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Prioritizing Sea-Dumped Munitions for Clearance

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ABSTRACT

Prioritizing sea-dumped munition piles for clearance exemplifies a sustainability governance challenge in which spatial decisions must be made amid diverse stakeholder interests and limited scientific information. Here, we present a co-creation process to design a multi-tier index that combines multiple knowledge types within the Analytical Hierarchy Process to enable such decisions. We use the Source-Pathway-Receptor-Consequence model to structure the selection of data sources. We introduce a two-level weighting structure in which stakeholder elicitation reveals preferences, while expert elicitation complements limited scientific information. We apply the process to develop MCA-DuMP, a multi-tier index, to prioritize 39 munition piles in the German Baltic Sea. We identify 10 high-priority piles for clearance, spatial hotspots, and the need to rezone contaminated areas. The index currently supports Germany's pioneering effort to systematically clear sea-dumped munitions, but can also be applied in other contexts. The co-creation process itself is applicable to spatial prioritization problems in general.

Sustainability governance entails making spatially explicit decisions among diverse stakeholders with conflicting interests and limited scientific information[1,2]. One contemporary example of such decision-making is deciding where to start the clearance of marine munitions. Sea-dumped munitions are an under-explored global issue that currently requires decision-support as countries begin to confront the long-term consequences of wartime disposal at sea. These munitions threaten marine ecosystems, human health, and offshore economic activities [3,4] through risks of explosion, physical injury, ecosystem contamination, and seafood pollution [5,6]. In German waters alone, an estimated 1.6 million tons of munitions from the two world wars remain in the sea (Fig. 1) [5,7,8]. After World War II, surplus munitions were dumped in piles within and around designated disposal sites[5,9]. Eighty years later, Germany is now the first country to begin a systematic clearance effort[10,11]. Given the scale, cost, and technical difficulty of the task, clearance of marine munitions will take several decades, while corrosion and other degradation processes steadily increase risks. Hence, prioritizing piles for clearance is essential to allocate limited resources effectively.

Prioritizing munition piles for clearance is challenging for two reasons. First, different stakeholder groups have conflicting interests. Environmental NGOs, for example, emphasize environmental protection, while coastal protection agencies focus on human health risks, and private companies on risks to economic activities such as shipping and offshore energy[11,12]. Balancing these trade-offs is central to building public support and political legitimacy for clearance decisions. The second reason why prioritization is challenging is that information on risks and opportunities is limited. Data on contamination levels, munition condition, and ecological vulnerability are incomplete, and data quality varies across sites[13,14].

Accelerating maritime use further intensifies these governance challenges through growing pollution, expanding resource extraction, and the rapid expansion of offshore, in particular wind power generation infrastructure[15–17]. As a result, decisions must often be made under high scientific uncertainty and with increasingly less space to accommodate diverse stakeholder interests.

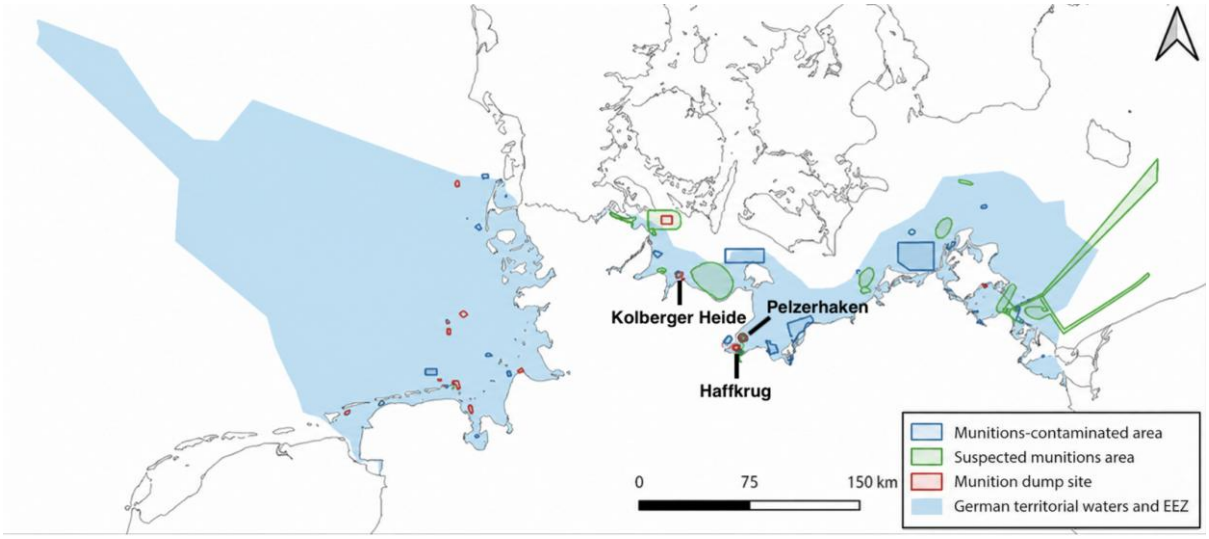


Fig. 1 Sea-dumped munitions in Germany. Map of munition-contaminated areas in Germany's territorial waters and exclusive economic zone (EEZ) (based on Böttcher et al. 2011)

To address these two governance challenges, we designed and carried out a co-creation process, involving experts and stakeholders, to develop a multi-tier index that supports spatial decision-making given diverse stakeholder interests and limited scientific information (Fig. 2a). We thereby built on the Analytical Hierarchy Process (AHP), an established multi-criteria analysis (MCA) framework[18], and other index-based spatial prioritization approaches that guide

resource allocation[19]. By implementing the prioritization through a co-creation process, we respond to calls for more transparent and inclusive decision-making that makes trade-offs visible and systematically combines diverse forms of knowledge[20,21]. The co-creation process comprised 11 workshops involving more than 130 stakeholders and experts.

In a first step, we co-design a problem definition and a two-level hierarchy of criteria (Fig 2a). Top-level criteria comprise societal interests that were identified to be relevant for the decision, while second level sub-criteria represent risks and opportunities associated with each top-level criterion.

We use the Source-Pathway-Receptor-Consequence (SPRC) model[22] to verify the hierarchy of criteria and to identify indicators to measure each sub-criterion, selecting the data that best quantifies the respective risks or opportunities. The SPRC model disaggregates risk genesis into a causal chain comprising source, pathway, receptor, and consequence, which together describe how a hazard, such as dumped munitions, leads to harmful or beneficial consequences. We use this model to build causal chains from the source (i.e., munitions) to all consequences on the respective top-level criteria. Next, we identify, for each causal chain, the best available data to measure risk, by selecting, among the scarce data available, the data that are closest to the end point of the causal chain (i.e. the consequence; Fig. 2 b). While the SPRC model has previously been used in MCAs, its use was limited to identifying and positioning criteria into the AHP hierarchy [23–25].

