Complex risk management in explosive-contaminated areas: Explosive remnants of war

by

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Preface

The work presented in this PhD thesis has been funded by the Norwegian Defence Research Establishment (Forsvarets Forskningsinstitutt). The thesis is submitted in fulfilment of requirements for the degree of Philosophiae Doctor at the University of Stavanger, Faculty of Science and Technology, Norway.

This PhD project has involved research regarding societal safety and risk management related to explosive remnants of war (ERW). These are the millions of tonnes of explosive objects that may remain in nature for decades or even centuries after hostilities have ended. Even in a country such as Norway, for which a war has not been waged within its own territory for nearly eight decades, the explosive remnants still represent a grave threat. Not only do they represent an explosive risk, but there is also a risk that their toxic constituents could have a severe environmental impact. Shortly prior to the beginning of this project, we witnessed the potential destructive force of these munitions, as a buried 250 kg German WWII aircraft bomb spontaneously detonated under an aircraft hangar at the airport of Kirkenes in Northern Norway in 2019. Societal concerns have intensified regarding the potential dangers these explosive remnants represent. However, the extent of the problem and its inherent risks have not been properly examined.

In 2020, as The Norwegian Defence Research Establishment was devising the framework for a new project regarding mapping the locations and risks related to dumped ammunition and explosive remnants of war, I was approached by Research Manager Øyvind Voie and was asked if I was interested in completing a PhD program in this topic. I had previously completed a Master's programme in Social Sciences at NORD University, with the specialisation of Societal Security and Terrorism Studies, and I was highly motivated to continue my research. Furthermore, as a career officer in the Norwegian Armed

Forces with a comprehensive background in the area of explosive ordnance disposal (EOD), I believed that I could contribute to both the enhancement of societal safety as well as the development of this specific field of expertise within the Armed Forces. My current unit at the time, The Norwegian Ministry of Defence, was highly accommodating and supportive of the idea, allowing me to complete a three-year secondment as a researcher at The Norwegian Defence Research Establishment.

After carefully considering numerous doctoral programmes and after having meetings with several relevant universities, I finally decided to select the University of Stavanger and their reputable doctoral programme in Science and Technology – Risk Management and Societal Safety.

To conduct the research I viewed as necessary, I also required comprehensive support from several agencies within the defence sector. Particularly, the Norwegian Defence Research Establishment contributed funding, knowledge and excellent research facilities as well as knowledgeable colleagues.

The Norwegian Defence Estates Agency provided both locations and relevant explosive objects for high explosive samples, as did several entities of the Armed Forces, particularly The Garrison of Sør-Varanger. The Norwegian Joint Headquarters and the Norwegian Joint Logistics Support Group Headquarters provided me with critical access to unexploded ordnance wherever and whenever they appeared and permitted me to perform required sampling on relevant objects prior to their final disposal. The Armed Forces Joint Ammunition and EOD School provided me with immense insight and support as well as the mandatory authorisations and dispensations to collect the required high explosive samples.

I would like to express my deepest gratitude to my main supervisor and co-author, Professor Eirik Bjorheim Abrahamsen at the University of Stavanger, for his excellent guidance and support throughout the process.

His outstanding guidance, support and inspiration throughout both the required training component and the research component of the doctoral program have been vital, and for this, I am eternally grateful.

I am equally grateful toward my co-supervisor and co-author, namely Associate Professor Morten Sommer at the University of Stavanger. Your guidance and support, as well as your time and willingness to formulate a PhD plan around my ideas for required research, made my selection of a university substantially easier. Your positive attitude and critical questions have been both inspiring and motivating. I have highly enjoyed the guidance you have provided.

I also extend my deepest thanks to my co-supervisor, namely Research Manager Øyvind Voie at The Norwegian Defence Research Establishment. I would like to express my deepest gratitude for your support and advice and for introducing me to the opportunity to complete this PhD program.

I would also like to thank several individuals within the defense sector, particularly within the EOD community. Due to the particularities of their special profession, they shall, however, remain anonymous. Nevertheless, the men and women of EOD deserve our greatest gratitude, as they selflessly place themselves in harm's way at the risk of losing their lives in service of a greater good. Lest we forget the fallen who have made the ultimate sacrifice on behalf of our nation. May they never be forgotten. In the words of Thucydides, ‘The bravest are surely those who have the clearest vision of what is before them, glory and danger alike, and yet notwithstanding, go out to meet it’.

Finally, I would like to extend my gratitude to my fiancé Liv Kristin and to my children Falk Petter and Selja Victoria, the brightest lights of my life. I am looking forward to spending more time with you!

Oslo, January 2023

Summary

The primary goal of this PhD thesis is to contribute to the improvement of risk assessment and management in explosive-contaminated areas. In particular, the research objectives of the thesis relate to providing new perspectives regarding how to view and understand the complex nature of ERW risk. Additionally, by providing new knowledge and insight, this thesis aims to improve decision-making on a strategic, operational and tactical level.

The traditional view of ERW-related risk typically focuses on the explosive threat the munitions represent if they are disturbed. Despite widespread knowledge of the fact that ERW exist in great numbers across the world, there appears to be minimal focus on the fact that the munitions also represent a broader and more diverse risk. ERWs have the potential to impose severe damage to life, health, the environment critical infrastructure and resources that significantly exceeds any initial blast radius damage, thus representing a critical societal threat. As our current risk approaches are generally predicated upon traditional probability-based risk assessments that are not particularly well suited for assessing complex risks, our uncertainty and lack of knowledge related to ERW risk assessments will inevitably result in assessments that are excessively based on assumptions and overgeneralisations. For example, several strategic decisions have been predicated on the assumptions that ERW will become harmless over time and that they are generally not considered to be a major societal threat. There is, however, no evidence to support this idea, and based on recent scientific studies, there is a growing concern that the risks may be increasing.

To ensure judicious choices, the relevant decision makers require both correct and timely information. However, it appears that a substantial proportion of the information available regarding ERW-related risks is either erroneous or utterly deceptive. As ERW are constantly

deteriorating, there is a time window during which action must be pursued to mitigate the associated risks. Consequently, there is an urgent need to raise awareness regarding both the extent of ERW, the risks associated with them, and how these risks can be effectively mitigated. This thesis contributes to this end by providing knowledge regarding ERW and their inherent risks, the development of a risk mitigation strategy and how ERW-related risks are managed today. Furthermore, it demonstrates how inadequacies in our strategies and risk mitigation techniques can result in unrealistic, inefficient and unsafe ERW risk management and increased societal and environmental risks.

The scientific contribution of this thesis consists of five papers that have been either published or submitted for possible publication. The contents and contributions of the papers are briefly summarised below.

It has always been recognised that ERW could represent a certain explosive risk if disturbed and that some of the constituents in the ammunition could be harmful to the environment. Recent research has proven that the complex risks related to ERW are composed of numerous factors; whilst the most prominent factor is regarded as the risk of an explosion, there is also a severe risk of environmental contamination, the risk of the explosives being misused for criminal activity and the risk of political, economic and societal consequences. Nonetheless, a tacit assumption amongst decision makers is that ERW are generally not considered to pose a major societal threat and that, if left alone, the ammunition will become harmless over time. Paper I discusses how this strategy has evolved over time and how new knowledge and broader risk perspectives can provide further insights regarding how the strategy could be revised. Furthermore, the paper explains how ERW-related risks could intensify rather than diminishing over time and that our current risk management strategy could prove to exacerbate the risk rather than mitigating it. As time elapses, the munitions will become increasingly less identifiable, and their chemical and technical conditions will become increasingly indeterminate, thus dramatically limiting the number of potential available risk-mitigating actions. The conclusion of this investigation is that on the basis of improved risk assessments highlighting the complex risk picture and the strength of the current knowledge, there is an urgent need to revise the current risk mitigation strategy.

There are several challenges related to assessing ERW-related risk; one pertains to the level of uncertainty as a result of not only complexity but also the lack of knowledge and relevant or available data. Events that seldom occur and events for which we have highly limited historical reference material are particularly difficult to assess from the traditional technical perspective regarding risk (e.g. a mathematical calculation of an assigned numerical value of probability (P), multiplied by an assigned numerical value that represents a given consequence (C), leading up to the formulation of Risk (R) = P x C). To make informed decisions, we must therefore map the uncertainty in risk assessments by utilising applicable and relevant methodology. Paper II outlines some of the particularities that differentiate risk assessments regarding unexploded ordnances from other, more familiar, types of risk assessments and discusses whether the current methodology can be considered relevant and appropriate. Furthermore, it discusses and illustrates how the current risk assessment methodologies we use today are principally unsuitable for this use; they are also sometimes ambiguous, inconsistent and incompatible, particularly as they do not include an evaluation of background knowledge and associated uncertainties. The conclusion of the paper is that the studied risk assessment methodology urgently needs to be revised to improve the decision-making framework in non-time-critical situations when assessing risks characterised by a high level of complexity and uncertainty (i.e. ERW).

The most prominent risk related to ERW is that of an unplanned explosion. Such an explosion could occur as the result of an intended act of terrorism or crime, utilising the explosive effect of high explosive munitions or harvested explosives from such; it could also occur accidentally as a result of the intentional or unintentional disturbance of the ordnance (e.g., construction work, moving, disposing of or rendering safe ammunition). An increasing number of spontaneous detonations have also been reported in ageing munitions, possibly resulting from deteriorating technical or chemical properties. However, only a very limited number of studies have analysed the properties of high explosives retrieved from ageing ERW. Paper III contributes new knowledge to the field of aging explosives, demonstrating that they are still in working condition and that their impact sensitivity does not appear to have been reduced over the last eight decades. Consequently, it disproves the claim that ammunition will slowly become harmless over time, thus providing ERW risk assessors and decision makers with vitally important information regarding aging munitions.

Systems thinking can be characterised as a conceptual framework for viewing interactions and the whole system rather than isolated parts of the system; the basic concept is that an understanding of the ‘why’ and ‘how’ of a phenomenon requires an understanding of the system or context. Paper IV discusses the importance of having a systems approach in ERW risk management, especially when introducing factors that could act as limitations in the system, such as regulations, procedures and instructions. The papers illustrates that without adopting a systems thinking approach, we may end up implementing safety measures and requirements without the effects intended; in the worst cases, the effects can even prove to be negative due to unforeseen negative side effects. Moreover, the lack of a systems approach results in an excessively complicated and bureaucratic intergovernmental process, unclear responsibilities and absent strategic guidance, resulting in a sub-optimal use of both human and economic resources. Paper IV therefore suggests an improved approach to gain better insight into the complexities of managing the risks related to ERW and to better prioritise resources allocated to mitigating this threat; this is expected to result in greater economic efficiency and a more favorable cost-to-benefit ratio.

These ERW represent a grave threat in many respects, and the human, societal and environmental impacts can be severe. These potentially lethal explosive objects must therefore be located and disposed of, which in itself involves serious risks. Therefore, various safety measures are continuously implemented to mitigate these risks. Some safety measures, however, could prove to have less than the desired effect, and in the worst cases, some could even increase the risk for both the EOD operator and society at large. Paper V discusses one of these safety measures, namely removing the option to blast-in-place when clearing ERW, and its unintended and potentially risk-increasing consequences.

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Part I

1 Introduction

1.1 Background

Risk analysis and risk management are vital aspects of everyday life throughout society. It is something we do all the time, as we assess what risk means, what it encompasses and how it is expressed and understood, and we construct systems in which we balance various aspirations and requirements and the avoidance of undesirable outcomes. Generally, decision-making processes are not excessively complicated, as the risks involved are usually manageable. However, if a risk is complex or the consequences could be severe, the optimal choices are not always obvious. In addition, if the risk picture is multifaceted, and if one accounts for factors of uncertainty and the element of surprises and black swans, the traditional probability-based paradigm will encourage an excessively narrow approach to most risk and uncertainty assessments (Aven, 2014). The consequences could be that decisions are highly misguided if important aspects of risk and uncertainty are concealed, omitted or inadequately described. A failure to understand the importance of the complexity and uncertainty of risk can ultimately lead to increased risk and, in extreme cases, injuries and loss of life.

Situations such as these, which also involve unidentified factors that could influence the outcomes of our actions and the potential for immense losses, require a broader, more holistic approach towards risk, as applying a more traditional risk management model to this problem would entail significant shortcomings and sub-optimal solutions (Olsen, Juhl, Engen, & Lindøe, 2020). In these types of situations, the ramifications of misguided risk decisions may prove to have consequences of much larger proportions then intended or estimated. In some situations, the risks may be overlooked or misinterpreted, which can result in accidents that could impact hundreds or even thousands of people, sometimes even with catastrophic humanitarian, environmental and economic consequences.

When dealing with colossal amounts of energetic materials, such as dumped ammunition and explosive remnants of war (ERW), there is always the potential for unintended explosions of large-scale proportions. For example, in 2021 alone, over 5,500 casualties from mines and other ERW were recorded; civilians represented most of the victims recorded, half of whom were children (United Nations, 2022). There are, however, also a disturbingly high number of singular incidents of immense proportions involving unplanned explosions at munition sites. For example, the explosion that occurred in Lagos, Nigeria on January 27th, 2002 caused a total of 6,500 casualties; the explosion in Yerevan, Armenia on August 8th, 1992 displaced a total of 300,000 people; and the explosion in Lozovaya, Ukraine on August 27th, 2008 resulted in the loss of over 95,000 tonnes of munitions/materiel (Small Arms Survey, 2015). Since millions of tonnes of explosives and ammunition components still remain in ship wrecks and dumping areas at sea, on shores, in lakes and in waste places, pits, streams and landfills (Monfils, 2005), it is clear that the inherent risk ought to be taken seriously. Whilst some analyses of high explosive substances extracted from WWII ERW have revealed the explosives to be in generally good condition, retaining their original properties, there is also evidence that explosives can become increasingly sensitive to external stress (Albright, 2012; OSPAR Commission, 2009) and that some may even prove to explode spontaneously (Ford, Ottemöller, & Bapite, 2005). Substantial uncertainty persists related to the chemical and technical conditions of aging munitions and explosives as well as deficient or missing data in relation to locations, types and amounts of ERW and reported related incidents. Nevertheless, an unintentional explosion at a site that is heavily contaminated with explosives has the potential to unleash disastrous societal and environmental ramifications, thus representing a complex risk with grave consequences. It is therefore imperative to gain further insights into the specifics of ERW risks.

An improved understanding of the links between risks, knowledge and complexity can improve the relevant risk assessment and risk management (Johansen & Rausand, 2014); by developing an understanding of the system, we can enable ourselves to reveal potential surprises, thus rendering the system less complex. Moreover, by addressing uncertainties and by synthesising new knowledge in relation to the specifics of ERW-related risks, we can make quicker, better and safer decisions by improving our decision-making basis.

In this context, the complexity of risk management means that it is difficult to accurately predict the systems' performance, even on the basis of strong knowledge of the specific functions and states of the systems' individual components (Jensen & Aven, 2018). As complex systems have causal chains with many intervening variables and feedback loops that prevent us from understanding or predicting the system's behaviour on the basis of each component's behaviour (Aven, 2020), we need a conceptual framework that enables us to see beyond snapshots of isolated parts of the system (Langdalen, Abrahamsen, & Selvik, 2020). Through a system analysis, it is possible to identify and define critical areas or areas of concern and to analyse them to understand their components and feedback relationships. Specifically, to understand the particularities of an element or an event, we first need to understand its general characteristics (Bennett, 2019).

Uncertainties in risk management can be defined as difficulties with accurately predicting the occurrence of an event or its consequences (Aven, 2020). This can, for example, be due to incomplete or invalid databases, variations, a lack of phenomenological understanding and modelling inaccuracies. In such cases, probability estimations established on the basis of historical data and related statistical analysis could prove to be weak predictors of the future. A high degree of uncertainty is, however, not always problematic, but it represents a major concern when dealing with situations in which there is a potential for severe consequences and in which the uncertainties are substantial (Aven, 2020). In such cases, it is important to be aware of how incomplete knowledge conditions the assessment outcomes (Turati, Pedroni, & Zio, 2018) and to acknowledge the need to revise and assess the decision-making basis, particularly in terms of the strength of knowledge within the accessible data and the assumptions that have been made (Aven, Røed, & Wiencke, 2010). Making assumptions is inevitable when performing most risk assessments, and cannot generally be avoided, however, uncertain and unsubstantiated assumptions must be treated and communicated appropriately (Flage & Berner, 2018), since a failure to address uncertainty may result in an oversimplification of risk and a distorted risk picture. The consequence of this could be that risks are overlooked or misinterpreted, resulting in an increased risk; alternatively, the expected effects of risk-mitigating actions could be less significant than intended or non-existent. In a worst-case scenario, such actions may even prove to have a negative effect on risk (Abrahamsen et al., 2018).

The lack of a common consensus of understanding and assessing ERW risks, combined with relatively weak background knowledge (i.e. missing, deficient or incomplete data) and the need for regulatory convergence, presents a major challenge for the advancement of the fields of ERW risk assessment and management. These are all critical elements in ERW risk assessments, and are mandatory in the development of the national risk management strategy required for handling ERW risk.

According to Vertzberger (1998), a common misconception is that risk taking is exclusively and incorrectly associated with active policy choices. Consequently, even astute decision makers far too often choose to neglect risks. Confronted with complex high-stake problems, decision makers are faced with the tyranny of resultant risks, which are often difficult to identify and define with precision or to anticipate with certainty. A broader view of risk should therefore account for the possibility that risk avoidance in the short term may ultimately have a risk-increasing effect.

The present thesis aims to contribute to the development of a coherent framework for understanding ERW risk and the development of an appropriate understanding of essential factors, such as uncertainty and complexity, in relation to ERW risk. The underlying purpose of this is to provide decision makers and ERW risk management contributors with the tools they need to prepare for and respond to the specific challenges associated with ERW-related risks. More specifically, the contributions relate to the objectives formulated in the following section.

1.2 Objectives

The overall objective of this thesis is to contribute to the further development of the foundations for understanding, assessing and managing risk, with a particular focus on improving ERW risk management.

More concretely, the objectives of the present thesis are to contribute to new knowledge, principles and methods in risk management, and to provide insights and guidance regarding the following:

1. Theoretical foundations and the development of ERW risk management strategies
2. Current ERW risk assessment methodologies and practices
3. Risk-related implications of the aging of high explosives
4. Complex ERW risk management

1.3 Scientific Approach

The presented work adheres to the criteria for scientific quality as presented by The Research Council of Norway (2000), in which the following elements are highlighted: *originality* in terms of newsworthiness and the innovative use of theory and methods; *solidity* in the form of an adequate substantiation of claims and conclusions; and *relevance* in terms of professional development or practical and societal benefits.

This thesis is professionally newsworthy and original because it further develops the existing theories and methods by linking the extant knowledge in new ways and by applying methods and theories to new problems. Furthermore, it contributes new and vital knowledge to specific areas within risk assessment and management. The work is based on scientific methods and principles and is relevant to several application areas for risk management. It provides contributions that advance the research forward and facilitate future research through the development of hypotheses and the opening of new areas within the field of risk management. Furthermore, it can yield both practical and societal benefits, as it aims to reduce societal risks and enhance safety and efficiency by improving the methodology and the quality of the existing decision-making framework.

