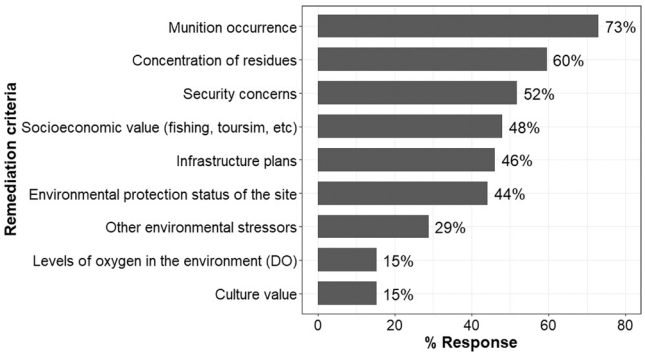


Fig. 10. Respondents' perspective on the criteria to prioritise for remediation (Q18).

relevant data [12,13].

The survey responses in the present study were predominantly provided by organizations based in Germany, likely reflecting the country's recent implementation of the German Immediate Action Programme for Contaminated Sites in the North and Baltic Seas by the German Federal Ministry for the Environment, Climate Protection, Nature Conservation and Nuclear Safety

BMUV [3,32]. This programme, supported by an estimated investment of €500 million and an annual operation cost of €100 million[5] to pilot submerged munition recovery operations in Lübeck Bay [33], may have increased institutional awareness, capacity, and engagement with the issue, thereby influencing stakeholder representation within the survey.

The high to extreme concern levels expressed by most respondents about the environmental, economic, and security/safety impact of submerged munitions in the present study are consistent with broader public and stakeholder perceptions [34,12,35,36]. This elevated concern may be driven by multiple, interconnected factors. These include the symbolic and emotional resonance of submerged munitions as legacies of war, danger and historical trauma, as well as the increasing visibility of the issue in public and policy discourse. Additional factors are ecological risk from the toxic munition compounds, as well as security and safety threats, particularly to critical infrastructure and individuals working in the marine environment. Evidence supporting these concerns is increasingly documented in European seas. In water sampled near several warheads in Lübeck Bay, Vedenin et al. [37] reported high concentrations of explosive compounds, including trinitrotoluene (TNT), approaching the toxicity threshold for aquatic organisms [38]. Niemikoski et al. [39,40] also detected CWA compounds in cod and hagfish sampled from munition dumpsites in the southern Baltic Sea and from a wreck area in the Skagerrak Strait, respectively. Beyond ecological impacts, direct consequences for human health and safety have also been reported. Injuries resulting from direct contact with submerged munitions [21] and white phosphorus ammunition residues [41] have been reported among fishermen operating in the Danish Sea and among holidaymakers at the Baltic Sea Coast, respectively. These findings indicate that stakeholder concerns are not solely based on perception but on documented environmental and safety hazards.

Although respondents expressed significant concern about the impacts of submerged munitions and generally viewed remediation as having positive environmental, economic, and security benefits, they also identified several challenges. These included the cost of remediation, coordination among authorities within the same state, limited regional and national capacity and capability to remediate, and the safety risks associated with remediation activities. Similar concerns,

[5] https://www.geomar.de/en/news/article/wie-wirkt-sich-die-munitionsbergung-auf-die-meeresumwelt-aus

particularly on financial costs, operational safety and hazards, and coordination/ capacity gaps, have been reported in prior studies and assessments [7,12,42]. Further, the respondents identified gaps that need to be addressed to initiate remediation. These gaps include institutional responsibilities, permitting and bureaucratic processes, risk assessment, available remediation technologies and methodologies, and a lack of environmental risk evaluation.

Consequently, despite broad support for remediation, stakeholders face structural and technical barriers that hinder action. For instance, uncertainty about institutional responsibilities and the permitting process may delay decision-making, while limitations in risk assessment frameworks and remediation technologies constrain the selection and implementation of appropriate interventions. Similar barriers have been reported in previous EU-level stakeholder assessments, where most respondents indicated that standard operating procedures for meeting more stringent and additional technical operational measures in case of higher-level threats should be improved [12]. Studies by Frey [43] and Novik et al. [44] also indicated that existing risk assessment approaches for submerged marine munitions are insufficient. These findings, together with the present study, provide additional lines of evidence on the need for decision-support tools, clearer governance frameworks, and improved access to risk assessment. The findings are particularly timely given the ongoing development of the EU Oceans Pact, adopted in 2025, and the associated Ocean Act, expected by 2027, which may provide an omnibus policy framework to address longstanding uncertainties related to institutional responsibilities, permitting processes, and risk assessment methodologies regarding dumped munitions.

The stakeholders indicated that the most appropriate approach to remediating submerged marine munitions should be site- and case-dependent, likely accounting for site-specific variables, including hydrodynamic conditions (e.g., currents and waves), sediment properties, munition characteristics (e.g., degree of corrosion and density), environmental factors (e.g., water depth, turbidity) and proximity to critical infrastructure [42]. These factors may influence risk outcomes and remediation strategies, tools, and technologies. In addition to tailoring remediation to the site and case, respondents indicated that physical removal of munitions is the preferred remediation approach, likely because it is perceived as having the least environmental, security and safety risks. Beyond tailoring remediation to site-specific conditions, future remediation strategies should also consider their long-term ecological outcomes. While reducing the risks posed by submerged marine munitions remains the primary objective, remediation should be designed and implemented to minimize unintended environmental impacts and support the long-term environmental health and resilience. Emerging concepts, such as the Nature Quotient, could help promote the integration of ecological considerations into remediation planning, encouraging remediation methods to be evaluated not only for technical effectiveness but also for their contribution to ecosystem integrity and recovery [45]. Incorporating these considerations into decision-making and policy frameworks may help ensure that remediation strategies balance effective risk reduction with the long-term protection and sustainability of marine ecosystems.