In a second and third step, we elicit weights for all criteria to represent both stakeholder preferences and expert knowledge (Fig. 2c). Stakeholder elicitation is used to weight the top-level criteria and represents different interests of stakeholder groups. Expert elicitation is used to weight the sub-criteria and represents the causal genesis of the different top-level criteria. Expert elicitation is widely used to support sustainable decision-making under uncertainty[26–29]. This type of two-level level elicitation is new in AHP applications, which typically use stakeholder elicitation to weight a single level of criteria and apply expert elicitation only to assess the performance of alternatives or to define indicators[30–33]. We call the resulting index MCA-DuMP (***multi-criteria analysis for dumped munition prioritization).***

In a fourth step, we apply MCA-DuMP to calculate clearance priority scores for 39 munition piles in three areas in the German Baltic Sea for which detailed data on dumped munitions are available: Pelzerhaken, Kolberger Heide, and Haffkrug (Fig. 1). This includes gathering data, normalizing indicators, and using the expert- and stakeholder-based weights to calculate the clearance priority score for each munition pile (Fig. 2a).

In a fifth and final step, we co-evaluate the resulting priority list and formulate policy recommendations with all stakeholders and experts involved.

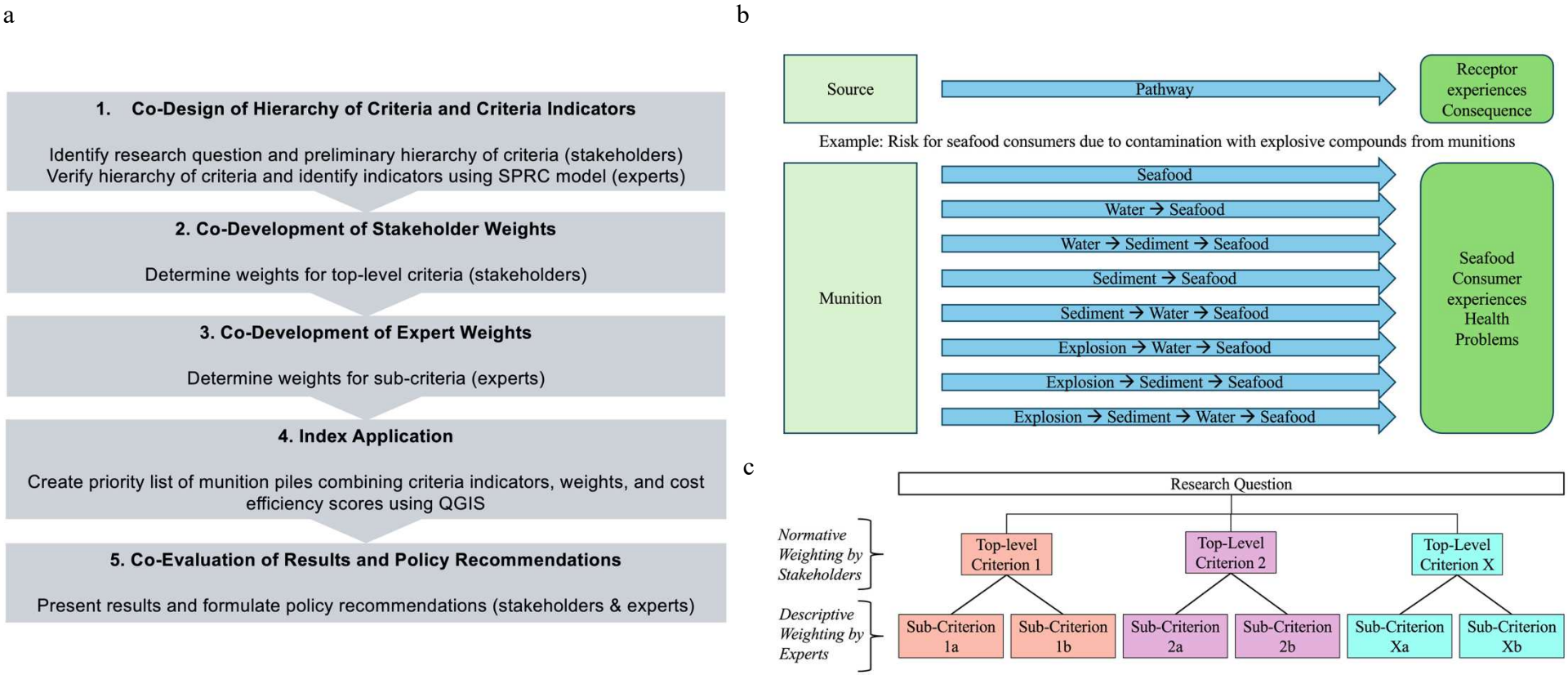


Fig. 2 Co-Creation Process. (a) The five steps of the co-creation process.
(b) The Source-Pathway-Receptor-Consequence (SPRC) model and an example illustrating how it was used to assess the risk of seafood consumer contamination.
(c) Illustration of the two-level hierarchy of criteria used in the multi-criteria analysis (MCA). Top-level criteria (e.g., Criterion 1, 2, etc.) are weighted by stakeholders to reflect normative priorities. These are further subdivided into technical sub-criteria (e.g., 1a, 1b, etc.) that are weighted by experts based on their causal contribution to the respective top-level criterion.