According to the Board of the Norwegian Association of Higher Education Institutions' *Recommended guidelines for the doctor of philosophy degree* (Universitets- og høgskolerådet, 2015), a doctoral thesis must be an independent research project or a research and development project that meets international standards with regards to ethical requirements, the academic level and the methodology used in the research field. Moreover, it must contribute to the development of new knowledge and achieve a level of quality meriting publication or public disclosure in a suitable format as part of research-based knowledge development in the field.

The work covered by this thesis has been conducted as part of an integrated research process in which the following activities have been central:

- The study of literature in specific fields related to the objectives presented
- Interviews and discussions with key stakeholders and relevant subject matter experts
- Guidance from supervisors
- The presentation of the performed research at national and international conferences and seminars with subsequent feedback and discussions; and
- The drafting, revision and, ultimately, the publication of papers in peer-reviewed international journals

The research applies an interdisciplinary approach that involves the scientific contributions of multiple scientific methodologies. As risk analysis builds upon many principles, approaches and methods (Aven & Flage, 2018), the use of different research approaches can prove to be beneficial when studying multiple or complex research questions (Bukve, 2016), as they can prove to generate complementary results (Ragin, 2014) that could strengthen the risk analysis. The present work can be best characterised as a synthesis of different types of research; parts of the work can be described as *descriptive*, as they systematically describe what ‘is’ in the ‘real world’ (Goundar, 2012), whilst other parts of the work can be categorised as *analytical*, as they utilise established theories and methods to search for new knowledge and critical evaluations. The work is both *applied* and *fundamental*, as it aims toward finding a solution for an immediate problem facing an identified subject, whilst simultaneously seeking information that has a broad base of applications; it thus adds to the already existing organised body of scientific knowledge. Furthermore, the work encompasses subject matter that is both *quantitative*, or applicable to phenomena that can be expressed in terms of quantity, and *qualitative*, as it explores more complex, non-numerical phenomena. Finally, parts of the work are *conceptual*, relating to abstract ideas and theories, whilst other parts can be regarded as *empirical*, wherein conclusions of the study are drawn strictly from concretely empirical and verifiable evidence.

The contributions presented in this thesis are, to the best of the author's ability, consistent with both the criteria highlighted by The Research Council of Norway (2000) as well as the recommendations of the Norwegian Association of Higher Education Institutions (Universitets- og høgskolerådet, 2015). For this PhD project, the aforementioned criteria and recommendations have been met, mainly through the peer-review process of the publicised research papers, but also through a continuous improvement and insurance of quality process involving both a supervision and mentoring structure as well as a continuous dialogue with relevant subject matter stakeholders.

1.4 Thesis Structure

The present thesis follows the recommendations of the Norwegian Association of Higher Education Institutions (Universitets- og høgskolerådet, 2015), which state that a doctoral thesis may consist of a compendium of several shorter manuscripts that includes an explanation of how the manuscripts are interrelated. In line with this approach, this thesis consists of two parts. Part I delineates the foundation and motivation of the work and then summarises and frames the work conducted as part of this thesis within a broader context. Part II elucidates the main scientific contributions of the thesis.

Part II consists of five scientific papers, four of which have been published in the following peer-reviewed international journals: *The Journal of Military and Strategic Studies*, *Safety Science*, *The Journal of Conventional Weapons Destruction* and *Science of the Total Environment*. The remaining paper has been submitted for possible publication in the peer-reviewed international journal *Progress in Disaster Science*.

The remainder of Part I is organised as follows. First, Section 2, entitled Theoretical Foundation, summarises some of the theoretical foundations of the thesis. Second, Section 3, entitled Research Areas and Contributions, provides a backdrop and context and a description of the scientific contributions of the articles published in Part II. Finally, in Section 4, entitled Further Work, some suggestions for future research are provided.

2 Theoretical Foundation

This section summarises some of the theoretical foundations that are relevant to the research areas and problems addressed in Chapter 3 and Part II of this thesis.

2.1 Risk Management

The term ‘risk management’ normally refers to all activities that are employed to address risk, such as avoiding, reducing, sharing and accepting risk. Risk management also includes using and evaluating risk assessments, developing decision-making rules and processes and determining the most appropriate action to address risks (Aven & Thekdi, 2022).

Historically, risk assessment processes have generally been separated from risk management, and most practitioners still argue that to be more useful, they must be divided in both practice and in appearance (Lackey, 1997). This separation requires that the risk assessors adhere to their clearly defined roles as technical experts and that they do not advocate certain policies or political standpoints. Some counterarguments have been levied against this separation; these arguments typically emphasise that it can be challenging to disentangle the risk assessors’ personal values from their technical activities and that the separation is therefore essentially illusory. Conversely, it could also be argued that all involved personnel should have the right to argue for their views and should not be excluded simply because of their status as technical experts, particularly because their function as technical experts grants them explicit insight into situations and problems that may be unknown to others.

Disconnecting the risk assessment from the risk management may not be as easy as it might appear, as the same persons are frequently involved in both activities. However, combining these activities can make it challenging to convince all stakeholders that the assessments and decisions are being executed without biases on the part of the involved personnel. Regardless of whether the activities are separated, the role of the analysts must be clear to everyone using their results (Lackey, 1997).

Risk management involves political decisions concerning how societal risks can be controlled, such as through various response strategies (Molak, 1997). In response to identified risks, we have historically employed numerous techniques for reducing and mitigating them (Covello & Mumpower, 1985). This has involved activities such as avoiding or eliminating the risk (e.g. prohibiting the use of potentially dangerous objects or substances); regulating or modifying activities to reduce the magnitude or frequency of adverse effects; reducing the vulnerability of exposed persons and property (e.g. by implementing safety devices); and developing and implementing post-event mitigation and recovery procedures (e.g. consequence management plans and procedures). A risk analysis generally produces numerous options and suggestions regarding how the identified risks can be managed. These may range from drastic, expensive options to those that aim to maintain the status quo. Regardless, all options must be presented as clear alternatives with statements of ecological benefits and costs and measures of uncertainty for each (Lackey, 1997).

The assortment of applicable options generally has dissimilar specific effects on both risk and development. For example, an option that could significantly reduce risk and simultaneously improve the robustness and resilience of the organisation could also prove to impede its productivity and development. Similarly, an option that promotes productivity and development could prove to have less than the required effect on risk reduction. The art of risk management therefore largely involves balancing development and protection, and the purpose of the risk assessments is to provide decision-making support to obtain this balance. Specifically, the process involves choices between alternatives, the acceptance of activities and products, and the implementation of risk-reducing measures (Aven, 2020).

However, not all risk decision choices can be measured in relation to balancing productivity and development. Both risk assessments and management are based on the fundamental premise that all benefits are accruable to man; this is influenced by the fact that the society may prioritise other more utilitarian factors. For example, one may opt to prioritise environmental protection, such as the preservation of untouched wilderness or of species that have no known value to man, even if the benefits may be intangible (Lackey, 1997). The decisions made in risk management should therefore also encompass a balance of value considerations incorporating a broader societal perspective (Engen et al., 2021). Whilst this may be relevant at all operational levels, it is particularly pertinent at the strategic level (e.g. in risk governance). Risk assessments aimed at this level should therefore encompass not only the factors of productivity and development but also considerations of the broader political and social contexts in which risks are assessed.

Complex societal problems, such as ERW-related risk, should therefore not be expected to have only technological and rational solutions. Although tools such as risk assessments might help at the margins of political processes, they cannot be expected to resolve key policy questions; scientists and risk assessors should therefore guard against technical hubris (i.e. a false sense of confidence in technology and technological solutions) whist performing risk assessments and managing complex societal risks (Lackey, 1997).

2.2 Fundamental Concepts

The concept of risk has evolved over centuries, and despite several attempts to establish broadly accepted definitions of key concepts that are fundamental within the risk field (Aven, 2020), there is still no universally agreed-upon definition of risk (Aven, 2012a). Therefore, the concept of risk is still understood and defined in many different ways and bears different meanings to different people (Thompson, Deisler, & Schwing, 2005).

In the literature, risk is often used to describe the potential or possibility of undesirable events and losses (e.g. Aven, 2012b; Meyer & Reniers, 2016; Renn, 2011). It is often related to a specific activity or situation and is regularly portrayed as a phenomenon that must be avoided or at least reduced. Another frequent definition posits that risk can be regarded as an occurrence of events with subsequent consequences and associated uncertainty. Within this definition, the consequences are not necessarily negative. Here, risk could be regarded as a necessary aspect of an activity in which the key to success lies in balancing the risk of undesired negative consequences with potential advantages (Aven, 2015).

The International Organisation for Standardisation (ISO) defines risk as the ‘effect of uncertainty on objectives’ (2009, Section 1.1). In this definition, the *effect* is regarded as a deviation from the expected outcome and can be considered either positive or negative. According to the ISO vocabulary, the word *objectives* encompasses different facets (such as financial, health and safety and environmental goals) and can be applied at different levels (such as strategic, organisation-wide, project, product and process); *uncertainty* is described as the state of deficiency of information, understanding or knowledge related to an event, its consequences or likelihood. Within this definition, risk is often characterised by references to potential events and consequences or a combination of these and is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of their occurrence.

The Risk Analysis Glossary of risk-related terminology developed by the Society for Risk Analysis (SRA) (2018) offers different perspectives and a systematic distinction between overall qualitative concepts and their measurements. After recognising the multiple failed attempts to establish broadly accepted definitions of key terms related to concepts fundamental to the risk analysis field, the SRA developed a glossary based on the idea that it is possible to establish an authoritative glossary that allows for different perspectives regarding fundamental concepts. This does not mean that all definitions that can be found in the literature are included in the glossary; rather, only those that meet certain basic criteria and are acknowledged by the SRA committee are included. Within the SRA glossary, risk is defined in relation to the consequences (effects, implications) of a future activity with respect to something that humans value. These consequences are often viewed in relation to specific reference values (planned values, objectives, etc.), and the focus is often on negative and undesirable consequences. Within this definition, there is always at least one outcome that is considered negative or undesirable. The SRA glossary provides the following set of overall qualitative definitions (Society for Risk Analysis, 2018, p. 4):

a) Risk is the possibility of an unfortunate occurrence.
b) Risk is the potential for realization of unwanted, negative consequences of an event.
c) Risk is exposure to a proposition (e.g., the occurrence of a loss) of which one is uncertain.
d) Risk is the consequences of the activity and associated uncertainties.
e) Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value.
f) Risk is the occurrences of some specified consequences of the activity and associated uncertainties.
g) Risk is the deviation from a reference value and associated uncertainties.

Within these SRA definitions, the ISO definition of risk as the ‘effect of uncertainty on objectives’ (International Organization for Standardization, 2009, Section 1.1) could, according to the SRA, possibly be interpreted as a special case of definition d) or g) above, in which the consequences are viewed in relation to the objectives (Society for Risk Analysis, 2018).

The definitions of risk provided by the SRA glossary are used as the basis for the scientific contributions presented in this thesis.

There are also, however, different approaches and methods related to how risk can be measured and how it is possible to make judgements about the significance of risks (Aven, 2020). Since the concept of risk, as described above, has two major features, namely values or consequences (C) in relation to something that humans value and uncertainty (U) (possibility, potential), it is not possible to know exactly what C will be. This can be formulated as 'A, C, U' which means both that activities, actions, events and scenarios (A) will produce consequences (C) and that these consequences are not known (U). For practical reasons 'A, C' is often shortened to merely 'C', resulting in the risk concept formulation 'C, U' (Aven et al., 2010).

To describe a specific risk related to an explicit activity, as we do in risk assessments, the potential consequences of the activity must be identified and assessed. This can be conveyed by the triplet (C', Q, K), in which C' represents the specified consequences, Q is a measure of uncertainty associated with C' (e.g. probability), and K is the background knowledge that supports C' and Q (Society for Risk Analysis, 2018). Relevant consequences C' can, for example, be a number of fatalities, costs or the occurrence of particular events, and the measure of uncertainty Q associated with C' can, for example, be a probability or an imprecise probability. In this description, where K represents the background knowledge that supports C' and Q, K encompasses warranted and justified statements and beliefs, often formulated as assumptions based on the risk analyst's perspective as well as the available data, information, testing, theories, models and argumentation (Bjørnsen & Aven, 2019).

2.3 Knowledge and Uncertainty

In line with the description and definition of risk, both knowledge and uncertainty are key elements in describing, assessing and managing risk. Knowledge is defined in the SRA glossary (Society for Risk Analysis, 2018) as skills and justified beliefs that are gained through, for example, scientific methodology and peer-review, experience and testing. The description of background knowledge included in the above risk characterisations, represented by K, encompasses warranted and justified statements and beliefs, often formulated as assumptions, predicated upon data, information, testing, theories, models and argumentation (Bjørnsen & Aven, 2019).

When a risk analysis is performed, a set of events and categories of associated consequence are identified and studied, along with their inherent uncertainties. This uncertainty is relative to the background knowledge, meaning that altered background knowledge could cause decreased or increased uncertainty (Flage & Aven, 2009). Consequently, the quality of the risk assessment will therefore rely heavily upon the quality and validity of the background knowledge.

Strong background knowledge (e.g. cases where substantial relevant and reliable data are available; there is a broad consensus amongst experts, the phenomena involved are well understood; the models used are known to yield predictions with the required accuracy; and the assumptions made are regarded as highly reasonable) would normally correspond to a low level of uncertainty. Similarly, weak background knowledge (e.g. missing, unreliable or irrelevant data; disagreement between experts; strong simplifications in the assumptions and a lack of understanding of the phenomena involved; models that are non-existent or known or believed to yield poor predictions) would correspond to a high level of uncertainty (Askeland, Flage, & Aven, 2017).

In situations in which the background knowledge is weak, with a corresponding high level of uncertainty, the assumptions that would form the basis for a risk assessment would be imprecise, which could lead to inaccurate and erroneous risk recommendations and decisions. However, even risk assessments based on strong background knowledge are capable of contributing to inaccurate risk assessments, as both the selection (the prioritisation of what data to include and what to disregard in the risk assessment) and the evaluation of the data will inevitably be influenced by the assessors' subjective beliefs. In practice, a risk assessment will always have to be based on certain background knowledge, including numerous assumptions and suppositions (Flage & Aven, 2009). One means of capturing this aspect of risk is to include an assessment of the strength of K in the risk characterisations (Bjørnsen & Aven, 2019). This could be done by including an assessment of the strength of knowledge (SoK) as a part of Q, in addition to, for example, probabilities (i.e. R' = (C', (P, SoK), K)).

In addition to this SoK assessment, Askeland, Flage and Aven (2017) have also suggested adding a fifth knowledge component (in addition to phenomena and models, data, expert judgement and assumptions) to address the degree to which the knowledge K has been scrutinised. The purpose of this component would be to stress potential surprises by considering the following:

i. Knowledge gaps
ii. Methods to increase knowledge
iii. The existence of relevant signals and warnings
iv. Changes in knowledge over time
v. The possibility of unknown knowns (wherein others have the knowledge but not the analysis group)
vi. The possibility that events are disregarded because of very low probabilities, acknowledging the critical assumptions in which the probabilities are based.

Another level of uncertainty that may influence our assessment of risk concerns the element of surprises and black swans. In a risk assessment context, surprises can be defined as events that may not be unimaginable or inconceivable but that are unforeseen and unexpected (Aven, 2014). In that regard, a surprising event may be regarded as one whose occurrence was not anticipated or which has been allocated such a low probability that the possibility of its occurrence was effectively disregarded (Kay, 1984). A black swan event can be considered a type of surprise which is regarded as a surprising event relevant to the present knowledge or beliefs (Aven, 2014). Aven and Krohn (2014) differentiate between three types of black swan events:

a) Events that were completely unknown (unknown unknowns)
b) Events that were unknown to the risk assessor but known to others (unknown knowns)
c) Events that were judged to have a negligible probability of occurrence and were thus not believed to occur

The term ‘black swan’ is regularly used to refer to any of these types of events, tacitly assuming that they carry an extreme impact relevant to the specific risk (Aven, 2014). Risks related to black swan events are, however, normally overlooked or ignored and omitted from risk assessments. The first category (a), namely the unknown unknowns, consists of events that are fully unthinkable and unknown to the scientific community and that are therefore absent in the risk assessment. The second category (b), namely the unknown knowns, encompasses events that are not captured by the relevant risk assessment, either because the risk assessor does not know them or because they have not made sufficiently thorough considerations. The third category (c) encompasses events that occur despite the fact that the risk assessor judged the probability of the occurrence of the event as negligible.

The risk concept, described in Section 2.1 as C, U or A, C, U, does not, however, include the phenomenon of unknown unknowns, as A and C simply express the actual events and consequences of the activity. However, when describing the specific risks related to an explicit activity as C’, Q, K or A’, C’, Q, K, there may be unknown unknowns, as the A’ and C’ do not necessarily encompass the true A and C. Hence, category (a) is encompassed within the risk concept but is not captured by the risk description (Aven, 2014). The same is also true for categories (b) and (c).

2.4 Understanding Complexity

Further contributing to the uncertainty related to risk assessments is the complexity level of the assessed system(s). A system is regarded as complex if it is characterised by causal chains with many intervening variables and feedback loops and if it is not possible to establish an accurate prediction model of the system based on knowledge of the specific functions and states of its individual components (Society for Risk Analysis, 2018, p. 5). Without any functioning prediction models, it will not be possible to adjust the outcome of complex behaviours as required in risk management (Arnold & Wade, 2015). However, complex systems are not solely viewed in a negative manner. Conversely, some instabilities are highly valued because they constitute the nomological nucleus of self-organisation, pattern formation, growth processes and phase transitions. Without complexity, there is no drive for self-development and change (Schmidt, 2011).

One approach to managing system complexity involves increasing our systemic knowledge and thereby remaking the system in a less complex or non-complex matter. In most cases, however, this may be neither feasible nor desirable (Jensen & Aven, 2018). Therefore, to advance the identification and assessment of potential risks that may affect risk assessment and management, we must introduce a conceptual framework for viewing the whole and interactions rather than isolated parts of the system (Langdalen et al., 2020). The basic idea is that understanding the ‘why’ and ‘how’ of a phenomenon requires an understanding of the system or context. Specifically, to understand the particularities of an element or an event, we must first gain a general understanding of it

(Bennett, 2019). Through a system analysis based on understanding connections and relations between seemingly isolated phenomena, we can discover organisational structures in systems, thereby creating insights into the organisation of causalities (Haraldsson, 2004). With the use of this skill set, it can be possible to identify and define critical areas or areas of concern and to analyse them to understand their components and feedback relationships.