There was no respondent in the present study who selected BiP as a preferred remediation method or approach; however, a survey commissioned by the European Commission [12] reported that, besides relocating to a safer place (5/7 of respondents), on-site detonation was the second-most-used disposal strategy (4/7 of respondents). Despite the low number of respondents in the EU survey, findings align with historical practice, as BiP has long been the most widely applied method for managing dumped munitions [46,47]. Nevertheless, the blast shock waves and overpressure associated with BiP operations have been documented to cause injuries in marine mammals and invertebrates [48–50]. BiP has also been shown to increase the release, bioavailability and bioaccumulation of explosive compounds, such as TNT and its metabolites, in marine organisms [23,51,52]. Hence, the contrast between the historical reliance on BiP and its lack of preference among respondents in the present study likely reflects a shift in stakeholder perceptions towards remediation approaches that prioritize long-term environmental risk reduction over operational convenience. The respondents' perceptions in the present study also align with recommendations by Koschinski & Kock [53] and Maser & Strehse [52] that the best option for remediating submerged munitions to prevent negative impacts on the marine environment and marine vertebrates in particular is to recover the munitions rather than BiP. Koschinski & Kock [53] highlighted other alternatives for the recovery and safe disposal of munitions, including freezing techniques, remotely operated salvage operations using robotics, in situ destruction with static detonation chambers and photolytic removal and recommended the use of bubble curtains if underwater detonation cannot be avoided.

4.1. Limitations

The survey employed a purposive stakeholder sampling approach targeting individuals and organizations with knowledge of or involvement in submerged marine munitions. While this approach ensured informed responses, it may have introduced sampling bias by underrepresenting stakeholder groups with limited engagement in the topic, as well as perspectives from European countries with lower institutional awareness or capacity. Consequently, the findings should not be interpreted as representative of all stakeholders or the wider public across Europe.

The predominance of respondents from Germany further suggests that the perspectives captured in the survey may be influenced by national experiences, regulatory frameworks, and remediation practices specific to the German context. Consequently, the findings should be interpreted with caution when extrapolating to a broader European scale. In addition, the moderate sample size ($n = 52$) limits the extent to which the results can be considered representative of all stakeholders engaged in or impacted by submerged marine munitions and their remediation in European coastal waters.

Nevertheless, the present study provides valuable insights into the concerns, needs, and priorities of a knowledgeable stakeholder group. It offers an informed indication of the key issues shaping the current discourse on the impacts and remediation of submerged marine munitions. Furthermore, the sample size in this survey is substantially larger than that of the stakeholder survey commissioned by the European Commission [12], providing a broader evidence base while recognizing the described limitations.

5. Conclusion

The present study provides evidence on stakeholder perspectives regarding the impacts and remediation of submerged marine munitions in European seas. The findings highlight broad support for remediation while recognizing that future management should be guided by site-specific, risk-based decision-making rather than a single universal remediation strategy. Consequently, remediation priorities should be determined by local environmental conditions, munition characteristics, ecological sensitivity, proximity to critical infrastructure, and the potential risks to human safety and marine ecosystems.

The study further demonstrates that progress towards remediation is constrained less by stakeholder acceptance than by institutional, regulatory, and technical barriers. Unclear governance responsibilities, complex permitting procedures, inconsistent risk assessment approaches, limited remediation capacity, and the need for further technological development remain key challenges to implementation. Addressing these barriers will require closer coordination among national authorities, harmonized governance frameworks, transparent, science-based and site-specific risk assessment, continued investment in remediation technologies and decision-support tools, and sustained stakeholder engagement throughout the decision-making process.

Given the vast quantities of submerged marine munitions present in

European waters, complete remediation is unlikely to be technically, economically, or environmentally feasible in the foreseeable future. Consequently, future management should prioritize interventions where submerged marine munitions pose the greatest risks to human safety, critical infrastructure, economically important marine activities, and environmentally sensitive areas, while applying long-term monitoring and adaptive risk management to lower-priority sites. Such prioritization frameworks would enable resources to be directed where they provide the greatest environmental, societal, security and economic benefits.

Finally, these findings provide timely evidence to support ongoing European initiatives, including the implementation of the EU Oceans Pact and the forthcoming Ocean Act, as well as collaborative efforts under projects such as MMinE-SwEEPER, MUNI-RISK, and MUNIMAP. Integrating stakeholder perspectives into future policy and management frameworks will help ensure that remediation strategies are scientifically robust, operationally feasible and socially acceptable. In addition, ecological considerations should ensure that remediation strategies not only reduce risks effectively but also support the long-term health and resilience of marine ecosystems, thereby contributing to the sustainable development of Europe's blue economy.

Data Statement

All data in this manuscript will be made available on request.

CRediT authorship contribution statement

Delove Abraham Asiedu: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Frank Akowuge Dugasseh:** Writing – review & editing, Writing – original draft, Methodology. **Maria del Rosario Domínguez Carrasco:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Carolyne Chercham:** Writing – review & editing, Writing – original draft. **Adeline Souf:** Writing – review & editing, Writing – original draft. **Hans Sanderson:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2026.107301.

Data availability

Data will be made available on request.

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