Results

Step 1: Co-created hierarchy of criteria

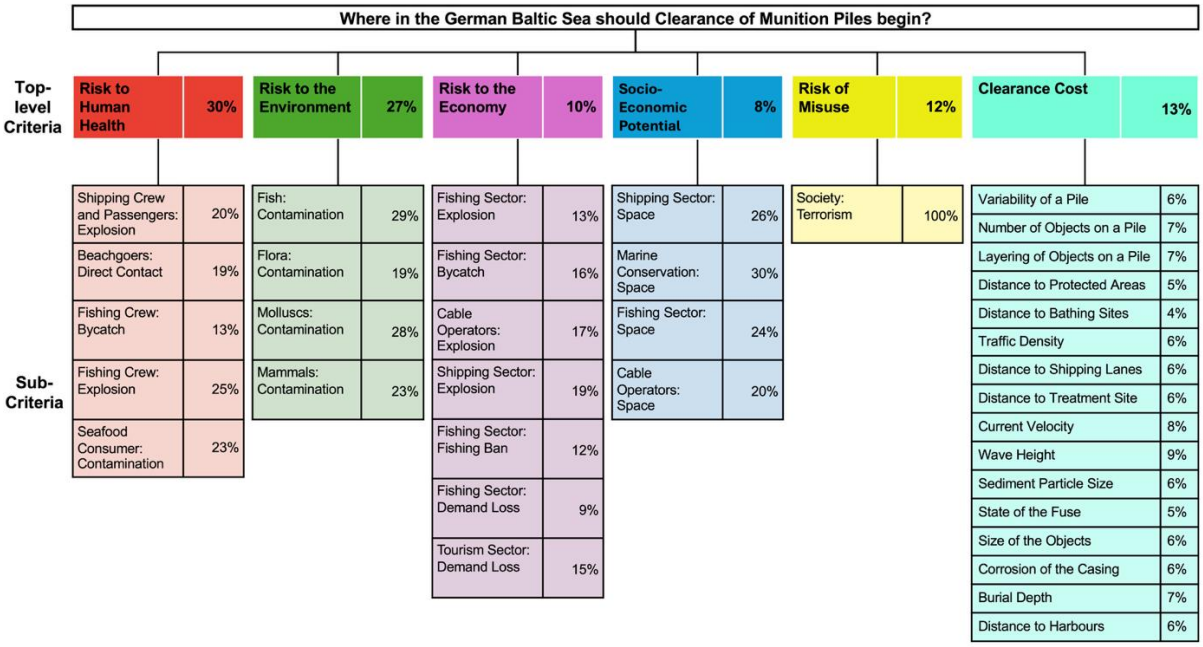
Six top-level criteria were identified by stakeholders to prioritize munition piles for clearance (Fig. 3a). These comprise i) Risk to Human Health, ii) Risk to the Environment, iii) Risk to the Economy, iv) Risk of Misuse from leaving piles uncleared, v) Socioeconomic Potential following clearance, and vi) Clearance Cost.

The sub-criteria for each top-level criterion represent the individual risks and opportunities that experts considered sufficiently relevant for determining the respective top-level criteria (Fig. 3a). The sub-criteria under Risk to the Environment, for example, address contamination risks but not environmental effects of possible explosions, because the negative consequences were not considered significant enough to outweigh the low probability of explosions. Explosion-related risks were nevertheless considered relevant to Risk to Human Health and Risk to the Economy, because their potential consequences were considered too severe to omit. More generally, similar but distinct risks occur under multiple top-level criteria. For example, risks related to fishing and shipping contribute to Socioeconomic Potential, Risk to Human Health and Risk to the Economy. Individual top-level criteria also comprise several related but distinct risks. For example, fishing-related risks under Risk to the Economy include those arising from fishing bans, loss of demand, bycatch and potential explosions of munitions. Risk of Misuse was represented by a single sub-criterion covering the risk to society from terrorism, the only misuse-related concern considered sufficiently substantial for inclusion. Clearance Cost was subdivided by munition-clearance experts into 16 sub-criteria describing site and munition characteristics.

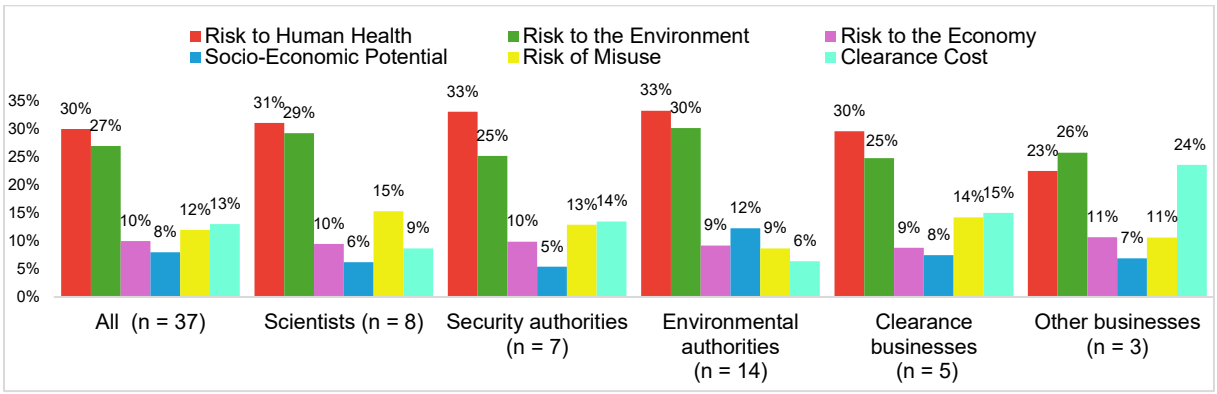
See our criterion descriptions (Supplementary Text 1) for definitions and detailed descriptions of each top-level criterion and sub-criterion, including their indicators.

Fig 3.

a



b



(a) Hierarchy of criteria used to prioritize munition piles for clearance in the German Baltic Sea and the weights elicited from stakeholder and expert for each criterion. For the top-level criteria, the weights express the aggregated stakeholder preferences of all stakeholder groups. For the sub-criteria, the weights express expert knowledge about the relative importance of each sub-criterion in causing its top-level criterion.
(b) Mean weights assigned to each top-level criterion by all stakeholders and by stakeholder group. Higher values indicate greater perceived importance of the respective risk, opportunity, or cost, and n indicates the number of stakeholders.

Step 2: Stakeholder-based weights for the top-level criteria

The aggregated stakeholder weights for the six top-level criteria (Fig. 3a) show that the societal preference lies on human health and the environment when prioritizing munition piles. Clearance Cost has the third highest weight, suggesting that financial viability is a relevant determinant for actors. Risk of Misuse was viewed as similarly relevant, reflecting concerns about the potential re-purposing of munitions for terrorism.

Weights disaggregated by stakeholder groups (Fig. 3b) show a rough overall agreement in preferences between groups. Most groups prioritized risks for human health and the environment. This finding indicates that the use of aggregated weights is appropriate, as it

suggests that the resulting priority lists would be supported by a majority of stakeholders. The small deviations in preferences between groups illustrate that organizational roles influence the weighting of risks and opportunities and point to potential conflicts among stakeholder groups. Businesses, no matter if they are related to munitions clearance or not, assigned greater importance to Clearance Cost than other groups. In contrast, environmental authorities, security authorities, as well as scientists, prioritized risks for human health and the environment while assigning relatively low weights to other criteria. The environmental authorities group also placed a higher value on Socioeconomic Potential than other groups, which includes the opportunity of using cleared areas for marine conservation.