Many different definitions of systems thinking can be found throughout the systems community. Arnold and Wade (2015) have proposed a singular definition based on key components distilled from the literature and fidelity tested through a systems test (i.e., ‘The System Test’). This test was devised as a means by which to test a systems thinking definition for systemic fidelity. It examines whether the definition fits the specifics of the systems thinking characteristics, acknowledging that systems thinking can be viewed as *a system* (i.e. that it comprises more than a collection of its parts). As for most systems, systems thinking should therefore consist of three specific characteristics:

i. Function, purpose or goal: This should describe the purpose of systems thinking in a manner that can be clearly understood and that relates to everyday life.
ii. Elements: These elements will manifest as characteristics of systems thinking.
iii. Interconnections: This refers to the manner in which the elements or characteristics feed into and relate to each other.

Based on definitions from the literature and the systems test, Arnold and Wade proposed defining systems thinking as ‘a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects’; additionally, they noted that ‘these skills work together as a system’ (2015, p. 675). In brief terms, systems thinking is a science based on understanding connections and relations between seemingly isolated phenomena and that deals with the organisation of logic and the integration of disciplines to understand patterns and relations between complex problems (Haraldsson, 2004). Understanding a cause and an effect enables us to analyse, parse and explain how changes arise both temporally and spatially in common problems; it also enables us to develop improved prediction models regarding potential risks that may affect risk assessment and the management of complex systems.

3 Research Areas and Contributions

This section presents and frames in a broader context the research areas addressed and the scientific contributions made by the five papers presented in Part II of this thesis. The papers all contribute to fulfilling the main objective of the thesis, which is to contribute to the further development of the foundations for understanding, assessing and managing risk, with a particular focus on improving risk assessment and management in relation to explosive-contaminated areas.

As outlined in Section 1.2, the research areas of focus in this work include the following:

1. An evaluation of the theoretical foundations and the development of ERW risk management strategies (Papers I, II)

2. An evaluation of current ERW risk assessment methodologies and practices (Papers II, IV)

3. Contributing to the development of new knowledge regarding the risk-related implications of the aging of high explosives (Paper III)

4. Contributing to increased SoK in the field of complex ERW risk management (Paper V)

By addressing these focus areas, the papers collectively aim to contribute to new knowledge, principles and methods in risk management, and to provide new perspectives regarding how to view and understand the complex nature of ERW risks. By presenting new knowledge and insights, they aim to also improve decision-making on a strategic, operational and tactical level. The relationship between the papers and the overall objective of this thesis are illustrated in Figure 1. This figure depicts the relationships between the different operational levels, in which the superior level(s) are always overarching the subsidiary level(s). One implication is that each individual action, right down to the tactical level, must be performed in harmony with the overall objectives (Forsvaret, 2014). The levels listed in the figure are the strategic level (developing and implementing political-military strategy), the operational level (planning and directing campaigns and major operations) and the tactical level (planning and executing tactical operations).

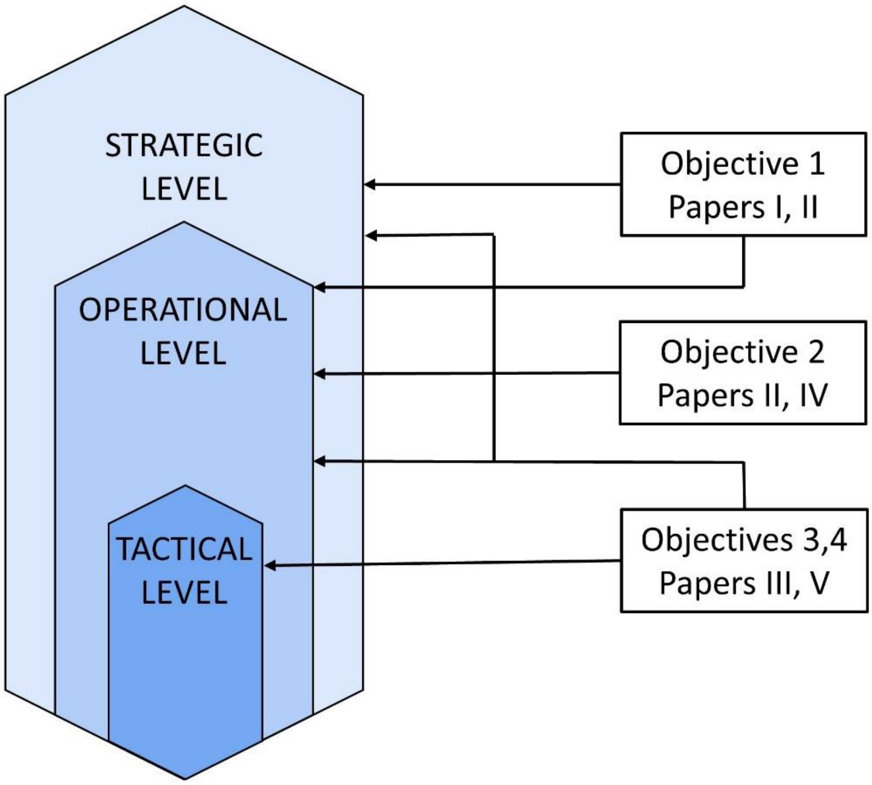

Figure 1 – The relationship between the papers and the overall objective of this thesis in relation to the research areas, as outlined in Section 1.2.

3.1 On Evaluating Current ERW Risk Management

According to James Reason (2011), there are two types of accidents: those that occur on an individual level and those that occur on an organisational level. Despite being the less frequent of the two, organisational accidents are often more profound, sometimes also with catastrophic impacts. While individual accidents are those in which a specific person or group is both the agent and the victim of the accident, organisational accidents can have devastating effects on uninvolved populations, assets and the environment. As opposed to individual accidents, organisational accidents often also entail the breaching of barriers and safeguards that separate damaging and injurious hazards from vulnerable people and assets. Some organisational accidents arise, however, not due to the breaching of established defences, but because such defences are either inadequate or lacking. To assess the functionality of the existing barrier level, it is necessary to regularly evaluate both the nature and variety of the defences and, based on a pre-defined set of criteria, to establish whether the existing barrier level is acceptable.

The research presented in Paper I includes a historical review and an evaluation of the traditional risk mitigation strategies applied when dealing with ERW. Moreover, it provides a detailed overview of how this strategy emerged and how it has developed over time. This enabled us to understand the formation of the strategy and provided us with better insights into the processes in which the strategy was formed. Furthermore, this knowledge will better enable us to understand the existing risk strategy and to evaluate it in light of the current knowledge.

Paper II outlines some of the particularities that differentiate risk assessments regarding ERW-related risks from others and evaluates whether the current risk assessment methodology can be considered relevant and appropriate. The added value of this investigation is to generate further insights into the variances between the methodologies implemented to assess ERW risks and to understand how their dissimilarities influence how risks are portrayed and how this can affect decision-making.

The challenges related to complex risks are briefly mentioned in Papers I and II and are further discussed in Papers IV and V. Included in these papers are also evaluations of to what extent our current risk approach accounts for complex risks and how unintended negative system feedback can influence safety. These evaluations provide us with an improved understanding and further knowledge of the complexity of ERW risks and the potential risk-increasing consequences of uncoordinated risk management.

These evaluations have enabled us to assess the functionality of the current risk approach. The following subsections present a brief overview of the research presented in Papers I, II, IV and V, focusing on the evaluation of the prevailing ERW risk management strategy and methodology. The presentation is divided into three subsections, one for each main evaluation topic: *ERW risk strategy development, ERW risk assessment methodology and the management of complex risk(s).*

3.1.1 Strategy Development

During the initial work in Paper I, which evaluates the traditional risk-mitigating strategy for dealing with dumped ammunition and ERWs, two facts became apparent. First, the existing ERW risk strategy was seemingly formed randomly and arbitrarily rather than via active decision-making; secondly, there is a status quo of deliberate or unintentional ignorance towards ERW-related risks.

Strategies are often comprised of both planning (e.g., a deliberate direction of a course of action into the future) and behavioural patterns (e.g., consistency in behaviour over time), and sometimes more of one than the other (Mintzberg, 1994). The realised strategy of an organisation (or of a government) could therefore often be a product of both an intended strategy as well as an emergent strategy in which the realised pattern was not expressly intended. In the latter, actions are normally pursued individually and converged over time to form a consistent pattern. All real-world strategies must combine these in some form, as a strategy that is excessively heavily predicated upon one or the other will generally be characterised by either a lack of learning and development (too heavily founded on the intended strategy) or by a lack of control (too heavily founded on the emergent strategy).

A former Norwegian minister of defence once stated when questioned about the Norwegian military participation in Afghanistan that there is 'hopefully a well-founded strategy supporting the Norwegian policies[1]' (Edström & Ystebø, 2011, p. 15). Another honest acknowledgement of the challenges of strategic development was uttered by the currently serving Norwegian prime minister Jonas Gahr Støre, who once stated that what can appear to be part of a highly advanced governmental strategy is often merely the unforeseen consequence of previous unplanned actions and that for the uninitiated, the factor of 'chance and short sightedness, and the need to hastily respond to events of the last day or week, are often underestimated[2]' (Høiback, 2011, p. 43). The emerging strategies of governments are therefore often defined by the avoidance of emerging unpleasantries rather than the planned deliberate direction of an intended strategy.

As concluded in Paper I, it appears tenable to argue that the current risk mitigation strategy is predicated upon ignorance and wishful avoidance, rather than an intentional strategy and active policy choices. One can even argue that several countries, including Norway, do not have a strategy for dealing with the grave risks related to dumped ammunition and ERW. However, as is the case with other emerging strategies, some

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[1] Authors translation

[2] Authors translation

strategies are formed without being officially formulated. One of the major challenges involved in this approach is that the decision-makers have no control over the strategy's formation, and no thought is devoted to assessing the risks. Thus, the decision-makers remain oblivious to the factors (which are presently considered mere details) that will eventually prove to be of strategic importance.

It would be reasonable to assume that at least some of the decision-makers at the strategic level possess a basic understanding of the severe societal risks posed by ERW and of their potentially devastating human and environmental consequences. Nevertheless, one can argue that no national strategy revisal has yet been initiated, and few, if any, active policy choices have ever been made regarding the subject. One possible explanation may be the common propensity to overlook potential events that are regarded as rare or improbable, particularly in the face of productive imperatives and the scarcity of attention and resources (Reason, 2011). There is plentiful evidence to support the notion that a lengthy period without negative consequences (such as incidents or a negative focus on a specific risk) will diminish the consciousness of the underlying risk potential, thus causing actors to disregard the fact that the risk, however well hidden, persists. Another potential explanation is that for many people, risk-taking is exclusively and erroneously associated with active policy choices (Vertzberger, 1998). However, passive policies may also entail risk-taking by striving to preserve the status quo and neglecting environmental signals that indicate a need for initiative and change. In other words, there are no risk-free decisions, including the decision to do nothing.

One of the primary benefits of revising the current emergence-based realised strategy and implementing a more intentional strategy with a deliberate direction and course of action into the future is the increased insight into the risks, including an enhanced ability to understand and predict possible events and their associated probabilities, consequences and uncertainties. The development process can itself be entrepreneurial, as it can facilitate the discovery of strategic options which were previously unavailable (Liotta & Somes, 2004). The aim of the proposed solutions, as suggested in Paper I, is to enable us to establish sufficient knowledge, upon which a revised and realigned ERW risk strategy can be founded. A revisal of the strategy would in any case entail a realignment of other key variables, such as a reevaluation of risks, as a change in one variable will typically result in the modification of others and in mismatches (see e.g. Barlett, Holman, & Somes, 2004).

3.1.2 Risk Assessments

Paper I further addresses several of the identified problematic issues related to traditional risk assessments; the evaluation of the current risk assessment methodology is therefore the main topic of Paper II.

The traditional risk approach, as practised by the Norwegian Armed Forces, is predicated upon the notion that the assessor estimates probabilities and thereby ascertains risks. This approach is based on an understanding that probability and risk are regarded as objective figures, such as height and weight. Complications arise, however, as most risk estimations includes factors that are difficult to measure with objective precision. As in the case of the implemented C x P approach, the *probability* P will have to be interpreted with reference to an uncertainty standard (Aven, 2012a). This means that the assessor assigns a numerical probability to the occurrence of a specific event. The assessor also must interpret potential consequences and the severity of the event and its consequences, once again with reference to the inherent uncertainty.

The applied numerical scale of potential profits or losses is often based on the number of injuries and casualties or monetary values (Engen et al., 2021). However, as the numerical convergence of qualitative data can be beneficial in some circumstances, there will always be a degree of uncertainty related to the assessed values. Even quantitative data, such as that regarding the frequency, occurrence or statistical probability of an event or a consequence, could comprise deficiencies and inaccuracies, resulting in imprecise or erroneous assessments. For example, if one wishes to estimate a generic probability of the unintentional detonation of ERW (e.g. a spontaneous detonation), the calculation would contain such an abundance of uncertainties, unknowns and variable factors that the validity, and therefore the utility, of the product would be severely limited. As such, any probability established on the basis of historical data and related statistical analysis will be a weak predictor of the future (Aven, 2020), unless it can be established that the SoK is strong and that the assumptions made are valid. Therefore, there could be added value in statistical data regarding the frequency and occurrence, but only if they are correct, comprehensive and relevant and are used with caution (Aven, Boyesen, Njå, Olsen, & Sandve, 2013).

Another characteristic of the traditional risk approach, as implemented in current ERW risk management, is the use of risk matrices for analysing, assessing and visualising risk (Goerlandt & Reniers, 2016). There are some benefits of using such matrices, as they are generally intuitive in their appeal and simplicity and are relatively easy to construct, score and explain. Furthermore, they are used extensively in risk communication (Abrahamsen, Amundrud, Aven, & Gelyani, 2014) and are therefore normally instantly recognised and comprehended. This makes them a valued tool in risk assessment and communication in time-critical situations in which there is limited time for planning. The added value of using risk matrices is, however, debated, and many argue that due to the required simplification and subjective classification of consequences and probabilities and by defining risk scores and their relation to the scaling of categories, one may lose critical elements in the analysis, or these elements may be diminished (e.g. Busmundrud, Maal, Kiran, & Endregaard, 2015). Paper II discusses the appropriateness of risk matrices in an ERW risk assessment context and highlights the challenges related to the oversimplification of the complex and multifaceted risk distinguished by a high degree of uncertainty.

Paper II further reviews and compares the Norwegian adapted version of operational risk management (ORM), as implemented by the Norwegian Armed Forces, with other ORM variants. It demonstrates that, although similar in appearance and function, there are some fundamental differences in its adaptation. Particularly, the Norwegian version essentially eliminates the option to, as described in the original US ORM fundamentals, apply an in-depth level of ORM in certain situations (i.e. when time is not a limiting factor and when the right answer is required). Moreover, the Norwegian Armed Forces regulations proclaim that risks are to be defined as the mere products of a multiplication of an assessed numeric value assigned to the factors of probability and consequences (i.e. C x P). However, this definition and approach to risk contradicts both the fundamental risk concept and the definitions of risk, as provided by the Society for Risk Analysis (2018) and ISO Guide 73:2009 (International Organization for Standardization, 2009), as described in subsection 2.1 of this thesis. Furthermore, it contradicts the guidelines and recommendations of most relevant Norwegian governmental documents from recent years.

3.1.3 Complex Risk Management

Both Papers I and II address several challenges related to assessing ERW risks; one such challenge is the uncertainty that may result from the complexity levels that ERW risks can entail.

As discussed in Paper IV, ERW risk is a complex phenomenon with multiple attributes, and systems thinking appears to be crucial in ERW risk management. As both the risks and the risk management systems are complex, it is evident that a lack of systems thinking can result in a suboptimal use of resources and a heightened societal risk. More precisely, the lack of a systems approach can result in an excessively complicated and bureaucratic intergovernmental process, unclear responsibilities and absent strategic guidance, resulting in the sub-optimal use of both human and economic resources.

Additionally, a lack of overall understanding can lead to an excessive focus on areas that seem manageable (i.e. the symptoms) and an insufficient prioritisation of the fundamentals (i.e. the source of the symptoms). This can result in short-term solutions that are adaptive at the time but that could impede the development of longer-term solutions (Amalberti & Vincent, 2019). Regarding ERW risk management, we could therefore conclude that the current approach to ERW risk mitigation (i.e. neglecting to perform risk assessments and prioritisations on a national level in addition to failing to harmonise risk-mitigating actions) is forcing us to focus merely on the symptoms, which is diverting us from confronting the fundamental issues underpinning the problem.

Through systems analysis, it is possible to identify and define critical areas or areas of concern and to analyse them to understand their components and feedback relationships. This analysis could offer an opportunity to identify feedback effects in the system, which may highlight potential future trajectories of change. Such feedback effects can arise when variables in the system affect each other in a cascading manner, ultimately leading back to a previous variable and creating a feedback loop (Groundstroem & Juhola, 2021).

Unidentified feedback effects can ultimately lead to an increase in overall risk, as otherwise prudent decisions may have unidentified negative feedback effects. Risk-mitigating actions based on factors over which one possesses limited knowledge (i.e. unidentified feedback effects) can therefore prove to cause disastrous consequences despite the judiciousness of the decisions that were the basis for the actions (Johnsen, 2018). In Paper IV, this is illustrated with an example that demonstrates that adequate ERW risk assessment and management is dependent upon a conceptual framework for viewing the whole and interactions rather than merely isolated parts of the system. The example further illustrates that complex problem solving is challenging to manage without systems thinking and in the absence of all the alternative stakeholders.

Paper IV further demonstrated that systems thinking should be used as a tool to gain better insights into the complexity of managing the risks related to ERW and to better prioritise resources allocated to mitigating this threat, resulting in greater economic efficiency and a more favourable cost-to-benefit ratio. Moreover, it has been established that without adopting a systems thinking approach, we may end up implementing safety measures and requirements without the effects that were intended, and, in the worst cases, the effects can even prove to be negative. This is particularly significant because it raises awareness of the fact that our current risk approach may even contribute to accelerating risks rather than mitigating them.

3.2 Improving the SoK in ERW Risk Management

One recurring topic within ERW risk management is the strength of knowledge in which risk assessments and assumptions are based. As this knowledge forms the foundation of our decisions and dictates the quality of the policies formed, it is imperative that we ensure that the data set that forms the background knowledge is accurate, relevant and comprehensive. However, in situations in which the background knowledge is considered weak, with the corresponding high level of uncertainty, the assumptions that would form the basis of a risk assessment would be imprecise and could lead to inaccurate and erroneous risk recommendations and decisions.

Papers I, II and IV all demonstrated that in ERW risk management, there is typically a lack of both knowledge and relevant or available data, and where such data exists, it is often both imprecise and inadequate.

One key argument that has been levied over the decades that has been characterised by indecisiveness and inactivity towards ERW-related risks posits that if they are neglected, the munitions will slowly become harmless over time. As stated in Paper I, however, there is no scientific evidence to support this idea. There is an abundance of research that documents the fact that ammunition and its constituents can remain in nature for decades and even centuries (e.g. NATO, 2010; OSPAR Commission, 2009; U.S. Department of Defense, 2016). There are similarly numerous studies that document that the leaking and bioaccumulation of toxic constituents from deteriorating ERW pose a threat to the ecosystem and that several of the chemicals used in munitions can be both carcinogenic and highly poisonous; these chemicals have been proven to contaminate living organisms as well as the surrounding soil and groundwater (Koske, Goldenstein, & Kammann, 2019; Koske et al., 2020; Schuster et al., 2021). Even so, the risk most commonly associated with munitions is their explosive effect; by arguing that their destructive properties will most likely diminish over time and that the sensitivity of the explosive substances will decrease to such a degree that they are considered safe to handle, the severity of the risks associated with ERW are effectively marginalised. However, Paper III demonstrates that this argument is erroneous and that explosives can retain their distinctive properties for many decades and perhaps even centuries.