Step 3: Expert-based weights for the sub-criteria

For the top-level criterion of Risk to Human Health (Fig. 3a), experts emphasized risks that could result in either severe immediate consequences, such as explosions, or long-term impacts, such as contamination affecting seafood safety. More likely but less harmful risks, such as health impacts from direct contact with munitions for beachgoers or fishers, were classified as less important.

For the top-level criterion of Risk to the Environment, all sub-criteria concerned contamination risks by explosive compounds such as trinitrotoluene (TNT) and its derivatives. Risk for fish and mollusks received the highest weights. Risks to mammals and flora were weighted lower; for mammals, experts cited limited contamination to date.

Sub-criteria for the top-level criteria of Risk to the Economy and those for Socioeconomic Potential were each weighted relatively evenly. This pattern reflects uncertainty about sector-specific risks and about the uses of newly available space.

Two sub-criteria under Risk to the Economy, concerning demand losses in the fishing and tourism sectors, lacked suitable indicators. Because experts identified these risks as relevant during the SPRC workshops and assigned them weights similar to those of the other sub-criteria, we included them in the model with indicator values set to zero.

Step 4: Priority list of munition piles

Our index tool identifies a set of 10 high-priority piles in the Pelzerhaken dumpsite that are recommended for clearance (Table 1; see Extended Data Table 1 for the full priority list). The ten top-ranked piles stand out with a noticeably higher clearance priority score [0.3 points gap between the piles ranked 10th and 11th] than the rest of the piles. These 10 piles are also characterized by a narrow range of scores [1.0 points on the 0–10 scale]. The narrow range also reflects the dataset's small geographic distribution and the limited resolution of some of the input layers, such as some fish and mollusk contamination samples, which are used for multiple piles. As all top piles are located in Pelzerhaken, this indicates that site-specific conditions drive both risk and potential, suggesting the effectiveness of area-based clearance strategies and the value of analyzing munition piles in spatial proximity to each other.

Pile ID	Rank	Clearance Priority Score	Risk to Human Health	Risk to the Environment	Risk to the Economy	Socio-economic Potential	Risk of Misuse	Clearance Cost
Pzh009	1	5.10	5.47	3.03	2.57	7.60	7.45	6.66
Pzh066	2	5.08	5.64	3.03	2.74	7.60	6.79	6.63
Pzh266	3	5.04	5.43	3.03	2.58	7.60	7.29	6.46
Pzh032	4	4.38	3.69	3.95	1.01	6.18	6.62	6.13
Pzh219	5	4.37	3.51	3.95	0.83	5.86	7.25	6.17
Pzh222	6	4.28	3.44	3.95	0.86	5.74	6.71	6.21
Pzh221	7	4.26	4.33	3.03	2.08	6.20	6.58	4.91
Pzh200	8	4.18	3.41	3.03	1.42	6.38	6.51	6.78
Pzh269	9	4.15	3.28	3.03	1.31	6.10	6.71	6.89
Pzh202	10	4.10	3.45	3.03	1.46	6.31	6.40	6.23
Kbh001	11	3.80	2.94	3.63	1.31	3.38	6.79	5.30
Haf320	12	3.56	1.62	4.29	0.42	1.19	7.55	6.37
Haf323	13	3.51	1.75	4.29	0.51	0.65	7.71	5.74
Pzh037	14	3.49	3.04	1.77	1.29	4.80	6.65	5.90
Pzh241	15	3.47	2.85	1.77	0.95	5.12	7.05	5.82

Table 1 Clearance priority scores and scores for all six top-level criteria of the top 15 munition piles ranked highest by clearance priority scores. The clearance priority scores and the top-level criteria scores can theoretically range from 0 to 10. For the top-level criterion Clearance Cost, higher scores indicate lower expected clearance costs, i.e. greater priority for clearance from a cost perspective. Table cells are color coded according to the quartiles of the scores of all piles, ranging from red (highest value), over white (median) to blue (lowest value). The interquartile-range rule was applied to the clearance priority scores for all piles. Scores more than 1.5 times the spread of the middle 50% of scores above the third quartile were flagged as upper outliers; the resulting threshold was 5.00. Pile IDs indicate locations in the dump sites: Kbh = Kolberger Heide (Kiel Fjord), Pzh = Pelzerhaken (Lübeck Bay), Haf = Haffkrug (Lübeck Bay).

Among the top ten piles, three munition piles clearly emerge as priorities for clearance, because these stand out as upward outliers based on the interquartile range (IQR) rule and rank highest across almost all top-level criteria. They fall into the top quartile for Risk to Human Health, Risk to the Economy, and Risk to the Environment, as well as for Socioeconomic Potential.

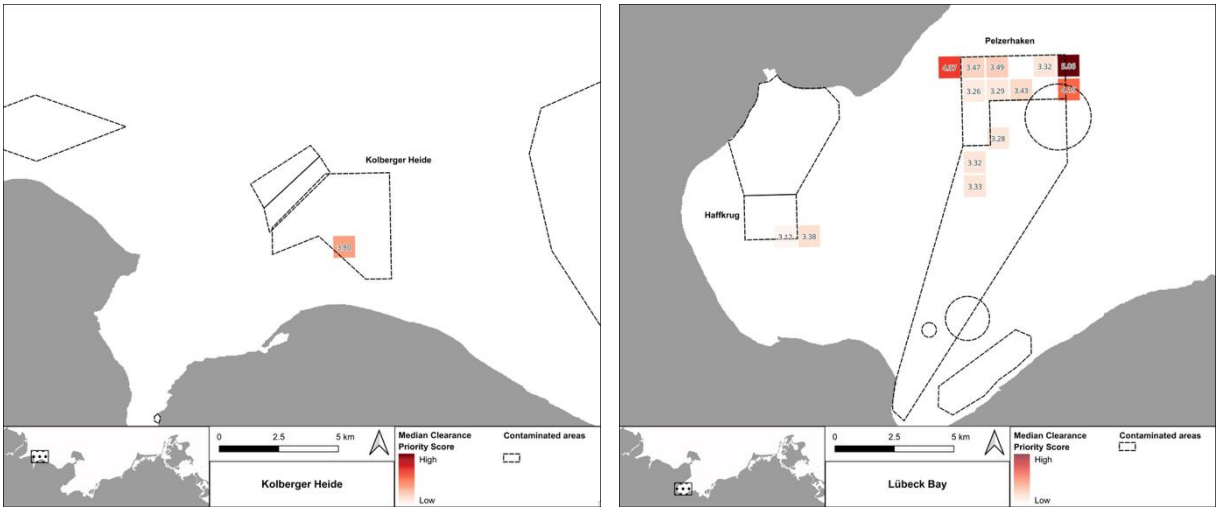


Fig. 4 Map of Kolberger Heide (left) and Lübeck Bay (right) showing median clearance priority scores of munition piles in a 1 km² grid. The dotted lines delineate the officially recognized munition contamination zones. For security reasons, exact coordinates of pile locations are not disclosed.

The geography of the prioritized munition piles (Fig. 4) reveals that the surroundings of the Pelzerhaken dumpsite is the primary hotspot, where most high-priority grid cells are located. Several high-priority cells are located outside officially recognized contaminated zones[5], suggesting that current boundaries may miss areas of greatest concern. An explanation could be the higher human activity outside the zones (which drives the clearance priority score). In these areas there are no restrictions on anchoring, fishing, shipping as there are in official zones.

Step 5: Stakeholder- and expert-based policy recommendations

We used our results to identify five policy recommendations together with the participants in the co-evaluation workshop. First, the ten highest-ranked piles should be used as the starting point for operational planning. German authorities confirmed the use of our study for informing the sequence of clearance. Participants also emphasized the merit of combining our results with additional operational information. For example, clearance firms should consider their experience with specific munition types and seasonal weather conditions when selecting among high-priority piles. Second, clearance campaigns should target areas with high median clearance priority scores to improve logistical efficiency. Third, the official munition contamination zones should be periodically re-evaluated to reflect new findings on munition locations. Fourth, additional data should be collected during clearance operations, including data on burial depth, fuze type, corrosion state, and munition integrity, in order to improve future applications of the tool. Fifth, a coordinated long-term monitoring program should be implemented to expand spatial coverage of munition-related contamination of water, flora, and fauna.

Discussion

Experiences gained from applying the co-creation process

Our results show how calls for inclusive and transparent decision-making[20,21] can be operationalized through a co-created prioritization index. In addition to condensing different risks, opportunities and costs into a single score per alternative, our process made the index

components and their aggregation transparent. It therefore produced information that supported interpretation and implementation of the resulting priority list. Instead of eliciting information from only experts or only from stakeholders, or not differentiating between them, our two-level weighting structure distinguished stakeholder preferences from expert assessments. This structure allowed us to examine where stakeholder preferences converged or diverged and how experts assessed different risks and opportunities. Our use of the Source–Pathway–Receptor–Consequence model to select indicators added a further layer of transparency by showing how available spatial data represented specific causal chains and where missing information required more indirect measures. These results suggest that the process provides more than a ranking. It creates a basis for discussing priorities, comparing trade-offs and identifying where additional information could most improve future decisions.

Applicability of the index to munition clearance in other contexts

Beyond supporting the first systematic clearance of sea-dumped munitions, MCA-DuMP can be applied in other contexts. Towards this end, the index's hierarchy of criteria and sub-criteria can be retained, while indicators of the sub-criteria can be adapted to the new context, in line with a context-based, goal-oriented and interactive form of knowledge co-production[34]. The SPRC model can thereby guide the selection of indicators so that the most relevant and reliable data available in the new context are used. In any case, stakeholders need to be involved to elicit new weights for the top-level criteria to reflect normative differences in interests. Expert weights for the sub-criteria may need to be reviewed to determine whether differences in the biophysical conditions of the application site require a new elicitation.

Applicability of the co-creation process to other sustainability governance issues

Beyond the MCA-DuMP index itself, the co-creation process presented here can be applied to other sustainability governance issues characterized by limited scientific information, diverse stakeholder interests, and the need to make prioritization decisions in the face of diverse risks, opportunities, and costs. These conditions are common in environmental restoration, where knowledge about degraded ecosystems must be translated into decisions about where and how to act. Potential applications beyond sea-dumped munitions management include zoning for offshore wind farm development, aquaculture siting, establishment of protection zones, carbon capture and storage, and the prioritization of legacy contamination from boreholes, chemical weapons, wrecks, or industrial dumping. Some of these issues involve greater conflict over objectives than in the issue of sea-dumped munitions. In the munitions case, there is broad support for clearance[12], whereas offshore wind development[35] or aquaculture[36] often involve more polarized views. In these cases, stakeholder elicitation becomes particularly important because it helps anticipate future conflict, creates trust, and builds political support for the use of prioritization results. In any case, when applying the co-creation process to similar sustainability governance issues, it must be adapted on a case-by-case basis. The problem definition and local setting should determine the criteria, their indicators and weighting procedures.

Limitations

While the co-creation process is designed to support decision-making under diverse stakeholder interests and limited scientific information, it cannot eliminate these challenges, which therefore shape how the results should be used. The participating stakeholders may not represent all actors affected by munition clearance, and some relevant preferences may

therefore be absent from the process. We sought to reduce this risk by inviting all stakeholder groups identified during the co-design phase and by asking participants to identify additional groups that should be involved. Nevertheless, we cannot exclude the possibility that some relevant actors were not identified or did not participate. In addition, some stakeholder groups were represented by more participants in the workshops than others. We addressed this imbalance by assigning equal weight to each stakeholder group. This procedure gives each group equal influence, but it does not give each individual participant equal influence. A group with few participants therefore contributes the same aggregate weight as a larger group. The resulting weights should consequently be interpreted as a structured representation of the participating groups' preferences, rather than as a representative measure of preferences across all affected actors.

Limited scientific information constrains the index because some indicators are based on data with a relatively small number of observations. For example, some fish and mollusk contamination measurements are used for multiple piles, which reduces spatial variation in these indicators. Limited observations can lead to smaller differences in scores among piles, making prioritization more difficult. We supplemented the available spatial data with expert knowledge when selecting and weighting indicators, so that the assessment did not depend solely on the limited observations. However, this approach cannot create spatial variation where several piles receive the same indicator value. The resulting priority scores should therefore be interpreted as support for identifying broad priorities and spatial patterns, whereas small differences between neighboring piles should be interpreted cautiously.

Future research

Future research should investigate how to create priority lists for piles for which locations are known or suspected but for which detailed information on munition properties is unavailable. Such an index could draw on historical records, documented munition encounters, and typical pile features identified through existing[37] or future research to predict size, number, variability and layering of objects on a pile. Similarly, data on water temperature, sediment type and current velocity could be used to predict the corrosion of the casing and the burial depth of objects on a pile.