Only a limited number of studies have analysed the properties of high explosives retrieved from ageing ERW; however, those that do exist suggest that the explosives have generally retained their original properties (e.g. Nawała et al., 2020). Paper III analysed explosives retrieved from a representative number of samples of actual ageing ERW, originating from WW2, devoting particular attention to the impact sensitivity of these explosives. Whilst the most sensitive part of the ordnance generally is the primary explosives, this particular study focused exclusively on a limited selection of two of the most commonly found secondary high explosives: trinitrotoluene (TNT) and pentaerythritol tetranitrate (PETN). The analysis revealed no indications of the deterioration of the high explosives in ERW that could suggest any significant reduction in performance or decreased impact sensitivity. The high explosives studied were still in good condition, and the impact sensitivity did not appear to have declined over the last eight to nine decades. Consequently, there is no evidence in this study to support the claim that dumped ammunition and ERW will slowly become harmless over time.

Another key factor for assessing risk involves an evaluation of the practicality and functionality of possible risk-mitigating actions. As discussed in Paper IV, there are several ostensibly risk-mitigating actions that, due to previously unidentified feedback effects, will prove to have a negative effect on risk, in other words, increasing the risk. Paper V examines one of the risk-mitigating actions that is being progressively implemented by organisations and nations (specifically, the prohibition of certain EOD techniques and methodologies, as their environmental impacts have been judged to be too severe).

However, applying a systems approach to the assessment reveals that what is seemingly a prudent decision can have unidentified feedback effects and that the implemented safety measures and requirements could prove to accelerate the risk rather than mitigating it. The study delineates the nature of various inherent disadvantages and limitations related to relevant EOD procedures and states that to make informed decisions, we need to increase the SoK regarding what these are exactly, how they affect risk and how they can be feasibly mitigated by introducing specific actions. Paper V concludes that enforcing a prohibition on certain EOD techniques (in this case high-order detonation techniques) while clearing ERW would effectively eliminate an option that could prove to be the safest, quickest, least resource-demanding and most environmentally friendly option, which could ultimately result in an increased societal and environmental risk.

3.3 Foundational Issues in ERW Risk Management

As outlined in Section 2, several fundamental issues are relevant to further developing the concept of ERW risk management.

Papers I and II present a revised view of ERW-related risk, accounting for the traditional one-dimensional risk perspective that revolves around the risk of an unplanned explosion due to physical contact (e.g. touching or otherwise disturbing the ordnance). However, beyond this traditional perspective, they also address the multifaceted risk picture ERW represent. This includes factors such as spontaneous detonations; the risk of the uncontrolled pollution of soil and groundwater; the toxicology of ERW related to several species of living organisms, including humans and human food sources; the risk of misuse involving criminal or terrorist activities; and the risk of adverse political, economic and societal consequences. The paper also addresses the fact that whilst most actions aimed toward mitigating ERW-related risks involve the potential of undesired adverse consequences (e.g. unplanned explosions, uncontrolled pollution, etc.), the time window for action is rapidly closing as the munitions continue to deteriorate.

A precondition of ERW risk management will always be a balancing act between various risks, wherein the end state will not be expected to be a society free from ERW risk but rather one in which risk is managed to the best of our abilities. Generally, it can be expected that this will consist of a selection of factors, such as risk elimination (e.g. removing or disposing of the ERW); risk avoidance (e.g. by imposing areal restrictions such as prohibitions against fishing, the use of open fires, and metal detection or a general prohibition against all human traffic); the regulation or modification of activities to reduce the magnitude or frequency of adverse effects (e.g. altering shipping lanes for certain passenger ferries to avoid predicted terminal blast areas from dumped ammunition and shipwrecks or altering shipping lanes from large-scale vessels to reduce underwater shockwaves of a certain magnitude); vulnerability reduction (e.g. by implementing safety devices); and the development and implementation of post-event mitigation and recovery procedures (e.g. consequence management plans and procedures).

These aspects must all be balanced not only by factors of productivity and development but also with considerations of the broader political and social contexts in which the risks are assessed. Paper IV argues that with the use of an appropriate skill set (i.e. systems thinking), a better understanding of the deep roots of complex behaviours can be achieved; this can enable better predictions and the adjustment of outcomes. In this paper, we contend that systems thinking can be beneficial when addressing the complexity and uncertainty of ERW risk and that it can serve as an important decision-making aid in balancing risks and developing future risk mitigation actions.

However, a prerequisite for successful risk management will always be the possession of sufficient and relevant data to make well-informed risk decisions. This is further delineated in Papers III and V, contributing to increased SoK in the field of complex ERW risk management and, more specifically, also generating new knowledge regarding the risk-related implications of the aging of high explosives (i.e. Paper III). As presented in Paper V, ERW-related risks represent complex societal problems and should not be expected to have merely technological and rational solutions. Since all decisions, including the decision to do nothing, are bound to have implications in many societal areas (e.g. production, development, safety, security, political, economic, environmental, etc), as well as certain negative feedback effects, there is no technological silver bullet and no panacea that encompasses all specific characteristics of ERW-related risks at every unique location.

As the papers collectively demonstrate, ERW risk management therefore does not mean eliminating all societal risks that ERW represent; rather, it means making well-informed risk decisions based on the constellation of factors that must be considered and thereby managing the risks according to a set of reasonable, acceptable and realisable criteria.

4 Further Work

The scientific contributions presented in this thesis have yielded some suggestions for further work. This section describes the propositions for further work, addresses general discussions and suggests more detailed proposals.

Given that we do not have sufficient knowledge at this time to perform a proper risk assessment, we must work decisively to establish further knowledge regarding certain essential factors. These include further analyses of the effects of aging and deterioration on munitions and their chemical components, their potential environmental impacts and how these are affected by specific environmental conditions. This should also include further research into possible variations in explosive properties, resulting in environmental, chemical or technical differences, to gain further knowledge regarding ageing ERW, thereby supplementing the contributions described in Paper III. Additionally, further studies of the unique properties of relevant explosive material and compositions thereof (i.e. in addition to TNT and PETN), are required to gain adequate knowledge to form a basis for more precise risk assessments. Moreover, accurate risk assessments regarding accidental and unintentional detonations would require further analyses of the sensitivity of the munitions as solid objects containing energetic material, with or without the part of the device (i.e. fuze) that initiates the function (i.e. detonation) of the munitions.

Notwithstanding the addition of the required supplementary information mentioned above, all ERW risk assessments will nonetheless involve assumptions based on uncertain or incomplete information. As argued in Paper I and Paper II, it is necessary to emphasise uncertainty in detailed risk assessments. As conventional techniques of risk assessment and analysis are generally unable to yield any authoritative answers in situations characterised by uncertainty, it is essential to map the uncertainty involved in risk assessments by utilising applicable and relevant methodologies to devise informed recommendations or decisions.

Furthermore, since the existing methodology does not adequately consider complex risks habitually associated with ERW, such assessments could severely impede the decision-making. It is therefore essential to adapt or develop other methods to serve this purpose. As discussed in Paper IV and Paper V, the implementation of systems thinking can advance the identification and assessment of potential risks related to ERW that may affect complex risk management. Through its implementation, it could be possible to better depict and review the functions of safety from a systemic perspective, to increase the ability to learn from experience and particularly to deal with the complexity of the interactions amongst diverse system components. This could help not only to prevent unintentional risk surges; it could also contribute to effectively reducing the societal risks related to ERW while also promoting economic efficiency and a more favourable cost-to-benefit ratio.

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Part II

Paper I

A Risk-Increasing Safety Strategy? Evaluating the Traditional Risk-mitigating Strategy in Dealing with Dumped Ammunition and Explosive Remnants of War

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A Risk-Increasing Safety Strategy?
Evaluating the Traditional Risk-mitigating Strategy in Dealing with Dumped Ammunition and Explosive Remnants of War

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Introduction

Scattered in Norwegian waters and lakes, on land and in soil lay the remnants of five years of war. In excess of one hundred thousand sea mines were laid in Norwegian coastal waters during the Second World War (WWII), and it is estimated that tens of thousands of these mines still remain.[1] Hundreds of thousands of landmines placed in Norway during WWII are believed to have been dumped at sea or in nearby lakes within the first few years following the end of the war. There are still several hundred shipwrecks originating from WWII. The majority of the sunken warships still contain relatively large quantities of explosive ordnance, several hundred tonnes in some cases.

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[1] Justis- og politidepartementet og Forsvarsdepartementet, *Ansvarsforhold og håndtering ved funn av eksplosive varer [Responsibilities and handling of explosive goods]*, Oslo: Ministry of Justice and Police and the Ministry of Defence, 2012, https://www.regjeringen.no/globalassets/upload/jd/vedlegg/rapporter/rapport_eksplosiver_2012.pdf?id=2327852.

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Immediately after the end of WWII, the Allied Joint Command in Norway ordered a large-scale destruction operation of the captured German war material, including weapons and ammunition. According to the Norwegian Army Supply Command, the hasty destruction and dumping operation that followed seemed to have been almost unplanned.[2] Reports from UK Explosive Ordnance Disposal (EOD) teams tasked with carrying out this work in 1945-46 seem to confirm this view and state that the official Allied policy at the time was that all German ammunition in Norway was to be disposed of within the first months following the end of World War II in Europe.[3] This resulted in a massive dumping operation, in which derelict vessels were often loaded with unwanted material and scuttled in designated areas. On other occasions, unwanted explosive ordnance was simply thrown overboard or from the shore, at will. The latter was particularly relevant where stockpiles of ammunition were located on the coastline, e.g. in the vicinity of coastal fortifications and fortresses, harbours, naval bases, and protective minefields.

There is no way to determine the exact amount of explosives originating from these dumping operations that remain in Norwegian waters, but the Allied dumping alone seems to surpass 200,000 tonnes. Just outside the country's capital, in the Oslofjord, it is estimated that there are over 30,000 tonnes of ammunition from planned dumping operations[4] and over 2000 sea mines are remaining.[5] This is in addition to hundreds of thousands of dumped landmines, ammunition dumped from coastal installations, and ammunition contained within shipwrecks. One wreck alone, the German cruiser Blücher, is believed to still contain over 700 tonnes of ammunition.[6]

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[2] Sverre Steinbakken et al., ed., *Ammunisjonstjenesten i Hæren etter 1945: Bind 1 [The Army ammunition service after 1945: Volume 1]* (Kolsås: Hærens forsyningskommando, 2000).

[3] F.L.W. Cartwright, "*RAF Bomb Disposal Norway." BBC: WW2 People's war*, 2005, https://www.bbc.co.uk/history/ww2peopleswar/stories/72/a7018472.shtml.

[4] Aftenposten, "Til bunns med død- og ødeleggelsestruselen [Sinking the threat of death and destruction]," *Aftenposten,* 9 October 1945.

[5] FFI, "Lanserer ny karttjeneste for dumpet ammunisjon [Launches new mapping services for dumped ammunition]," Norwegian Defence Research Establishment, Last modified 6 September 2018, https://www.ffi.no/aktuelt/nyheter/lanserrer-ny-karttjeneste-for-dumpet-ammunisjon.

[6] Kystverket, "Status 2006 for tidligere undersøkte vrak med potensiell olje langs norskekysten [Status 2006 for previously investigated wrecks along the Norwegian coast potentially containing oil]," Norwegian Costal Administration, 2006, https://www.kystverket.no/globalassets/beredskap/vrak/vrakrapport_2006.pdf.

In the years following WWII, several governments continued to believe that the best method for disposing of explosive ordnance was to dump it at sea, as the sea was seen to have unlimited absorptive capacity.[7] The sheer amount of ordnance also made it impracticable to store, and the amount of ammunition considered to be in surplus meant that the cost of proper management and/or in-land disposal would far exceed its monetary value.

In many countries, the dumping of ammunition continued on an unparalleled scale after the end of WWII. The dumping even escalated, not only in terms of sheer numbers but also in that the previous limitations in the form of regulatory restrictions, which had been in place for decades, were now systematically ignored. As a result, in many countries, including Norway, both bulk explosives and ammunition were now dumped into waste places, pits, streams, and shallow lakes, seemingly forgetting why there had once been such strict prohibitions against this practice.

Although recognized in general, the risks related to the explosive remnants of war in Norway are little studied. Norway, like many other countries, has gradually taken a "passive monitoring" attitude towards both shipwrecks and other locations known to be heavily contaminated with explosive ordnance.[8] Some measures have been taken to monitor certain locations with raised concern about other contaminating constituents, such as oil and heavy metals, and in some cases, oil has been offloaded from potentially polluting WWII shipwrecks in Norwegian waters.[9] But the risks related to explosive ordnance are normally disregarded and often written off as more of a "hypothetical" risk, as reflected in this statement from The Norwegian Coastal Administration:[10]

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[7] Rean Monfils, "The global risk of marine pollution from WWII shipwrecks: Examples from the seven seas," *International Oil Spill Conference Proceedings*, (2005): pp. 1049–1054. https://doi.org/10.7901/2169-3358-2005-1-1049.

[8] Ibid.

[9] Rune Bergstrøm, "Lessons Learned from Offloading Oil from Potentially Polluting Ship Wrecks from World War II in Norwegian Waters," *International Oil Spill Conference Proceedings*, (2014): pp. 804-813, https://doi:10.7901/2169-3358-2014.1.804.

[10] Arne Edvardsen, "Rustne tønner på det tyske krigsvraket er trolig smøreolje [Rusty barrels on the German war wreck are probably lubricating oil]," *Bergens Tidene,* 10 July 2015. https://www.bt.no/nyheter/lokalt/i/6Bq1o/rustne-toenner-paa-det-tyske-krigsvraket-er-trolig-smoereolje

> There is little doubt that there are explosives on board these war wrecks, but the danger of something being triggered is more theoretical. It cannot be stated that it is safe to dive on such war wrecks, but normally it takes a greater external strain for explosives to go off after so many years on the seabed.[11]

It is recognized, however, that the ammunition can contain potentially harmful chemicals, but, even so, a tacit assumption by decision-makers is that, if left alone, the ammunition will slowly become harmless. It is therefore repeatedly stated by official sources that dumped conventional ammunition is not considered to be a major threat to the environment.[12] There is, however, no scientific evidence to support this idea.

History shows us that leaking and bioaccumulation of toxic chemicals from corrosive munitions pose a threat to the ecosystem. It has been known for over a century that several of the chemicals used in ammunition are poisonous to humans, and recent studies show that chemicals from dumped ammunition in the sea may also enter the marine food chain and thereby directly affect human health.

Dumped ammunition, however, represents not only an environmental risk but also a security and safety risk, as the population eventually can come into contact with it, and fear grows that aging munitions can explode and/or be misused. In recent years, several concerns have been raised by the presence of dumped ammunition and explosive remnants of war, and the potential dangers they represent.

Traditional risk assessments, solely reliant on the probability-based risk perspective, on which our national strategy is generally founded,[13] do not take into account the complex risk and coherent uncertainty that dumped ammunition and explosive remnants of war represent. As the probability-based regime provides too narrow an approach to risk and uncertainty assessments, the consequences could be that the decisions are strongly misguided, as important aspects of risk and uncertainty

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[11] Author's translation.

[12] Rune Bergstrøm, "Lessons Learned from Offloading Oil from Potentially Polluting Ship Wrecks from World War II in Norwegian Waters," *International Oil Spill Conference Proceedings*, (2014): pp. 804-813, https://doi:10.7901/2169-3358-2014.1.804.

[13] Hæren, *Risikohåndtering [Risk Management]*. Hæren, 2020; Hæren, *UD 2-1 Forsvarets sikkerhetsbestemmelser for landmilitær virksomhet 2020/2021 [The Norwegian Armed Forces Safety Rules and Regulation for Land Based Military Activities]*, Hæren, 2020.

are concealed and/or inadequately described.[14] Nor does it address the strength of the background knowledge on which the probabilistic risk indices are based. This raises a concern that our current risk-mitigating strategy might be founded on what could prove to be incorrect or incomplete information, and that the strategy consequently needs to be revised on the basis of improved risk assessments highlighting the complex risk picture and the strength of the knowledge concept.

In this article, we will first provide an insight into how the strategy has evolved over time and what could be some of the crucial issues facing this strategy, as well as how this strategy could be revised.

The Basis of Our Current Risk-Mitigating Strategy

Early on in WWII, as stockpiles of obsolete and deteriorating ammunition were building up, it became apparent to the relevant governments that their experiences from WWI were being repeated. The waste stockpiles of unserviceable ammunition, together with unexploded ordnance from both training and warfighting, required hasty destruction. Previously, burning or detonation of explosives was often regarded as the most practical solution for disposing of ammunition, but, when faced with larger quantities, dumping at sea could be considered a more relevant disposal technique.

As one contemporary regulation states:[15]

> In the demolition of duds or of large quantities of unserviceable ammunition there are many expedients that have been used. Perhaps the most satisfactory means of disposing of large quantities of ammunition is to dump them at sea. If the proper spot is selected, the dumping ends all further problems and eliminates the handling as well as being the safest method.

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[14] Terje Aven, *Risk, Surprises and Black Swans. Fundamental Ideas and Concepts in Risk Assessment and Risk Management* (New York: Routledge, 2014).

[15] US Ordnance School, *Ordnance Field Guide, Volume III (Vol. 3)*, Harrisburg, Pennsylvania: Military Service Publishing Company, 1945.

The same regulation states in another unrelated paragraph, however, that particles found within certain types of ammunition (in this example, white phosphorus) will be poisonous to food and water.

Another regulation[16] correspondingly states that "whenever possible, having due regard to safety in handling, blind and unserviceable ammunition may be dumped in deep water." This regulation emphasizes that dumping in the sea is even a viable solution for disposing of ammunition containing white phosphorus (i.e. a substance used in the manufacture of munitions, pyrotechnics, and explosives considered "extremely toxic to humans)."[17]

The general perception that dumping at sea is considered the safest and easiest way to destroy unusable ammunition was confirmed by *most* relevant documents and regulations at the time. There are, however, some restrictions to be found in *some* of the regulations. Since long before WWI, it has been stated in various regulations[18] that, whilst dumping at sea is considered particularly advantageous, the dumping of explosives or ammunition into waste places, pits, wells, marshes, shallow streams, or inland waterways is absolutely prohibited. This must be viewed in the context of the fact that most of the high-explosive compounds found in ammunition were considered to be poisonous.[19] In yet other contemporary regulations, it was clearly stated that all dumping of ammunition should be avoided, as the explosives could result in future accidents and as the chemical components within the ammunition were considered to be poisonous.[20]

Due to the sheer number of obsolete and unserviceable explosives and ammunition components in and after the two world wars, in addition to a lack of

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[16] The War Office [UK], *Regulations for Army Ordnance Services, Part II, Pamphlet No. 4* (London: William Clowes & Sons, Ltd.), 1933.