In addition, future research should improve existing sub-criteria by increasing the number and geographic distribution of observations for existing indicators and by collecting data for new indicators that measure risks and opportunities more directly. Our correlation analysis identified strong relationships among sub-criteria, reflecting that some sub-criteria describe distinct risks or opportunities but rely on the same or similar indicators (see Supplementary Table 1 for an overview of indicators per sub-criterion; see Supplementary Tables 3–7 for correlation calculations and Supplementary Text 2 for analysis). For instance, future research could compile spatially explicit records of bycatch events to replace fishing intensity as the indicator for the risk of bycatch. This would help distinguish the risk of bycatch from the risk of explosion for fishing crews, which is also partly represented by fishing intensity.

Future research should also develop indicators for the two sub-criteria concerning demand loss that were included in the hierarchy but assigned indicator values of zero because suitable data were unavailable. For the fishing sector, fishing intensity could represent the fishing activity that could be affected by restrictions, while information on the amount of explosive material and condition of munitions could help estimate where contamination related restrictions are more likely. For the tourism sector, the number of nights spent by tourists in each municipality could indicate the level of tourism activity and help assess potential losses in demand associated with contamination concerns.

Methods

We implemented the MCA-DuMP tool through a structured co-creation process combining stakeholder preferences, expert knowledge, and spatial data within the AHP (Fig. 2). To ensure relevance and legitimacy, we implemented the co-creation process through a sequence of workshops with stakeholders and experts (see Extended Data Table 2 for an overview of all workshops). The following subsections describe each step of the co-creation process.

Step 1: Co-Design of the Hierarchy of Criteria and Criteria Indicators using the SPRC model

We started with an initial co-design workshop with 26 stakeholders to co-design the problem definition and generate an initial list of criteria. The decision problem was defined as "Where in the German Baltic Sea should clearance of sea-dumped munitions begin?". Focusing on munition *piles* rather than individual munition *objects* reflected the greater efficiency of planning clearance for multiple nearby objects together rather than for individual objects. Focusing on munition *piles* rather than entire dump *sites* reflected both the available data resolution and the desired operational flexibility of clearance activities. This way, the resulting model produces actionable prioritization results and is not limited to strategic recommendations at a larger spatial scope.

The initial list of criteria was created by splitting participants into breakout groups presenting them with an initial hierarchy of criteria, which had been developed by the research team based on their prior knowledge, literature review, and project goals. The participants provided feedback on the relevance of the proposed criteria, which were then refined and adjusted accordingly in preparation of the next phase.

Next, we conducted seven SPRC-workshops designed to identify and refine sub-criteria and to gather expert input on suitable data sources to quantify them. Together, the workshops involved over 30 experts from environmental organizations, universities, the private sector, and governmental bodies. Each workshop followed a structured set of questions for each sub-criterion:

1. Is this criterion relevant for prioritization?
2. What data is needed to quantify the sub-criterion?
3. What data is available?
4. Is the data available for individual munition piles or whole dumping sites?

Answers to these questions informed the development of an SPRC-based data selection index (Supplementary Table 2). The index includes all data sources for each sub-criterion identified through the workshops and additional research, categorizing them according to their position in the SPRC causal chain (Fig. 2b). We prioritized those indicators and data that are closest to the *consequence* level of the SPRC, i.e. data that are closest to representing the risk end point. Where consequence-data were not available, receptor-data were used. If also no receptor data was available, we selected pathway- or ultimately resorted to source data or combinations thereof (see Supplementary Table 1 for an overview of indicators per sub-criterion).

To ensure traceability and transparency, we developed detailed criterion descriptions for each sub-criterion (Supplementary Text 1). These include criterion's definition, its SPRC causal chain, source, spatial and temporal coverage, value range, processing steps, and selected indicators.

Step 2: Co-Development of top-level criteria weights using stakeholder preferences

We conducted three weighting workshops in which 37 stakeholders completed a survey to assign weights to the top-level criteria (see Supporting Files 1 in the MCA-DuMP repository for the calculations: https://git.geomar.de/open-source/mca-dump). In this survey, stakeholders evaluated the top-level criteria from a normative perspective. Participants were instructed to provide their opinion on how important they believed the different top-level criteria should be. Specifically, participants made pairwise comparisons between the top-level criteria using the standard AHP 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance of one criterion over another[18].

We transformed the responses for analysis using the balanced-n scale. This scale ensures more even spacing of local weights across all comparisons, correcting for known distortions in the standard AHP scale, which tends to overweight stronger preferences[38]. The transformation produced reciprocal pairwise comparison matrices from which we derived weights using the geometric mean, which is mathematically equivalent to the eigenvector method for consistent matrices and is less sensitive to small inconsistencies[39].

Following Wind & Saaty[40], we evaluated consistency ratios (CR) for pairwise comparison matrices of all participants individually. We used an eigenvector calculation to assess the internal coherence of each respondent's answers. While a CR below 0.1 is typically considered acceptable, we adopted a threshold of 0.2 as tolerable in line with Wedley[41], who notes that such values are acceptable for larger matrices and applied settings where perfect logical consistency is difficult to achieve.

We offered a revision opportunity if a participant's consistency ratio exceeded the threshold of 0.2 but did not exceed 0.5. Responses whose consistency ratios exceeded 0.5 were excluded from the calculation. To identify possible revisions, we used the Excel-based analytical hierarchy process template described by Goepel[42]. The template calculates priorities and consistency indices from pairwise comparison matrices and highlights the three most inconsistent pairwise comparisons. We used this information to identify one proposed adjustment for each affected participant. Affected participants were presented with these adjustments and gave their approval. We only applied changes if the direction of preference remained the same, i.e., if criterion A continued to be considered more important than B. This ensured that revised responses respected participants' original judgments while increasing mathematical reliability.

After validating the consistency of all responses, we calculated the final weights. We classified stakeholders into groups reflecting their organizational roles and primary protection mandates: Scientists, Security Authorities, Environmental Authorities, EOD Businesses, and Other Businesses. This structure distinguishes between knowledge providers, regulatory bodies with different protection mandates (safety vs. environment), and private actors directly (i.e. Clearance Business) or indirectly (i.e., Other Businesses) affected by clearance activities. We first averaged responses within each stakeholder group and then calculated the overall weights by averaging across groups to ensure equal representation, regardless of group size. This was done to eliminate a bias towards scientists and environmental authorities, who were overrepresented during the weighting workshops (see Figure 3b for participants per stakeholder group).

Step 3: Co-development of sub-criteria weights using expert knowledge

Similar to the elicitation of top-level criteria weights from stakeholders (Step 2), we used the AHP to elicit weights from experts for the sub-criteria representing individual risks and opportunities (see Supporting Files 1 in the MCA-DuMP repository for the calculations). While

the same comparative logic and calculation procedure were used in both the stakeholder and expert surveys, the final weights were calculated differently. In the expert survey, experts were assigned to top-level criteria according to their expertise and asked to weight the respective sub-criteria from a descriptive, causal perspective. Only participants who agreed that they had sufficient expert knowledge on a given criterion were asked to complete the survey. Experts were instructed to compare the relative contribution of the sub-criteria to their respective top-level criterion. For the final weights, we calculated the simple mean of all expert responses per sub-criterion.

Step 4: MCA-DuMP Application

The fourth step consisted in collecting and processing the data for all criteria and sub-criteria, applying the index to calculate the clearance priority score for each pile and examining the correlations between the criteria, sub-criteria and clearance priority scores in order to assess the influence and potential overlap of model components.

Data Collection and Processing

We collected data from both the CONMAR project consortium and external sources, including the HELCOM Map and Data Service, Marine Data Infrastructure Germany, Spatial Data Infrastructure Germany and the GeoSeaPortal of the Federal Maritime and Hydrographic Agency. We reprojected all spatial data to the World Geodetic System 1984 / Universal Transverse Mercator zone 32N coordinate reference system (EPSG:32632) and clipped them to the German Baltic Sea study area. For the fishing intensity and fishing effort datasets, we summed annual values for each spatial grid cell to represent total fishing activity and effort over the 2016–2021 observation period.

Photomosaics, which are composite visual records assembled from many underwater photographs, were used to generate data on pile properties for 39 piles[37]. Four experts visually assessed each photomosaic for the state of the fuse, the state of corrosion of the casing, the burial depth, the layering of objects and the variability of objects on a pile. Three experts annotated each photomosaic by counting the number of objects and measuring their size. The expert ratings and annotations were averaged and assigned to each pile.

We calculated the Clearance Cost score for each pile using a direct weighting method developed within the CONMAR project[43], rather than the AHP-based weighting procedure applied to the risk- and opportunity-based criteria. The Clearance Cost criterion captures the relative resource intensity of investigating and clearing a given munition pile. We identified an initial set of potential sub-criteria by drawing on the German framework for land-based munition clearance[44] and adapting it to the marine context. Five representatives of munition-clearance companies then assessed this set and contributed to the selection of the 16 sub-criteria retained for the German Baltic Sea. The participants individually indicated the relevance of the 16 sub-criteria for the clearance cost leading to a score ranging from 0 to 4 across five dimensions. These comprised the two applicable explosive ordnance disposal phases, investigation of target points and munition clearance and disposal[45], as well as personnel costs, equipment costs, and processing time. In doing so, practitioners could assign scores directly according to each sub-criterion's expected influence on clearance-resource intensity rather than compare the relative importance of every pair of sub-criteria. We summed the scores for each sub-criterion across the five dimensions and normalized the resulting totals to produce weights that sum to 1 (see Supporting Files 1 in the MCA-DuMP repository for the calculation). We applied these weights to the corresponding sub-criterion indicators for each pile and aggregated the weighted values into one Clearance Cost score per pile (Table 1; see Supplementary Text 1 for technical details, including the sub-criterion definitions and weights).

We oriented the indicator values so that lower expected clearance costs received higher scores. This orientation reflects the role of the criterion in the prioritization index. Piles with lower expected clearance costs should receive higher priority from a cost perspective. For example, higher current velocity is expected to increase clearance costs. We therefore assigned higher scores to piles with lower current velocity.

Calculation of the scores

The index scores were calculated by implementing MCA-DuMP as linked geoprocessing steps within QGIS (v 3.30) Graphical Modeler. Each top-level criterion and its sub-criteria were implemented in a separate QGIS project with a corresponding model file. An additional convergence model combines the resulting top-level criteria scores into a clearance priority score. In total, seven models were created (see the MCA-DuMP repository for access to all models and data layers).

The main inputs to the model were the locations and properties of the munition piles. We organized the indicator datasets according to the top-level criteria whose sub-criteria they measure. The graphical model processes these inputs step-by-step extracting the values from raster (e.g. shipping density, current velocity) or vector (e.g. contamination, fishing intensity) layers and normalizing the resulting sub-criterion scores to a 0–10 scale. These results are saved as spatial data layers, allowing them to be visualized or combined in the convergence model to produce the clearance priority scores.

We also calculated median scores per spatial grid cell, which contain multiple piles. This enables the production of a public map, since individual pile locations cannot be disclosed for security reasons. We used the median rather than the mean because a single unusually high or low pile score could otherwise disproportionately affect the value assigned to a grid cell. The median therefore provides a robust summary of the clearance priority scores within each grid cell while preserving the overall spatial pattern of the results.

Correlation analysis

We conducted a correlation analysis to understand how the criteria were related and how closely each criterion was associated with the prioritization outcomes (see Supporting Files 2 in the MCA-DuMP repository for the calculations). The analysis was based on the scores calculated for each munition pile across all criteria layers.

To determine the appropriate correlation measure, we first applied the Shapiro-Wilk test to assess whether top-level criterion and sub-criterion scores are normally distributed[46]. Since none of the top-level or sub-criteria followed a normal distribution, we used Spearman's rank correlation coefficient throughout[47,48].

The analysis was structured around four objectives. First, we calculated correlations between each top-level criterion and clearance priority scores. This helped identify which top-level criteria were most closely associated with the clearance priority scores.

Second, we calculated correlations among all top-level criteria. This helped assess whether they captured sufficiently distinct aspects of the decision problem to be treated as separate decision factors. Pairwise correlations above 0.8 were considered indicative of critical collinearity[49,50].

Third, we calculated correlations between each sub-criterion and its respective top-level criterion. This helped identify which sub-criteria were most closely associated with their respective top-level criterion.

Fourth, we calculated correlations among all sub-criteria under each top-level criterion. This helped identify potential data needs. Some sub-criteria represent related but distinct risks

or opportunities. Their scores may nevertheless be highly correlated when they depend on the same or similar indicators, particularly where scientific information is limited.

Step 5: Co-Evaluation of results and policy recommendations

The final step involved a co-evaluation workshop with 42 stakeholders including practitioners, authorities, scientists, munitions specialists and experts to assess the plausibility of the prioritization results and the usability of the MCA-DuMP tool. Participants were presented with the prioritization outcomes, the underlying model logic, and the resulting policy recommendations.