[17] Environmental Protection Agency, *Phosphouros, A summary* (EPA, 2000). https://www.epa.gov/sites/production/files/2016-09/documents/phosphorus.pdf.

[18] US War Department, *Miscellaneous Ammunition, Ammunition General, TR 1370-A* (Washington: War Department, 1930; US War Department, *Technical Manual - Ammunition, General, TM 9-1900*. Washington: War Department, 1942); US War Department, *Technical Manual - Ammunition, General, TM 9-1900* (Washington: War Department, 1945).

[19] Naval Ordnance Department [UK], *Handbook on Ammunition 1945, B.R. 932 (1945)* (Naval Ordnance Department, 1945).

[20] Riks- og Reservepolitiet, *Veiledning i ammunisjonstjeneste [Ammunition Field Guide]* (Stockholm: Militærattacheen, 1944).

alternative means of disposal, the decision was taken by several governments to dump the ammunition in deep waters. If dumping in deep waters was not practically feasible, for example, due to the chemical or technical condition of the ammunition, time or weather constraints, etc., the ammunition was dumped in the sea wherever it seemed practicable. The personnel tasked with the dumping did not always stick to the rules either, as they were "well motivated to get rid of this stuff as fast as they could,"[21] which meant that, in many cases, the ammunition was dumped on route to the designated dumping area, and not in it.

It seems that this behaviour gradually led to a false sensation that the dumping of ammunition was not regarded as harmful to the environment, and over time the dumping of ammunition escalated enormously.[22] Decision makers (both military and civilian) seemingly forgot earlier warnings about poisonous ammunition constituents, and that the regulations up until then had strict provisions for the dumping of ammunition. Consequently, explosives and ammunition were now dumped not only in deep sea but also in shallow water, waste places, pits, streams, and lakes.[23] This behaviour continued right up until the 1970s and 80s, when, due to the acute pollution situation, the world was once again reminded of the environmental risk that dumped explosives and ammunition represent.[24]

Faced with this "new" knowledge or, rather, old re-confirmed knowledge that the various chemical constituents in the ammunition are not only explosively hazardous but are also frequently of toxic character, most governments discontinued the dumping

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[21] Daniel Ross, "Government won't remove thousands of tons of potentially toxic chemical weapons dumped off US coast," *Truthout,* 3 October 2017. https://underwatermunitions.org/2017/10/17/government-wont-remove-thousands-of-tons-of-potentially-toxic-chemical-weapons-dumped-off-us-coasts/.

[22] Jacek Bełdowski, Matthias Brenner, and Kari K. Lehtonen. " Contaminated by war: A brief history of sea dumping of munitions," *Marine Environmental Research*, no. 162 (2020). doi:https://doi.org/10.1016/j.marenvres.2020.105189.

[23] Sverre Steinbakken et al., ed., Ammunisjonstjenesten i Hæren etter 1945: Bind 1 [The Army ammunition service after 1945: Volume 1] (Kolsås: Hærens forsyningskommando, 2000).

[24] United Nations, *Convention for the Prevention of Marine Pollution by Dumping from Ships and Aircraft (with annexes), Signed at Oslo on 15 February 1972*, UN, 1974. https://treaties.un.org/doc/Publication/UNTS/Volume%20932/volume-932-I-13269-English.pdf.

of ammunition as a means of disposing of old and unserviceable munitions.[25] Consequently, the dumping of ammunition was subject to international agreements banning the dumping at sea of hazardous or industrial waste, as stated in the Oslo Convention of 1972 and subsequent amendments.[26]

As dumping of waste material in the sea and pollution from all sources (both military and non-military) proved to have a negative environmental effect,[27] new facilities had to be set up to handle pollution abatement and waste recycling. Contemporary regulations state that "disposal by dumping in the world's oceans (…) has been shown to be not only dangerous but an addition to world pollution and as such, a persistent universal health hazard," and that the former practice of dumping ammunition in deep sea was now to be considered "absolutely prohibited."[28]

The question then subsequently arose of what to do with the millions of tons of explosives and ammunition that had already been dumped. Most governments concerned with challenges related to explosive remnants of war now seemed to take a mutual line of approach in dealing with this problem. A common denominator seems to be that risks related to large accumulations of explosive ordnance, such as dumping areas and shipwrecks, were intentionally neglected.[29]

It was recognized, however, that the ammunition *could* contain some amounts of potentially harmful chemicals, but, nevertheless, a tacit assumption by decision makers was that, if left alone, the ammunition would slowly become harmless over time.

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[25] Jacek Bełdowski, Matthias Brenner, and Kari K. Lehtonen," Contaminated by war: A brief history of sea dumping of munitions," *Marine Environmental Research,* no. 162 (2020). doi:https://doi.org/10.1016/j.marenvres.2020.105189.

[26] Adrian Wilkinson, "Stockpile Management: Disposal and Destruction," in *Conventional Ammunition in Surplus*, edited by James Bevan (Geneva: Small Arms Survey, 2008).

[27] United Nations, *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention),* Adopted on 29 December 1972, UN, 1977. https://treaties.un.org/doc/Publication/UNTS/Volume%201046/volume-1046-I-15749-English.pdf.

[28] US Department of the Army, *Military Explosives TM 9-1300-214,* Department of the Army, 1984.

[29] David E. Alexander, "The strange case of the Richard Montgomery: on the evolution of intractable risk," *Safety Science,* no. 120 (2019): pp. 575-582; Jacek Bełdowski, Matthias Brenner, and Kari K. Lehtonen, "Contaminated by war: A brief history of sea dumping of munitions," *Marine Environmental Research,* no. 162 (2020). doi:https://doi.org/10.1016/j.marenvres.2020.105189.

It was therefore considered a safety measure to make sure that areas contaminated by ammunition, such as dumping sites and shipwrecks, remained undisturbed. This has been the prevailing policy for both Norway and most other countries when faced with an incomprehensible problem such as large accumulations of dumped explosives and ammunition, for which there is no obvious solution, and where the only certainty is that any action will involve a great deal of risk-taking and large-scale costs.

As the explosive objects have been regarded as reasonably stable and safe, as long as they are left undisturbed, the focus on major environmental threats caused by the remnants of war has traditionally been on the risk of contamination of land, water, and soil from other harmful substances, such as the various chemicals, metals or oil found in shipwrecks.

Risk assessments that led to a prioritization of what was to be considered the best possible action on managing the environmental risk regarding remnants of war have therefore typically been based on the type and amount of oil and other dangerous chemicals and metals present,[30] apart from those contained within the ammunition,[31] as well as the assessed environmental vulnerability of the area in which the contamination is located. As far as dumped ammunition is concerned, the view has generally been that, although most of the ammunition could be considered as dangerous today as when it was new, it is also viewed to pose no significant environmental threat by itself. As appearing in various reports regarding the environmental threat represented by various shipwrecks, it has until recently been stated that it is only considered necessary

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[30] Kystverket, "Status 2006 for tidligere undersøkte vrak med potensiell olje langs norskekysten [Status 2006 for previously investigated wrecks along the Norwegian coast potentially containing oil]," Norwegian Costal Administration, 2006, https://www.kystverket.no/globalassets/beredskap/vrak/vrakrapport_2006.pdf.; Kystverket, "Sentralt styringsdokument for Miljøtiltak ved vraket av U-864 [Central guidance document for environmental measures at the wreck of U-864]," Norwegian Costal Administration, 2014. https://kystverket.no/oljevern-og-miljoberedskap/ansvar-og-roller/skipsvrak/u-864/; National Oceanic and Atmospheric Administration, "Risk Assessment for Potentially Polluting Wrecks in U.S. Waters," NOAA, 2013, https://nmssanctuaries.blob.core.windows.net/sanctuaries-prod/media/archive/protect/ppw/pdfs/2013_potentiallypollutingwrecks.pdf

[31] Jacek Bełdowski et al., "Sea-dumped ammunition as a possible source of mercury to the Baltic Sea sediments," *Science of The Total Environment*, no. 674 (2019): pp. 363-373. doi:https://doi.org/10.1016/j.scitotenv.2019.04.058

to perform a risk assessment on the explosive objects as such, if there is a risk of disturbing the ammunition whilst performing any work on the wrecks, during survey or oil recovery operations for example, and if there is a possibility that the ammunition could be affected. The only threat to be regarded then is, or so it seems, the threat of a possible explosion occurring as a result of a disturbance of the ammunition caused by some sort of work in an area known to contain explosive ordnance. In addition, no particular attention is paid to any other aspects of ammunition that can prove to represent a societal and environmental risk. Although it is sometimes recognized that the ammunition contains chemical components known to be hazardous to the environment, this is normally not followed by a specific environmental assessment, as ammunition is pre-defined as not to be considered a major environmental threat.[32]

In a White Paper on societal safety and civil-military cooperation from 2004,[33] the Norwegian Royal Ministry of Justice and Police states that there is a need to identify the issues that may arise around the responsibilities for and handling of buried explosives originating from WWII. This is further deliberated in a White Paper on fire safety from 2009,[34] in which it is stated that, if explosive remnants of war are expected to represent an acute threat to life, health or public movement, the government is responsible for removing the risk that the explosives represent, and that it is of vital importance to remove the explosives as soon as possible, so that the public is not exposed to any danger and can feel safe. It continues, however, to deliberate on the fact that, when it comes to dumped ammunition, as well as certain explosive remnants of war, the inter-governmental responsibilities need clarification. The subsequent report regarding these issues[35] states that the explosive remnants of war generally represent no danger where

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[32] Rune Bergstrøm, "Lessons Learned from Offloading Oil from Potentially Polluting Ship Wrecks from World War II in Norwegian Waters," International Oil Spill Conference Proceedings, (2014): pp. 804-813, https://doi:10.7901/2169-3358-2014.1.804.

[33] Justis- og politidepartementet, *Samfunnssikkerhet og sivilt-militært samarbeid [Societal safety and civil-military cooperation]* (St.meld. nr. 39 (2003-2004), Oslo: Ministry of Justice and Police, 2004.

[34] Justis- og politidepartementet, *Brannsikkerhet [Fire safety] (St.meld. nr 35 (2008-2009).* Oslo: Ministry of Justice and Police, 2009.

[35] Justis- og politidepartementet og Forsvarsdepartementet, *Ansvarsforhold og håndtering ved funn av eksplosive varer [Responsibilities and handling of explosive goods]* (Oslo: Ministry of Justice and Police and the Ministry of Defence, 2012), https://www.regjeringen.no/globalassets/upload/jd/vedlegg/rapporter/rapport_eksplosiver_2012.pdf?id=2327852.

they lie, as long as one does not physically come into contact with the ammunition. It does, however, include a proviso that, over time, the ammunition will deteriorate and that it may contaminate the environment and that the current risk assessment is based on available knowledge but that there has been just too little comprehensive research to make any general conclusions regarding the risks related to human and environmental safety. The report suggests various recommendations and actions but states that the government must assume overall responsibility for the problem, regardless of whatever authority is responsible for any singular subject matter area. Some of these recommendations have been implemented, especially regarding mapping and further research on implications, but in general the overall strategy remains virtually unaffected.[36]

As to why exactly this blindness-to-risk approach first arose is not easily identifiable. There are an overwhelming number of sources that document not only the potential explosive hazards the ammunition represents but also the fact that some of the constituents are frequently of a toxic character, many of them highly poisonous. Regardless of the origin of the current policy, it has resulted in the avoidance-/ignorance-based strategy that we employ today, which further contributes to the erroneous conclusion that over time the ammunition will become harmless, despite research clearly indicating that the negative consequences related to dumped ammunition and explosive remnants of war may be greater than we first anticipated and that they may still increase over time and as recent studies provide us with new knowledge.

Current Risk Mitigation Strategy

Unexploded ordnance plays an instrumental part in major societal challenges in many countries today. Historically, the risk related to explosive remnants of war has

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[36] FFI. "Lanserer ny karttjeneste for dumpet ammunisjon [Launches new mapping services for dumped ammunition]," Norwegian Defence Research Establishment, Last modified 6 September 2018, https://www.ffi.no/aktuelt/nyheter/lanserrer-ny-karttjeneste-for-dumpet-ammunisjon; Mareike Kampmeier et al., "Exploration of the munition dumpsite Kolberger Heide in Kiel Bay, Germany: Example for a standardised hydroacoustic and optic monitoring approach," *Continental Shelf Research* 198, 104108 (2020) doi:http://dx.doi.org/10.1016/j.csr.2020.104108.

typically only been regarded from a one-dimensional perspective: the risk of an unplanned explosion due to physical impact or disturbance of some sort. We have generally focused on disturbances caused by human activity, as either an intended or unintended act, as this generally has been considered to have the greater likelihood of direct consequences, human casualties and/or damage to infrastructure for example. Apart from the personnel directly involved in handling and disposing of such munitions, it seems that the explosives pose especially great risks to children, who may be unaware of the danger.[37] It is predicted that civilian casualties will increase as civilians gain access to formerly inaccessible areas and as interest in and technology for discovering war relics is improving and becoming more readily available to the public. Research also indicates that some explosives can become increasingly sensitive to external stress[38] and have proved to explode spontaneously, even without human interaction.[39]

The risk related to explosive remnants of war is, however, multifaceted, and, aside from the risk of an unplanned explosion, there are more dimensions that need to be considered.[40] While an explosion may be the most apparent danger from unexploded ordnance, there is a more covert threat from munitions' constituents leaking into the ground and water. Primarily derived from explosives, munitions' constituents include residue resulting from munitions that have partially detonated, the corrosion of explosive objects, and the breakage of munitions without detonation.[41] Toxic substances from the explosives can contaminate living organisms, as well as the surrounding soil

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[37] Jacqueline MacDonald Gibson and Carmen Mendez, *Unexploded ordnance cleanup costs: implications of alternative protocols* (RAND Corporation, 2005) https://www.rand.org/pubs/monographs/MG244.html.

[38] Richard Albright, *Cleanup of Chemical and Explosive Munitions: Location, Identification and Environmental Remediation* (2nd ed.) (Massachusetts, United States: William Andrew, 2012).

[39] G. Ford, L. Ottemöller, and B. Bapite, *Analysis of Explosions in the BGS Seismic Database in the Area of Beaufort's Dyke, 1992-2004* (British Geological Survey, 2005) https://webarchive.nationalarchives.gov.uk/20121203195642/http://www.mod.uk/NR/rdonlyres/712B6133-E353-4030-9DD0-F677DC3B6F38/0/bgs_beauforts.pdf.

[40] Odd Einar Olsen et al., *Standardization and Risk Governance: A Multi-Disciplinary Approach*. Milton: Routledge, 2020.

[41] Jacqueline MacDonald Gibson and Carmen Mendez, *Unexploded ordnance cleanup costs: implications of alternative protocols* (RAND Corporation, 2005) https://www.rand.org/pubs/monographs/MG244.html.

and groundwater,[42] and may also enter the food chain, directly affecting human health upon the consumption of contaminated food.[43]

The proliferation of Improvised Explosive Devices (IED) by armed groups, resulting from accessible explosive materials of military origin, is also a growing and substantial issue facing the international community.[44] Easy access to military explosive components and the subsequent pilfering of manufactured precursor materials has been a significant driving factor behind the proliferation of IEDs.[45] Various terrorist organizations are tending to increase their use of explosive remnants of war and abandoned ammunition as key ingredients in their IEDs. Security is therefore a serious factor that must be taken into account if, as in Norway, explosives are contaminating wide areas and liable to illicit retrieval and harvesting for use in terrorism or other criminal activity.[46]

As previously mentioned, traditionally, risk assessments related to dumped ammunition and explosive remnants of war have largely been probability-based, in the sense that there has been a strong focus on estimating or assigning probabilities and meeting predefined probabilistic risk acceptance criteria. Over recent decades, the underlying view on risk, as conceptualized in terms of probability, has been challenged, and there has been an increased focus on the knowledge dimension when assessing and

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[42] ATSDR, *Toxicological profile for 2,4,6-trinitrotoluene*, US Department of Health and Human Services – Agency for Toxic Substances and Disease Registry, 1995. https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=677&tid=125; Jehuda Yinon, *Toxicity and Metabolism of Explosives*. Florida, United States: CRC Press, 1990; FFI, *Påvirkes fisk og skalldyr av dumpet ammunisjon? – en undersøkelse i fire dumpefelt for krigsetterlatenskaper [Does dumped munitions harm fish and shellfish? – an assessment in four dumping grounds], FFI-Rapport 21/01396*, Norwegian Defence Research Establishment, 2021, https://publications.ffi.no/nb/item/asset/dspace:7168/21-01396.pdf.

[43] Edmund Maser and Jennifer S. Strehse, "Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9.

[44] NATO, *Environmental Impact of Munition and Propellant Disposal*, NATO, 2010, https://www.sto.nato.int/publications/pages/results.aspx?k=RTO-TR-AVT-115&s=Search%20All%20STO%20Reports.

[45] Alex Firth, "The Consequences of Poor Storage of Ammunition Stockpiles and IED usage," AOAV, 20 January 2017, https://aoav.org.uk/2017/consequences-poor-storage-ammunition-stockpiles-ied-usage/.

[46] M.T K. Nordaas, "Ammunisjonen kan bli brukt til bomber i tilsiktede handlinger [The ammunition can be used for bombs in intentional acts]," *Nærnett,* 13 October 2019, https://www.nernett.no/artikler/nyhende/sjodumpet-ammunisjonukjente-konsekvenser; Small Arms Survey, *Unplanned explosions at munitions sites, excess stockpiles as liabilities rather than assets* (Geneva: Small Arms Survey, 2015).

managing risk.[47] One implication is that risk cannot be properly described without addressing the strength of the background knowledge on which the probabilistic risk indices are based.[48] As many aspects of risk assessments related to dumped ammunition and explosive remnants of war are based on assumptions, it will be impossible to truly evaluate and manage the risk related to societal and environmental safety without addressing the level of knowledge on which the assumptions are made. Some assessments can be made on the basis of one or several uncertain assumptions, which can have a significant influence on the risk we face. As the probability-based paradigm provides too narrow an approach to risk and uncertainty assessments, the consequence could be that decisions are strongly misguided, as important aspects of risk and uncertainties are concealed and/or inadequately described.[49]

The *true* risk related to explosive remnants of war consists of a number of factors, the most prominent being the risks of explosion, environmental contamination, and of explosives being misused for criminal activity. Regardless of policy choices, whether active or passive, there will also always be a risk of political, economic, and societal consequences. As these factors are inevitably evaluated based on uncertainties (lack of knowledge), any risk assessments related to these factors will consequently require additional characterizations that can provide further insights into knowledge and lack of knowledge, as well as potential surprises (relative to one's beliefs/knowledge) and surprising extreme events with a very low probability (i.e., "Black Swan Events").[50]

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[47] Terje Aven, *Foundations of Risk Analysis*, 2nd ed. (Chichester: John Wiley & Sons, 2012); Terje Aven, "The risk concept-historical and recent development trends," *Reliability Engineering and System Safety*, no. 99 (2012): pp. 33-44; Terje Aven, *Risk, Surprises and Black Swans. Fundamental Ideas and Concepts in Risk Assessment and Risk Management* (New York: Routledge, 2014); Terje Aven and Roger Flage, "Risk assessment with broad uncertainty and knowledge characterisations: An illustrating case study." In Knowledge in Risk Assessment and Management, ed. Terje Aven and Enrico Zio (New York: Wiley, 2018), pp. 3-26.