Feedback from this co-evaluation informed the interpretation of the results in the main text of this article and helped identify opportunities for future refinement of the MCA-DuMP tool, including needs for additional data collection and monitoring. No changes were made to the weights or the model structure at this stage; rather, the workshop served to validate the applicability of the tool and evaluate the robustness and relevance of the generated recommendations.

Data availability

The data and processing files used in this study are available through the MCA-DuMP repository at https://git.geomar.de/open-source/mca-dump/. The repository contains the QGIS models and linked QGIS projects used to calculate criterion scores and clearance priority scores, the calculation files for the stakeholder- and expert-based weights, the calculation files for the correlations and accompanying documentation. Processed input data are provided where redistribution is permitted by the licenses of the original data providers. The inventory and recorded characteristics of the munition piles used in this study are available through the PANGAEA dataset *Munition pile inventory in the German Baltic Sea, 2017–2024*, https://doi.org/10.1594/PANGAEA.988426. Geographic coordinates of individual munition piles are not made available for security reasons. Other third-party datasets remain subject to the access conditions and licenses of their original providers.

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Extended Data

Pile ID	Rank	Clearance Priority Score	Risk to Human Health	Risk to the Environment	Risk to the Economy	Socio-economic Potential	Risk of Misuse	Clearance Cost
Pzh009	1	5.10	5.47	3.03	2.57	7.60	7.45	6.66
Pzh066	2	5.08	5.64	3.03	2.74	7.60	6.79	6.63
Pzh266	3	5.04	5.43	3.03	2.58	7.60	7.29	6.46
Pzh032	4	4.38	3.69	3.95	1.01	6.18	6.62	6.13
Pzh219	5	4.37	3.51	3.95	0.83	5.86	7.25	6.17
Pzh222	6	4.28	3.44	3.95	0.86	5.74	6.71	6.21
Pzh221	7	4.26	4.33	3.03	2.08	6.20	6.58	4.91
Pzh200	8	4.18	3.41	3.03	1.42	6.38	6.51	6.78
Pzh269	9	4.15	3.28	3.03	1.31	6.10	6.71	6.89
Pzh202	10	4.10	3.45	3.03	1.46	6.31	6.40	6.23
Kbh001	11	3.80	2.94	3.63	1.31	3.38	6.79	5.30
Haf320	12	3.56	1.62	4.29	0.42	1.19	7.55	6.37
Haf323	13	3.51	1.75	4.29	0.51	0.65	7.71	5.74
Pzh037	14	3.49	3.04	1.77	1.29	4.80	6.65	5.90
Pzh241	15	3.47	2.85	1.77	0.95	5.12	7.05	5.82
Pzh155	16	3.43	2.75	1.77	1.29	3.25	6.47	7.13
Pzh108	17	3.35	2.14	1.57	0.98	6.40	6.46	6.69
Pzh002	18	3.33	2.62	1.59	1.48	3.35	6.40	6.95
Pzh107	19	3.33	2.15	1.57	0.99	6.40	6.47	6.52
Pzh012	20	3.33	2.70	0.85	1.46	5.92	7.01	6.15
Pzh109	21	3.33	2.18	1.57	1.15	6.46	6.20	6.53
Pzh192	22	3.32	2.61	1.59	1.49	3.73	6.36	6.67
Pzh287	23	3.32	2.10	1.57	0.94	6.30	6.72	6.42
Pzh242	24	3.32	2.50	0.85	1.32	5.89	6.64	6.98
Pzh122	25	3.29	2.70	1.77	0.98	3.62	6.79	5.90
Pzh035	26	3.29	2.92	1.77	1.47	1.38	7.06	6.07
Pzh187	27	3.28	2.58	1.59	1.46	3.58	6.40	6.50
Pzh186	28	3.26	2.64	1.59	1.48	2.90	6.41	6.61
Pzh127	29	3.26	2.35	1.77	0.74	3.63	6.95	6.49
Pzh185	30	3.25	2.57	1.59	1.42	2.80	6.54	6.66
Pzh126	31	3.22	2.28	1.77	0.70	3.59	7.07	6.32
Haf319	32	3.20	1.66	2.72	0.43	1.53	7.60	6.46
Haf314	33	3.14	1.63	2.11	0.23	2.18	7.90	6.81
Haf332	34	3.14	1.68	2.11	0.27	1.99	7.98	6.70
Haf002	35	3.12	1.84	2.11	0.51	1.20	7.86	6.64
Haf324	36	3.12	1.83	2.11	0.46	1.75	8.05	6.19
Haf316	37	3.08	1.60	2.11	0.23	1.73	7.94	6.67
Haf315	38	3.07	1.73	2.11	0.35	1.72	7.92	6.25
Haf318	39	3.01	1.80	2.11	0.47	1.28	7.54	6.14

Extended Data Table 1 *Full list of clearance priority scores and scores for all six top-level criteria per munition pile ranked by clearance priority scores*

The clearance priority score and the top-level criteria scores can theoretically range from 0 to 10. Table cells are color coded according to the quartiles of the scores of all piles, ranging from red (highest value), over white (median) to blue (lowest value). The interquartile-range rule was applied to the clearance priority scores for all piles. Scores more than 1.5 times the spread of the middle 50% of scores above the third quartile were flagged as upper outliers; the resulting

threshold was 5.00. Pile IDs indicate location in dump sites: Kbh = Kolberger Heide (Kiel Fjord), Pzh = Pelzerhaken (Lübeck Bay), Haf = Haffkrug (Lübeck Bay).

Workshop Name	Focus Area	Number of Participants
Co-Design Workshop	Overview of MCA criteria	26
1st SPRC Workshop	Risks to flora, fauna & seafood consumers	3
2nd SPRC Workshop	Risks to flora, fauna & seafood consumers	6
3rd SPRC Workshop	Munition properties & human health risks	5
4th SPRC Workshop	Risks to maritime economy & potential of cleared areas	5
5th SPRC Workshop	Risks to maritime economy & potential of cleared areas	5
6th SPRC Workshop	Risks to maritime economy & potential of cleared areas	6
1st Weighting Workshop	Stakeholder preferences & Expert knowledge	12
2nd Weighting Workshop	Stakeholder preferences & Expert knowledge	19
3rd Weighting Workshop	Stakeholder preferences & Expert knowledge	6
Co-Evaluation Workshop	Evaluation of results and derived policy recommendations	42

Extended Data Table 2 *Overview of workshops conducted to implement the MCA-DuMP tool*

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.pdf