[48] Christine Louise Berner, "Contributions to Improved Risk Assessments" (PhD diss., University of Stavanger, 2017).

[49] Terje Aven, *Risk, Surprises and Black Swans. Fundamental Ideas and Concepts in Risk Assessment and Risk Management* (New York: Routledge, 2014).

[50] Terje Aven, *Risk, Surprises and Black Swans. Fundamental Ideas and Concepts in Risk Assessment and Risk Management* (New York: Routledge, 2014).

Risk Factors

Risk of Explosion

For the most part, unplanned explosions in explosive remnants of war result from a sudden unintended incident or external stimuli. There are numerous examples of this, but, to mention a recent one, a German WWII aircraft bomb detonated under an aircraft hangar at an airport in Kirkenes in northern Norway in 2019.[51] The investigation concluded that the detonation was the result of a lightning strike.

The structural collapse of shipwrecks, physical alteration of the ordnance, the shifting of ordnance in the tide or deteriorating containers and packaging could all cause sufficient stress to potentially start an explosive reaction. In an ammunition dumping area, one such explosion, through detonation transfer, could evolve into a mass detonation involving hundreds or thousands of tons of explosives.

Unintended detonations can of course also result from human interaction, which greatly increases the risk to human life. In 2019, a Norwegian newspaper[52] reported that human lives could be lost when Equinor ships found dumped war ammunition in an underwater cable route and decided to hoist it on board. According to the newspaper, some of the ammunition exploded when hoisted, and it was sheer luck that no one was hurt in this incident. In December 2020, seven fishermen were injured north of Cromer, Norfolk, UK, when what appears to be a WWII bomb detonated just beneath the hull of their ship.[53] The fishermen were hauling in a line of crab pots when they are believed to have dredged up the unexploded munitions.

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[51] Christian Kråkenes, "Lynnedslag traff bombe fra andre verdenskrig [Lightning struck in WW2 bomb]," *NRK,* 24 August 2019, https://www.nrk.no/tromsogfinnmark/lynnedslag-traff-bombe-fra-andre-verdenskrig-1.14672572.

[52] "Gransking: Skudd gikk av da Equinor ryddet kabeltrasé for Johan Sverdrup [Investigation: Ammunition exploded when Equinor cleared cabel route for Johan Sverdrup]," *Stavanger Aftenblad*, 23 September 2019, https://www.aftenbladet.no/aenergi/i/kJXww9/gransking-skudd-gikk-av-da-equinor-ryddet-kabeltrase-for-johan-sverdr.

[53] Nick Enoch, "Seven crab fishermen escape death when their 42ft boat is blasted out of the water 'by a WWII bomb' 25 miles off the Norfolk coast," *Daily Mail*, 23 December 2020, https://www.dailymail.co.uk/news/article-9082601/Norfolk-crab-fishermen-injured-boat-blasted-sea-WWII-bomb.html.

Explosive remnants of war are coming into increasing contact with human activities like development and fishing. Some decades ago, for example, trawlers would rarely trawl below 120 metres; now, they can trawl in depths of 1500 metres,[54] and dumped waste material is becoming much more than a nuisance: it has become a direct threat to life and health. Increased underwater development and utilization of poorly surveyed land can lead to infrastructure being built in explosive-contaminated areas. Sometimes, this is even done on purpose, reassured by a false assumption that the ammunition does not pose any significant risk. In the spring of 2011, a German mine containing several hundred kilos of TNT was discovered right next to a gas pipeline that runs between the Norwegian and British sectors in the North Sea.[55] Any rupture in international pipelines (e.g. oil, gas, electric, communication) due to an explosion could have huge consequences, both economic and environmental.

Recent studies show, however, that explosive objects are not only prone to detonate when disturbed but are also inclined to self-detonate, even without external stimuli.[56] A recent example of this is a 205-kg US aerial bomb self-detonating in a field outside Limburg in western Germany in 2019. Authorities confirmed that the bomb had exploded by itself, without any external trigger, citing the decomposition of the detonator as the probable cause of ignition.[57] According to Wolfgang Spyra, a professor and engineer at the Brandenburg University of Technology in Cottbus, cited in

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[54] Rean Monfils, "The global risk of marine pollution from WWII shipwrecks: Examples from the seven seas," International Oil Spill Conference Proceedings, (2005): pp. 1049–1054, https://doi.org/10.7901/2169-3358-2005-1-1049.

[55] Justis- og politidepartementet og Forsvarsdepartementet, *Ansvarsforhold og håndtering ved funn av eksplosive varer [Responsibilities and handling of explosive goods]* (Oslo: Ministry of Justice and Police and the Ministry of Defence, 2012), https://www.regjeringen.no/globalassets/upload/jd/vedlegg/rapporter/rapport_eksplosiver_2012.pdf?id=2327852.

[56] G. Ford, L. Ottemöller, and B. Bapite, *Analysis of Explosions in the BGS Seismic Database in the Area of Beaufort's Dyke, 1992-2004* (British Geological Survey, 2005) https://webarchive.nationalarchives.gov.uk/20121203195642/http://www.mod.uk/NR/rdonlyres/712B6133-E353-4030-9DD0-F677DC3B6F38/0/bgs_beauforts.pdf; M.T K. Nordaas, "Ammunisjonen kan bli brukt til bomber i tilsiktede handlinger [The ammunition can be used for bombs in intentional acts]," *Nærnett,* October 13, 2019, https://www.nernett.no/artikler/nyhende/sjodumpet-ammunisjonukjente-konsekvenser.

[57] Jenipher Camino Gonzalez, "WWII bomb self-detonates in German field, leaves crater," *Deutsche Welle,* 24 June 2019, https://www.dw.com/en/wwii-bomb-self-detonates-in-german-field-leaves-crater/a-49331435.

Deutsche Welle,[58] the self-detonation of WWII-era bombs occurs once or twice per year in Germany. The British Geological Survey[59] has also detected spontaneous explosions in munition-dumping areas and, between 1992 and 2004, a total of 47 underwater explosions has been confirmed in the Beaufort's Dyke area. It is stressed, however, that the database almost certainly remains incomplete, as smaller explosions (< ML 1.5) may not have been detected by the seismic networks or have been detected but discarded, due to past routine practice.

Propellants, primers, and explosives are inherently unstable, and managing them requires comprehensive physical and chemical surveillance.[60] A failure to institute these necessary management practices can cause the ammunition to become unstable, and it may ignite or explode, and its constituents may contaminate the environment. It has been known for over a century that, during the storage of some types of explosives (e.g., propellants), a slow but continuous deterioration occurs.[61] Deterioration may be due to chemical instability (i.e., a natural tendency to decompose slowly, frequently accelerated by impurities or the products of decomposition). For some explosives, the effect of chemical deterioration is decreased sensitivity and/or a loss of efficiency. For others, it may be the opposite. This will be dependent on its unique characteristics, and the presence of various factors such as moisture, metals, temperature, pressure, etc.[62] With propellants, the decomposition may proceed so rapidly as to lead eventually to the formation of sufficient heat to cause spontaneous ignition. Such deterioration can also be caused by changes in the physical condition of the ammunition, brought about

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[58] Ibid.

[59] G. Ford, L. Ottemöller, and B. Bapite, *Analysis of Explosions in the BGS Seismic Database in the Area of Beaufort's Dyke, 1992-2004* (British Geological Survey, 2005), https://webarchive.nationalarchives.gov.uk/20121203195642/http://www.mod.uk/NR/rdonlyres/712B6133-E353-4030-9DD0-F677DC3B6F38/0/bgs_beauforts.pdf.

[60] James Bevan, "Introduction," in *Conventional Ammunition in Surplus*, ed. James Bevan (Geneva: Small Arms Survey, 2008).

[61] Small Arms Survey, *Unplanned explosions at munitions sites, excess stockpiles as liabilities rather than assets* (Geneva: Small Arms Survey, 2015); US Army, *Prediction of Safe Life of Propellants, Technical Report 4505,* Picatinny Arsenal, 1973, https://semspub.epa.gov/work/06/9530612.pdf.

[62] FFI, *Pikrinsyre og metallpikrater – dannelse av metallpikrater i dumpet ammunisjon [Picric acid and metal picrates – formation of metal picrates in dumped ammunition] FFI-Rapport 17/00818,* Norwegian Defence Research Establishment, 2017.

by unstable temperatures, ingress of moisture, etc.[63] Physical changes include the melting, freezing or crystalline change of the explosive or any of its components, the absorption of water from damp atmospheres and the loss of volatile constituents.[64]

The probability of self-detonation occurring in ammunition will of course be dependent on several factors, such as type, quantity, structure, material, chemical composition, external milieu, etc. And, although the risk of self-detonation in most cases is considered unlikely, the potential consequences could be extreme. Research indicates that explosive ordnance both can become increasingly sensitive to external stress[65] and is frequently found to explode spontaneously without any human interaction.[66] The risk of self-detonation in ammunition should therefor always be assessed.

Risk of Pollution/Contamination

Up until the end of WWII, the dumping of ammunition was strictly regulated with respect to requirements regarding the dumping site (e.g. depth and distance from the shoreline) and prohibitions as to where and when ammunition was allowed to be dumped. For example, the dumping of explosives or ammunition into waste places, pits, wells, marshes, shallow streams or inland waterways was absolutely prohibited.[67]

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[63] Tony DiGiulian, "Naval Propellants - A Brief Overview," *NavWeaps*, 26 March 2022, http://navweaps.com/index_tech/tech-100.php

[64] Naval Ordnance Department [UK], *Handbook on Ammunition 1945. B.R. 932 (1945)*, Naval Ordnance Department, 1945.

[65] Richard Albright, *Cleanup of Chemical and Explosive Munitions: Location, Identification and Environmental Remediation*, 2nd ed. (Massachusetts, United States: William Andrew, 2012); Mick Hamer, "The doomsday wreck," *New Scientist*, 21 August 2004.

[66] G. Ford, L. Ottemöller, and B. Bapite, *Analysis of Explosions in the BGS Seismic Database in the Area of Beaufort's Dyke, 1992-2004* (British Geological Survey, 2005) https://webarchive.nationalarchives.gov.uk/20121203195642/http://www.mod.uk/NR/rdonlyres/712B6133-E353-4030-9DD0-F677DC3B6F38/0/bgs_beauforts.pdf.; M.T K. Nordaas, "Ammunisjonen kan bli brukt til bomber i tilsiktede handlinger [The ammunition can be used for bombs in intentional acts]," *Nærnett*, 13 October 2019, https://www.nernett.no/artikler/nyhende/sjodumpet-ammunisjonukjente-konsekvenser.

[67] US War Department, Miscellaneous Ammunition, Ammunition General, TR 1370-A, Washington: War Department, 1930; US War Department, *Technical Manual - Ammunition, General, TM 9-1900*, Washington: War Department, 1942; US War Department, *Technical Manual - Ammunition, General, TM 9-1900*, Washington: War Department, 1945

This must be viewed in the context of the fact that most of the high-explosive compounds found in ammunition were known to be poisonous.[68]

History shows us that leaking and the bioaccumulation of toxic chemicals from corrosive munitions could pose a threat to the ecosystem.[69] It has been known for over a century that several chemicals used in ammunition are poisonous to humans; in addition, new knowledge shows that chemicals from ammunition dumped in the sea may also enter the marine food chain and by that means directly affect human health. The hazard potential of these chemicals still has to be determined and the exposure to be estimated, e.g. the nature and extent to which animals or humans are exposed to the chemicals. From the combined assessment of the hazard potential and exposure, the actual risk is derived.[70]

Whilst some toxicity studies suggest that chemical components of munitions are unlikely to cause acute toxicity to marine organisms,[71] there is increasing evidence that they can have sub-lethal and chronic effects in aquatic biota, especially in organisms that live directly on the sea floor or in subsurface substrates. These chemicals may also enter the marine food chain and directly affect human health upon the consumption of contaminated seafood.[72] The latter could prove to be of special concern to the

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[68] Naval Ordnance Department [UK], *Handbook on Ammunition 1945, B.R. 932 (1945)*, Naval Ordnance Department, 1945.

[69] FFI, *Påvirkes fisk og skalldyr av dumpet ammunisjon? – en undersøkelse i fire dumpefelt for krigsetterlatenskaper [Does dumped munitions harm fish and shellfish? – an assessment in four dumping grounds], FFI-Rapport 21/01396*, Norwegian Defence Research Establishment, 2021, https://publications.ffi.no/nb/item/asset/dspace:7168/21-01396.pdf; Jacek Bełdowski et al., "Sea-dumped ammunition as a possible source of mercury to the Baltic Sea sediments," *Science of The Total Environment*, no. 674 (2019): pp. 363-373, https://doi.org/10.1016/j.scitotenv.2019.04.058; US Army, *Summary Review of the Aquatic Toxicology of Munitions Constituents, ERDC/EL TR-13-8*, US Army Engineer Research and Development Center, 2013, https://apps.dtic.mil/sti/pdfs/ADA583083.pdf.

[70] Edmund Maser and Jennifer S. Strehse," Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9.

[71] Edmund Maser and Jennifer S. Strehse," Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9; FFI, *Påvirkes fisk og skalldyr av dumpet ammunisjon? – en undersøkelse i fire dumpefelt for krigsetterlatenskaper [Does dumped munitions harm fish and shellfish? – an assessment in four dumping grounds], FFI-Rapport 21/01396*. Norwegian Defence Research Establishment, 2021. https://publications.ffi.no/nb/item/asset/dspace:7168/21-01396.pdf.

[72] Edmund Maser and Jennifer S. Strehse," Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9.

Norwegian fish farm industry, as many fish farm sites in Norway are located in the immediate vicinity of ammunition dumping areas.

Many studies of ammunition dumping sites at sea show that several types of munitions are already perforated by water,[73] and whilst some studies at some dumping sites do not yet show any significant ecological effects generated from leakage in dumped ammunition,[74] harmful constituents will, eventually, leak into the environment as ammunition casings continue to deteriorate.[75] Both differences in individual ordnance and local environmental conditions will strongly affect the rate of deterioration. The different chemicals break down and react differently in different environments, and metals corrode at different rates, depending on water depth, salinity, and temperature, as well as on the quality, thickness, and metallurgical composition of the casings. Each type of ammunition and each dumping site, therefore, needs to be considered on an individual basis, and it is not possible to make general assumptions about the properties of a dumping area that have not been thoroughly studied. As the individual properties vary to such an extent, and the rate of degradation of the munition components is heavily dependent on a number of technical- and environmental factors,[76] some ordnance could start leaking after a relatively short time, whilst others can remain intact for centuries[77]. It is therefore virtually impossible to estimate when a peak in the release of munition components will be reached. The explosives within the ammunition will in turn have different properties, which can result in continuous leakage of potentially deadly chemicals from a dumping site for

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[73] J. Beddington, and A. J. Kinloch, "Munitions dumped at sea: A litterature reiew," IC Consultants Ltd., Imperial College London, 2005, http://www.environet.eu/pub/pubwis/rura/000ic_munitions_seabed_rep.pdf.

[74] J. Beddington, and A. J. Kinloch, "Munitions dumped at sea: A litterature reiew," IC Consultants Ltd., Imperial College London, 2005, http://www.environet.eu/pub/pubwis/rura/000ic_munitions_seabed_rep.pdf.

[75] OSPAR Commission, *Assessment of the impact of dumped conventional and chemical munitions (update 2009),* OSPAR Commission, 2009, https://www.ospar.org/documents?v=7110.

[76] Jörn Peter Scharsack et al., "Effects of climate change on marine dumped munitions and possible consequence for inhabiting biota," *Environmental Sciences Europe 33,* no. 102 (2021) https://doi.org/10.1186/s12302-021-00537-4

[77] J. Beddington, and A. J. Kinloch, "Munitions dumped at sea: A literature reiew," IC Consultants Ltd., Imperial College London, 2005, http://www.environet.eu/pub/pubwis/rura/000ic_munitions_seabed_rep.pdf.

hundreds of years. The important point to note is that the effect these processes will have on the environment is dependent on their precise location.[78]

This results in the fact that the only way to gain adequate knowledge on the leakage of harmful constituents is to continuously monitor not only the extent at those sites where leakage has already been confirmed but also the sites in which the leakage is expected to occur sometime in the future.

There is an undisputable direct link between the occurrence of dumped munitions and increased concentrations of toxic substances, with implications for the edibility of fish, mussels, and other seafood.[79] Explosives such as TNT and its derivatives are known for their toxicity and carcinogenicity, thereby posing a direct threat to both marine and human life. Furthermore, where it was previously thought that ammunition dumped in deep waters at sea would not affect human life, recent reports now suggest that the metal shells of the ammunition are corroding, such that harmful chemicals are leaking out and being distributed in the marine environment.[80]

A lack of studies conducted on ammunition dump sites makes it difficult to accurately determine the potential environmental consequences of the harmful constituents in dumped ammunition.

Risk of Misuse

Conventional ammunition is in high demand on the illicit market. It is a commodity that has many applications, ranging from misuse of bombs and illegal firearms to unlawful mining and fishing. The use of conventional ammunition, such as

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[78] NATO, *Environmental Impact of Munition and Propellant Disposal*. NATO, 2010. https://www.sto.nato.int/publications/pages/results.aspx?k=RTO-TR-AVT-115&s=Search%20All%20STO%20Reports.

[79] Edmund Maser and Jennifer S. Strehse," Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9.

[80] FFI, *Vurdering av følsomhet til dumpet ammunisjon som inneholder TNT [Sensitivity assessment of dumped ammunition containing TNT] FFI-Rapport 18/02521,* Norwegian Defence Research Establishment, 2018, https://www.ffi.no/publikasjoner/arkiv/vurdering-av-folsomhet-til-dumpet-ammunisjon-som-inneholder-tnt; Mareike Kampmeier et al., "Exploration of the munition dumpsite Kolberger Heide in Kiel Bay, Germany: Example for a standardised hydroacoustic and optic monitoring approach," *Continental Shelf Research* 198 , no. 104108 (2020) doi:http://dx.doi.org/10.1016/j.csr.2020.104108.

explosive remnants of war, in homemade bombs (IEDs) is well documented. A significant majority of IEDs in conflict areas are manufactured from conventional ammunition and military explosives,[81] but, although the challenges involving the use of explosive remnants of war are substantially greater in conflict areas like Iraq, Afghanistan, and the Occupied Palestinian Territories, illicit use even in peaceful societies is more common than one would expect. Explosive ordnance is regularly retrieved unlawfully from former battlefields, shipwrecks, or dumping sites, and in many cases, this ammunition is found to be unlawfully trafficked or used in criminal activity.[82] Bombs used in a number of terrorist acts and criminal activities have been found to contain explosives recovered from sunken mines, torpedoes, aerial bombs, or unexploded ordnance left over from World War II.[83] Several governments and international organisations, such as NATO and the UN have also raised concerns regarding WWII ordnance being salvaged for illegal fishing or the construction of homemade weapons.[84] There is an expressed concern that the explosives represent a clear threat to public safety if illegitimately recovered by criminals.[85]

There is also the risk of a deliberate act of sabotage or terrorism, where an explosive object is deliberately detonated in an area heavily contaminated with other pieces of ammunition, such as a dumping site or a shipwreck. Another scenario could involve one or several explosive objects being purposely detonated within a critical range of vital infrastructure (ferries, harbours, gas, oil, power main lines, etc.). Such

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[81] Adrian Wilkinson, James Bevan, and Ian Biddle, "Improvised Explosive Devices (IEDs): An Introduction," in *Conventional Ammunition in Surplus*, edited by James Bevan (Geneva: Small Arms Survey, 2008).

[82] Small Arms Survey, *Unplanned explosions at munitions sites, excess stockpiles as liabilities rather than assets* (Geneva: Small Arms Survey, 2015).

[83] Monica Massari, "Guns in the family, Mafia violence in Italy," in *Small Arms Survey 2013: Everyday Dangers*, edited by G. M. Emile LeBrun, et al., (Cambridge: Cambridge University Press, 2013), pp. 75-101; The Scotsman, "Fisherman's WWII bomb find helped Mafia kill 21," *The Scotsman,* 13 November 2012, https://www.scotsman.com/news/world/fishermans-wwii-bomb-find-helped-mafia-kill-21-2468018.

[84] NATO, *Environmental Impact of Munition and Propellant Disposal*, NATO, 2010, https://www.sto.nato.int/publications/pages/results.aspx?k=RTO-TR-AVT-115&s=Search%20All%20STO%20Reports; Rean Monfils. "The global risk of marine pollution from WWII shipwrecks: Examples from the seven seas," International Oil Spill Conference Proceedings, (2005): 1049–1054, https://doi.org/10.7901/2169-3358-2005-1-1049.

[85] M.T K. Nordaas, "Ammunisjonen kan bli brukt til bomber i tilsiktede handlinger [The ammunition can be used for bombs in intentional acts]," *Nærnett,* 13 October 2019, https://www.nernett.no/artikler/nyhende/sjodumpet-ammunisjonukjente-konsekvenser.

scenarios could potentially lead to a severe loss of life or infrastructure and the potential loss of vital military or civilian capacity.

Concerns are raised that dumped munitions are open to terrorist access.[86] Many areas containing huge quantities of highly attractive explosive ordnance are readily available to the public; in some places, large calibre ammunition can even be found openly, next to inhabited areas, at the shoreline, or in shallow waters. Buried ammunition and ammunition located in deeper waters have for many years remained undiscovered and unrecoverable to the public, as the available technology for the most part has been too ineffectual in use or too expensive to obtain. However, in recent years, this has changed considerably, and ammunition that was previously practically unrecoverable is now readily available for anyone with access to a strong magnet, a metal detector, or a relatively cheap underwater ROV.

Whilst it could also be argued in the past that it was an easier alternative for criminals and terrorists to make their own explosives (especially since, traditionally, they had not been too concerned with safety, security or performance), access to many of the required precursor materials is now becoming progressively controlled. High explosive large calibre ordnance is, therefore, increasingly desirable to such actors, and the illicit recovery, proliferation, and misuse of explosive remnants of war, therefore, represents a noteworthy and increasingly important threat to societal safety and security.

Risk of Political, Economic and Societal Consequences

Many factors determine the consequences of an unplanned explosion in dumped ammunition or of explosive remnants of war. Key factors include the proximity to exposed personnel and populated areas, the amount of explosive detonating, the typography of the area, the surrounding environment, and the effectiveness of the emergency response. The impacts may be both direct and indirect, and there may be long-term consequences, like ongoing clearance of unexploded objects, investigations,

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[86] NATO, *Environmental Impact of Munition and Propellant Disposal*, NATO, 2010, https://www.sto.nato.int/publications/pages/results.aspx?k=RTO-TR-AVT-115&s=Search%20All%20STO%20Reports.

and the cordoning off of potentially large areas for several years. It is only possible to fully understand and illustrate the risk represented by dumped ammunition and explosive remnants of war with adequate knowledge of these various effects. Unplanned explosions can have a direct and indiscriminate potential to kill and injure, but they can also result in political, economic, and social consequences. Because accumulations of explosive remnants of war often run into hundreds of tons of explosives, if a detonation of any of the explosive objects occurs, it can lead to a mass detonation, with large-scale loss of life, major environmental damage, drastic impacts on local economies and the destruction of important infrastructure.

The effects of such a large-scale explosion would be wide-ranging and long-lasting. Large numbers of unexploded ordnance are likely to be jettisoned from the explosion site, often many kilometres, and people may encounter such ordnance accidentally, or they may seek them out of inquisitiveness or deliberately to harvest the explosives or metals for either commercial or nefarious purposes. It seems that the unexploded ordnance poses an especially great risk to the personnel tasked with the subsequent clearing operation but also to children who may be unaware of the dangers related to them.[87] Casualties could therefore accrue for months and even years after an explosion. In their study on unplanned explosions at munition sites, the Small Arms Survey[88] has found that, although culpability often goes undetermined or unpublished, the political repercussions of some incidents may mean that high-ranking officials do, at times, face sanctions for their role in the incident. They further suggest that, although the political impact may become apparent relatively quickly, information about the underlying criminal and political responsibility is not likely to emerge until an investigation is complete. Regardless of the ownership of the munitions involved, the government has the overall responsibility for upholding public- and national security, and their civil authorities and agencies are responsible for ensuring public safety.[89]

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[87] Jacqueline MacDonald Gibson and Carmen Mendez, *Unexploded ordnance cleanup costs: implications of alternative protocols,* (RAND Corporation, 2005) https://www.rand.org/pubs/monographs/MG244.html.

[88] Small Arms Survey, *Unplanned explosions at munitions sites, excess stockpiles as liabilities rather than assets* (Geneva: Small Arms Survey, 2015).

[89] Norwegian Government, *Support and Cooperation, A description of the total defence in Norway,* Oslo: The Norwegian Government, 2018, https://www.regjeringen.no/contentassets/5a9bd774183b4d548e33da101e7f7d43/support-and-cooperation.pdf.

Neglecting or failing in these responsibilities can, however, have severe political implications, even without a large-scale explosion. Even minor explosions or the detection of harmful chemicals in food or in nature will raise the question of whether the authorities did enough to protect their people or simply neglected their duties as elected representatives.

Risk Approach

The Norwegian White Paper on societal safety[90] states that the population shall rest assured that their life, health, and important values are well protected, yet other official governmental reports[91] specify that there is reason to believe that ordnance may, in fact, constitute a potential explosion and contamination hazard and that it is of vital importance that the government removes the explosives as soon as possible so that the public is not exposed to any danger and can feel safe. However, our current risk management strategy is still based on the erroneous assumption that if the ammunition is left alone, it will slowly become harmless over time.

In addition, any assessments made regarding the risk surrounding dumped ammunition and explosive remnants of war must also reflect the uncertainty related to the fact that (some) assumptions are based on incorrect or incomplete information (e.g. cases of insufficient research and overgeneralization). In addition to the strength of knowledge perspective, surprises may also occur relative to the knowledge of the analysts or experts conducting the assessment. When assessing risk, it is therefore imperative to explore the type of situations and events that are of interest and importance to us when discussing unforeseen and surprising events and to

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[90] Justis- og beredskapsdepartementet, *Risiko i et trygt samfunn. Samfunnssikkerhet [Societal safety] (Meld. St. 10 (2016-2017)),* Oslo: Ministry of Justice and Public Security, 2017.

[91] Justis- og politidepartementet, *Brannsikkerhet [Fire safety] (St.meld. nr 35 (2008-2009).* Oslo: Ministry of Justice and Police 2009; Justis- og politidepartementet og Forsvarsdepartementet, *Ansvarsforhold og håndtering ved funn av eksplosive varer [Responsibilities and handling of explosive goods],* Oslo: Ministry of Justice and Police and the Ministry of Defence, 2012, https://www.regjeringen.no/globalassets/upload/jd/vedlegg/rapporter/rapport_eksplosiver_2012.pdf?id=2327852.

conceptualize them, link them to risk, and confront them.[92] A failure to assess and describe the risk relative to the strength of knowledge and potential surprises/black swans will inevitably lead to an inadequately described risk and, in turn, to incorrect conclusions and distorted decision-making biases.

Proposed Solutions

Based on this study, it seems obvious that the essential risks posed by conventional ammunition include a safety risk to the public, a significant security risk to states and societies, and a severe political, environmental, and economic risk. Dumped ammunition and explosive remnants of war will always represent a latent threat, from any perspective.[93]

To enable us to evaluate these threats, we must start by acknowledging the fact that we do not have sufficient knowledge at this time to perform a proper risk assessment. We must then, to the greatest possible extent, establish knowledge of exactly what has been dumped, where it is located, its inherent risks, and possible risk-mitigating measures. The next step would be to carry out individual risk assessments of the various dumping sites and, based on the relevance and feasibility of available mitigating actions, develop a prioritized action plan.

As accurate archives are, for the most part, missing or incomplete, this task could prove to be a mammoth one, probably continuing for years to come. Although the practice of dumping ammunition has now ceased, the damage has already been done. For one thing, there are no complete archives of what exactly has been dumped – or where – and those tasked with the dumping did not always adhere to the rules.[94]

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[92] Terje Aven, *Risk, Surprises and Black Swans. Fundamental Ideas and Concepts in Risk Assessment and Risk Management* (New York: Routledge, 2014).

[93] James Bevan, "Introduction," in *Conventional Ammunition in Surplus*, edited by James Bevan (Geneva: Small Arms Survey, 2008).

[94] Daniel Ross, "Government won't remove thousands of tons of potentially toxic chemical weapons dumped off US coast." *Truthout*, 3 October 2017, https://underwatermunitions.org/2017/10/17/government-wont-remove-thousands-of-tons-of-potentially-toxic-chemical-weapons-dumped-off-us-coasts/.

Several studies[95] have already attempted to identify and assess the extent of harmful constituents leaking from munitions, the possibility of bioaccumulation and whether it can be harmful to marine or human life. As can be expected, when individual properties vary to such an extent, the results are to some degree contradictory. Whilst certain studies do not yet show leakage of harmful constituents at some of the ammunition dumping sites, it is recognized that they will, eventually, leak into the environment as the ammunition casings deteriorate. Some explosives are known for their toxicity and carcinogenicity, and recent studies have shown an undisputable direct link between the occurrence of dumped munitions and increased concentrations of toxic substances, with implications for the edibility of fish, mussels and other seafood.[96] The only way to gain more knowledge on exactly how, and to what extent, harmful munitions' constituents affect human and marine life is to carry out additional research on this topic.

Key factors to determine whether munitions' constituents pose an environmental or human hazard are the quantity and dispersal of munitions within a disposal site, the depth of the disposal area, the effects of currents (e.g. direction, speed), and tidal flushing, and the quantity of munitions' constituents released in a given period of time.[97] These factors should also be registered and monitored regularly for individual dumping sites.

Based on the mapping and available research, individual risk assessments of the various dumping sites should be performed, taking into account the level of knowledge related to the identification and condition of the ordnance and the potential societal and

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[95] Jacub Nawała et al., "Analysis of samples of explosives excavated from the Baltic Sea floor," *Science of The Total Environment* 708, no. 135198 (2020), https://doi.org/10.1016/j.scitotenv.2019.135198; FFI, *Påvirkes fisk og skalldyr av dumpet ammunisjon? – en undersøkelse i fire dumpefelt for krigsetterlatenskaper [Does dumped munitions harm fish and shellfish? – an assessment in four dumping grounds]. FFI-Rapport 21/01396*. Norwegian Defence Research Establishment, 2021, https://publications.ffi.no/nb/item/asset/dspace:7168/21-01396.pdf; Jacek Bełdowski et al., "Sea-dumped ammunition as a possible source of mercury to the Baltic Sea sediments," *Science of The Total Environment*, no. 674 (2019): pp. 363-373, doi:https://doi.org/10.1016/j.scitotenv.2019.04.058; US Army, *Summary Review of the Aquatic Toxicology of Munitions Constituents, ERDC/EL TR-13-8*, US Army Engineer Research and Development Center, 2013, https://apps.dtic.mil/sti/pdfs/ADA583083.pdf.

[96] Edmund Maser and Jennifer S. Strehse," Can seafood from marine sites of dumped World War relicts be eaten?" *Archives of Toxicology*, no. 95 (2021): pp. 2255–2261, https://doi.org/10.1007/s00204-021-03045-9.

[97] US Department of Defense, *Research Related to Effect of Ocean Disposal of Munitions in U.S. Coastal Waters* (Washington: US Department of Defense, 2016).

environmental threat the individual site represents.[98] As existing methodology (i.e. probability-based risk assessments) does not to a satisfactory extent consider complex risk and strength of knowledge, such assessments could be severely misleading to the decision-making. It is therefore essential to adapt or develop other methods to serve this purpose. Developing an improved method of risk assessments, by highlighting complex risks and the strength of knowledge concept, could make it possible to perform individual risk assessments of relevant sites and, based on the relevance and feasibility of available mitigating actions, to develop a prioritized action plan for reducing the total environmental and societal risk derived from ammunition dumping sites and explosive remnants of war.

Any positive action on sea-disposed ammunition must of course be balanced against the potential harm to marine life, as well as the increased explosives safety risk to workers and the surrounding communities.[99] The final decision may nonetheless be that the ammunition should be left undisturbed. But it must be stressed that this is then an active policy choice, based on all available relevant facts, rather than a passive policy of ignorance/avoidance. A common mistake by decision-makers is to identify risk-taking exclusively and incorrectly with active policy choices. Passive policies may also entail risk-taking, by attempting to preserve the status quo and ignoring environmental signals that indicate a need for initiative and change. There are no risk-free decisions, including the decision not to decide.[100]

After a given period of time, any implemented actions should then be evaluated in terms of expected and achieved effect, and the risk assessments, action plans, and strategy they are founded on should be evaluated in light of achieved results, recent research, and the development of new knowledge and technology.[101]

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[98] Jacqueline MacDonald et al., *Ordnance - A Critical Review of Risk Assessment Methods* (Santa Monica, CA: RAND, 2004).

[99] US Department of Defense, *Research Related to Effect of Ocean Disposal of Munitions in U.S. Coastal Waters* (Washington: US Department of Defense, 2016).

[100] Yaacov Y. I. Vertzberger, *Risk Taking and Decisionmaking - Foreign Military Intervention Decisions* (California: Stanford University Press, 1998).

[101] Terje Aven, *The Science of Risk Analysis* (Oxon: Routledge, 2020).

Conclusion

Research has proved that the complex risk related to explosive remnants of war is comprised of several factors and, whilst the most prominent is regarded as the risk of an explosion, we cannot neglect the potential risk of environmental contamination, the risk of the explosives being misused for criminal activity and the risk of political, economic and societal consequences. Even so, a tacit assumption by decision-makers is that, if left alone, the ammunition will slowly become harmless over time. It is therefore considered a safety measure to see to it that ammunition-contaminated areas, such as dumping areas and shipwrecks containing ammunition, remain undisturbed. This is also the basis of our main risk-mitigating strategy when it comes to large accumulations of dumped explosives and ammunition.

It is clear that dumped ammunition can remain in salt water fully intact and in pristine condition for over one hundred years, but it can also rust so thoroughly in a few decades that only non-soluble explosive filler and a few metal fragments remain.[102] As time passes, the objects will become less and less identifiable, and their chemical and technical condition will become increasingly indeterminate, thus dramatically limiting the number of potentially available risk-reducing actions.

Whilst some may go as far as to call the current risk-mitigating strategy a government-imposed "doctrine of denial,"[103] it may be safe to say at least that it is a strategy built on ignorance and wishful avoidance, and that the employed risk-mitigating action in itself could be acting as a risk accelerator.

There are several risks that the current risk-mitigating strategy does not seem to fully factor in. Likewise, the strategy does not sufficiently differentiate between different risks at various sites, nor does it provide us with sufficient knowledge to consider possible necessary risk-reducing actions or to prioritize where action is

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[102] James V. Barton and Steven B. Pollack, "Assessment of Lethal Chemical and Conventional Munitions in the Nation's Waters," *CDC/NCEH*, 2017, https://truthout.org/wp-content/uploads/legacy/documents/2017_1002/CDC_report.pdf.

[103] James V. Barton and Steven B. Pollack, "Assessment of Lethal Chemical and Conventional Munitions in the Nation's Waters," *CDC/NCEH*, 2017, https://truthout.org/wp-content/uploads/legacy/documents/2017_1002/CDC_report.pdf.

needed. This leads to great uncertainty and concern that the current risk mitigation strategy desperately needs to be revised.

Such a revision should describe the need for: mapping, monitoring, and further research; developing an improved method of risk assessments, by highlighting complex risks and the strength of knowledge concept; performing individual risk assessments of relevant sites; and, based on the relevance and feasibility of available mitigating actions, developing a prioritized action plan in order to reduce the total environmental and societal risk derived from ammunition dumping sites and explosive remnants of war.

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Paper II

Improving the decision-making basis by strengthening the risk assessments of unexploded ordnance and explosive remnants of war

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Improving the decision-making basis by strengthening the risk assessments of unexploded ordnance and explosive remnants of war

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ABSTRACT

For many countries, the legacy of armed conflict in the form of unexploded ordnance has a severe impact on society and daily life, as millions of tonnes of explosive remnants of war represent a grave threat to both the environment and societal safety and security. Recent and dramatic changes in the security situation in Europe sadly demonstrate that explosive remnants of war are not, however, only a thing of the past. This makes it especially relevant to evaluate how we assess and manage this risk today and how, if possible, this practice could be improved.

In the present paper, we will outline some of the particularities that differentiate risk assessments of unexploded ordnance from other, more familiar, risks and discuss whether the current methodology can be considered relevant and appropriate.

We find that the different risk assessment methodologies generally in use today, as described in applicable guidelines and regulations, are principally unsuitable for this use and, in addition, sometimes also ambiguous, inconsistent and incompatible. In particular, we find that any model based on a risk assessment that does not include an evaluation of background knowledge and associated uncertainties cannot be regarded as an optimal or appropriate risk assessment tool, when assessing a risk typically characterized by high complexity and uncertainty.

The conclusion of this investigation is that the current risk assessment methodology for assessing risks related to unexploded ordnance and explosive remnants of war urgently needs to be revised, in order to improve the decision-making basis.

1. Introduction

To one extent or another, most countries throughout the world face daily challenges related to potentially dangerous ammunition and explosives remaining in former training areas and firing ranges, as well as in present or former theatres of war and armed conflict. Unexploded ordnance (UXO) and explosive remnants of war (ERW) can potentially remain deadly for centuries. Their constituents can be poisonous to living organisms and also contaminate the surrounding soil and groundwater, making it a major environmental concern (Koske et al., 2019; Koske et al., 2020a; Maser and Strehse, 2021). As more concerns are raised on the potential devastating environmental and societal effects, more knowledge is being gained through an increase in research related to potential undesired consequences. Although the once established practice of dumping obsolete and unserviceable ammunition has all but ceased, decades of ammunition dumping operations have left us with a legacy of millions of tonnes of munitions dumped at sea, in landfills or in lakes (Bełdowski et al., 2019; Kampmeier et al., 2020; OSPAR Commission, 2009). In addition, countries that have seen warfighting on their territory are left with the explosive heritage of ammunition that has been left on the battlefield, stores or depots that were partially destroyed, and ordnance that failed to function as planned, leaving it scattered across the terrain, potentially detonating at the slightest touch, killing and wounding indiscriminately (Duttinea and Hottentota, 2013).

The potential dangers related to UXO/ERW risk makes clearing them a highly prioritized task for many countries, as well as for organizations such as the United Nations (UN) and the North Atlantic Treaty Organization (NATO) whilst conducting operations in conflict-affected areas throughout the world. For example, the mandate for protecting civilians

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in UN peacekeeping operations includes protecting them from harm associated with the presence of explosive ordnance, including mines, ERW and improvised explosive devices (United Nations, 2019), while NATO states that, because ERW kill and maim people long after the cessation of hostilities, they are considered a major barrier to safety and security, as well as post-conflict recovery and development (NATO, 2010). Any interaction with UXO/ERW is, however, inherently risky, and clearing them involves taking calculated risks, dependent on risk appetite and risk tolerance. To obtain a factual estimation of the risk, in order to make the required decisions, one must manage the risk by identifying it, analysing it, and then evaluating whether or not it can be mitigated in any way, in order to satisfy the determined risk criteria (NATO, 2019).

Although there are numerous ways to assess and manage different forms of UXO/ERW risk, many of them share a common approach towards certain fundamental views on how risk is to be understood and how it may be evaluated. This is also applicable to many of the standards and policies that form the basis of both national and international practice in the field of UXO/ERW risk management. In this paper, we will study a common risk management approach, often used in military risk management in major international organizations such as the UN and NATO, and evaluate whether or not the methodology employed is suitable for assessing risk related to UXO/ERW and how this corresponds with other guiding principles and international development trends. We will also discuss whether the current methodology can be considered relevant and appropriate with regard to recent advances made in the risk field, most particularly in situations characterized by large uncertainties (Aven, 2016).

The remainder of this paper is organized as follows. In Section 2, we introduce the particular characteristics of risk related to unexploded ordnance and ERW. Section 3 presents a case study of the current risk perspective and development of the methodology of risk assessments regarding UXO/ERW in Norway. In addition to other examples related to risk assessment methodology, the case study is used throughout the paper to illustrate the discussion. Section 4 discusses the relevance and appropriateness of the current perspective and methodology; finally, in Section 5, we make some concluding remarks and recommendations.

2. Specific characteristics of UXO/ERW-related risk

Some of the discussions on risk management within the defence- and justice sector have centred around the different factors involved when assessing different risks, for example the different properties involved whilst assessing risk related to safety vs security or intended and unintended, undesired (for the assessor) events. Some of the challenges related to risk management of UXO/ERW are similarly those of the diversity and complexity an unexploded object could represent regarding the uniqueness of the individual object, in terms of its technical and chemical condition, its variable constituents, the situation and the environment in which it is located. For example, an unplanned (for us) detonation of high explosive munitions could be the result of a number of causes. Such a detonation could occur as a result of an intended act of terrorism or crime, an accidental disturbance (e.g., construction work in an ammunition-contaminated area), an intentional disturbance (e.g., during the moving, rendering safe or disposal of ammunition), a spontaneous detonation without external stimuli, as a result of deteriorating technical or chemical properties, or other causes, all of which can have a different and unique set of consequences. Their properties will naturally also have to be unique and dependent on a wide range of factors.

This makes it problematic to discuss risk related to UXO/ERW, in terms of probabilities as a defined figure. On one hand, we can argue that, for some events, we have good historical data which we can interpret to obtain a theoretical frequentist probability of certain events occurring or of the events having certain consequences. For example, we can monitor spontaneous explosions in dumped ammunition, to study frequency and trends. In this way, we can, theoretically, identify a probability that represents the fraction of conditions (scenarios) for which a detonation occurs, given a specific condition. This is problematic, however, as there will always be other possible interpretations, for example reflecting variations due to different conditions such as climate, temperature, inherent technical or chemical differences within the ammunition, etc. We can also monitor the rate of recorded explosions, possibly revealing a trend of an increasing or decreasing number of explosions, indicating a trend-change in the defined probability. However, there will also here be conditions that can influence the validity of the data, such as the effort made and the technology available to record such explosions, as well as external factors such as a variability in conditions that can influence the stability of the ammunition or the explosives, or that can have a mechanical effect on the ordnance. This interpretation of a probability as a property of the situation under consideration is problematic because it is thereby presumed that a probability exists which characterizes the situation, an objective property of the situation, in the sense that, if we could repeat it infinitely under similar conditions, the probability would be equal to the proportion of times that the consequence would occur (Aven, 2014). In other words, frequentist probabilities can be helpful for identifying frequency and development trends but are dependent on probabilistic modelling, and both the assumptions underpinning the model and the functional relationships within the model therefore need to be justified.

Probability can also be interpreted as a judgement made by the assigner of the probability, in which the probability expresses the degree of belief of the assigner (Aven, 2014), in this case a way of expressing his/her uncertainty about whether or not an explosion will occur, given a set of specific conditions. In a given scenario, if a probability of (say) 0.000 001 % ($P = 10^{-6}$) is assigned, the assigner has the same degree of uncertainty about an explosion occurring as randomly drawing a specific ball out of an urn that contains one million balls. These probabilities are often referred to as subjective probabilities or knowledge-based probabilities and will always be conditional on some background knowledge, which could include data, information, assumptions and beliefs. To express the probability of an event of interest (A) given a certain level of background knowledge (K), we write $P(A|K)$ (Aven, 2014). The major challenges with this approach are that, if the background knowledge is weak, it may be hard to precisely (non-arbitrarily) assess the probability of different deviations (Berner, 2017), the assumptions can conceal important aspects of risk and uncertainty, and the probabilities can appear to be the same, suppressing the fact that they could be built on either strong or weak knowledge (Aven, 2014).

In addition to the demands regarding the strength of background knowledge, risk assessments of UXO/ERW are also subject to the fact that surprises will occur, for example in terms of black swan and/or natech events. Black swan events could be a surprising extreme event (extreme in the sense that the consequences are large/severe) that lies outside the realm of regular expectation, because nothing in the past can convincingly point to its possibility (a predicted very low probability). Examples of this can be the mass-detonation of explosives or ammunition at dumping sites or in ships/shipwrecks loaded with munitions. These are examples of events that can have occurred numerous times in the past, but where the probability is still assessed as so low that the risk is normally regarded as negligible. Other events that could be regarded as black swan events are surprising extreme events relevant to one's belief/knowledge. For example, one Norwegian governmental report (Justis- og politidepartementet og Forsvarsdepartementet, 2012) assesses the risks related to UXO/ERW and, based on the authors' background knowledge, states that the ammunition "generally represents no danger". However, other assessors with a different set of understanding and/or background knowledge would easily identify several significant factual errors and critical deficiencies in the assessments, resulting in erroneous conclusions in the report. Other black-swan events could be so-called unknown-unknown events: extreme events for which there are no indications of this ever happening before and that no one expects to happen, as it is completely unknown to science (e.g., due to novel chemistry or technology). Natech events include large technological accidents triggered by major natural hazards such as the Fukushima Daiichi nuclear power plant meltdown during the Great East Japan Earthquake and Tsunami (GJET) in 2011 but could also include events triggered by "minor" natural hazards, such as a collapsing shipwreck resulting in a mass explosion of dumped ammunition or ERW. Whether an event is categorized as a black swan, a natech or otherwise will be dependent upon the definition and the perspective employed. An interesting observation is the fact that many of these events are generally foreseeable and therefore preventable if the associated risk is managed responsibly and if warning signs are not ignored (Krausmann and Necci, 2021).

Another factor that characterizes risk related to UXO/ERW is that the risk is multifaceted. Apart from the risk of an unplanned explosion, there are more dimensions that need to be considered (Olsen et al., 2020). While an explosion may be the most apparent danger from unexploded ordnance, there is a more covert threat from munitions' constituents leaking into the ground and water. Some munitions' constituents have been proven to contaminate living organisms, as well as the surrounding soil and groundwater (ATSDR, 1995; Koske et al., 2019; Koske et al., 2020a; Schuster et al., 2021; Yinon, 1990), and may also enter the food chain and directly affect human health upon the consumption of contaminated food (Maser and Strehse, 2021). Recent studies reveal the presence of explosive compounds (explosives including their degradation products) in biota at or near ammunition dumping sites (Koske et al., 2020b; Straumer and Lang, 2019), and a 2021 study on dumped ammunition in Norwegian waters reveals that biota in the vicinity of dumping areas are in fact exposed to several types of explosives and decomposition products; in fact, explosives were identified in biota from *all* the ammunition dumping areas that were examined (Johnsen, 2021). Recent reports also indicate that sea-dumped ammunition can act as a major source of mercury contamination to bottom sediments (Bełdowski et al., 2019; Kwasigroch et al., 2021); based on these reports, the ammunition dumped in Norwegian waters alone would represent mercury contamination that could amount to hundreds of tonnes, concentrated in the relatively small areas encompassed by the dump sites. As the rate of degradation of the munition components is heavily dependent on a number of technical- and environmental factors and, consequently, even on variations as a result of climate change effects (Scharsack et al., 2021), it is virtually impossible to estimate when a peak in the release of munition components will be reached.

All actions (or absence of action) taken towards mitigating risk from one perspective will (almost) always have an effect on another. For example, an explosive object located on the seabed could, from one perspective, be regarded as dangerous to move but relatively safe to neglect (regarding consequences to human health and safety in the case of an unplanned explosion), while, from an environmental perspective, the effect of neglecting the object could be that of leaking constituents polluting the environment. In addition, abandoned/neglected explosives will always represent a future threat to societal health and safety, in respect of people accidentally interacting with the ammunition and/or the ammunition being illicitly retrieved and the explosives harvested for use in terrorism or other criminal activity. If, on the other hand, the decision is made to remove or destroy the explosives, one must take into account that a planned or accidental detonation during recovery can result in habitat destruction, injuries to mammals and other marine life, the distribution of harmful substances into the marine environment or injuries to workers or the public (U.S. Department of Defense, 2016). If the explosive object is located next to secondary hazards, for example pipelines, shipwrecks or dumping areas, the negative environmental effect of an explosion could also include major emissions of harmful substances, such as oil, metals, contaminated soil and chemicals trapped in the sediments, etc., which potentially could have a major environmental impact. If an explosion should occur within critical distance of another explosive object (such as in a dumping area or shipwreck), there is a high chance of a mass explosion occurring, which could potentially result in the simultaneous detonation of tons of explosives (Alexander, 2019; Nordaas, 2019). What further complicates risk assessments regarding UXO/ERW is that there will also always be a risk of political, economic and societal consequences, from either perspective, as any policy choices, whether active or passive, could result in extreme consequences.

3. The Norwegian UXO/ERW risk approach: A case study

In relevant official Norwegian governmental documents concerning societal safety and security, risk is generally defined as a product of the probability of an incident and its related (negative) consequences, should the incident occur (e.g., Justis- og beredskapsdepartementet, 2017, 2021). The documents also mention that there is a level of uncertainty related to risk, but how the uncertainty-level is portrayed varies greatly. This is illustrated in some of the national risk assessments (i.e., Politidirektoratet og Politiets sikkerhetstjeneste, 2020; Politiet, 2021), which emphasize that a risk assessment will always contain a degree of uncertainty, and that one method for tackling this problem in a standardized and structured way is to use probability words in the analysis. For example, instead of quantifying the probability of an event (e.g., 60–90%), the probability is described using such words and phrases as "probably" or "there are reasons to expect that…". In these risk assessments, it appears that this specification is the *only* measure taken to manage uncertainty, and neither the strength of knowledge nor the level of uncertainty on which the assumptions are based is further addressed in the assessments. Another assessment, however, seems to abandon the use of probability words as a means of handling uncertainty or, rather, merges the probability words with the traditional quantified probability assessments (Politiets sikkerhetstjeneste, 2021). Although the report states that the use of probability words is implemented to reduce uncertainty and misunderstandings, the probability words are defined in the risk assessment as quantitative measures (e.g., *Likely* is defined as "there is a good reason to expect 60–90% probability"), indicating that the reasoning behind introducing probability words into the risk assessment in the first place (i.e., to *handle* uncertainty) is not fully assimilated.

Other definitions of risk, as well as formulations, also exist in other official documents, but there are some discrepancies amongst them (see Table 1). Whilst some documents define risk as merely probability times consequence (Risk = P × C) (e.g., Hæren, 2023; Klima- og miljødepartementet, 2009; Nærings- og handelsdepartementet, 200)), other documents state that the traditional approach, based on a mathematical calculation of P × C, is regarded as insufficient for managing risk, as it does not implement the uncertainty level to a satisfactory degree. Some documents state that there can be uncertainty related to both the probability and the assessment of possible consequences, and that risk therefore could be defined as the consequence of an event given an inherent uncertainty (e.g., Finansdepartementet, 2018; Forsvarsdepartementet, 2016). This is formulated as Risk = Consequences (C) + Uncertainty (U), or C, U, or, to visualize the activities (A), as Risk = A, C, U, where C is the consequences of an event (A) occurring.

In the Norwegian security sector, there are also several different approaches to risk assessments. In one comparative study by The Norwegian Defence Research Establishment (Busmundrud et al., 2015) on various applied approaches to security risk assessments for protection against intentional unwanted actions, some of the approaches used within the defence and justice sector are addressed. It appears that two main approaches are applied. One is based on the Norwegian Standard NS 5814:2021 (Standard Norge, 2021), in which risk is defined as an "expression for the combination of likelihood and consequences of an unwanted event". This is often referred to as the "two-factor model". The second approach is based on another national standard, as described in the NS 583-series (i.e., NS 5830, NS 5831, NS 5832 and NS 5834), where security risk is defined as "the relationship between threats towards a given asset and this asset's vulnerability to the specified threat"

Table 1
Examples of definitions and interpretations of ‘risk’ found in Norwegian governmental documents.

Source	Definition of ’risk’
Nærings- og handelsdepartementet [Ministry of Trade and Industry] (2001, p. 27)	“Can be expressed as a combination of probability and consequence as in the following simplified equation: Risk = Probability × Consequence“
Klima- og miljødepartementet [Ministry of Climate and Environment] (2009, p. 96)	“Probability × consequence”
Forsvarssjefen [Chief of Defence] (2010, p. 3)	“An expression of the combination of the probability and consequence of an undesirable incident“
Justis- og politidepartementet og Forsvarsdepartementet [Ministry of Justice and Police and Ministry of Defence] (2012, p. 15)	“Expression of the danger that undesirable incidents represent to people, the environment or material values. Risk is expressed by the probability and consequence of an undesirable incident“
Forsvarsdepartementet [Ministry of Defence] (2016, p. 41)	“Can be made as a product of the probability of an event occurring and the consequence if it occurs. It will be related uncertainty to both the probability and the assessment of possible consequences“
Justis- og beredskapsdepartementet [Ministry of Justice and Public Security] (2017, p. 26)	“A product of the likelihood that an event occurs and the consequences if it occurs“
Luftforsvaret [Air Force] (2017, p. 5)	“An expression of the combination of the probability and consequence of an undesirable incident“
Finansdepartementet [Ministry of Finance] (2018, p. 145–146)	“Consequences (related to a reference) + Uncertainty. C + U = (C, U). To visualize activities (A), we can say that Risk = A, C, U, where C is the consequences of an event (A) occurring“
Hæren [Army] (2020, p. 8)	“The degree of risk is the possibility of the danger occurring. Probability grade × degree of consequence“. Danger is defined as “an event that can cause death, injury, illness, material damage, or that of a failed mission. One can refer to danger as risk“.
Politidirektoratet og Politiets sikkerhetstjeneste [National Police Directorate and Police Security Service] (2020, p. 7–8)	An assessment of a threat, vulnerability to the threat and its consequences, where the assessment of of threats always include a degree of uncertainty
Justis- og beredskapsdepartementet [Ministry of Justice and Public Security] (2021, p. 11)	“An expression of the combination of the probability and consequences of a adverse event“
Politiets sikkerhetstjeneste [Police Security Service] (2021, p. 36)	“A combination of value, threat and vulnerability (…)”
Hæren [Army] (2021, p. 7)	“The possibility of unwanted incidents occurring, or probability × consistency“
Hæren [Army] (2023, p. 31)	“The possibility of unwanted incidents occurring. Risk is understood as probability × consequence“

(Standard Norge, 2012, 2014a, 2014b, 2016). This approach is often called the “three-factor model”, and the assessment of the likelihood of a scenario is intentionally omitted (Busmundrud et al., 2015). Within the justice sector, the Norwegian Police Directorate has recommended implementing the three-factor model in connection with risk assessments at all levels of the police service, but this is not noticeable in the various guidelines for risk and vulnerability analyses. For example, the national procedure for the cooperation of emergency services in the event of ongoing life-threatening violence has a clear two-factor approach to risk, and other guidelines state that the three-factor model should be employed but still exemplify the risk analysis methodology using the two-factor model (Sletten, 2018).

A white paper on fire safety from 2009 (Justis- og politidepartementet, 2009) states that, if explosive remnants of war are expected to represent an acute threat to life, health or public movement, the government is responsible for removing the risk that the explosives represent, and that it is of vital importance to remove the explosives as soon as possible, so that the general public is not exposed to any danger, and so that they can feel safe. Whenever explosives and ammunition of military origin are discovered and reported to the authorities, the police normally request assistance from explosive ordnance disposal services (EOD) within the Armed Forces to clear the ammunition. A subsequent report, concerning the inter-governmental responsibilities regarding explosive remnants of war, states that it appears reasonable that the Armed Forces are the body that must be responsible for the actual clearing of explosive war remnants, regardless of origin, even when the risk is not acute but where there is a well-founded need for clearing, for example in connection with the development of infrastructure (Justis- og politidepartementet og Forsvarsdepartementet, 2012). The report further states that the Armed Forces must be able to provide risk assessments related to known or possible instances of ERW. As the Armed Forces support relevant government agencies, as well as civilian society, with guidance and risk assessments, on a regular basis, this must be seen as a confirmation of an established practice. The risk assessments conducted are, however, not necessarily consistent or correlative. Whilst some would be based on international practice for military risk management, such as NATO standards (e.g., Allied Joint Publication-3, AJP-3), others could be based on various civilian standards.

In a directive from the Chief of Defence regarding safety management in the Armed Forces (Forsvarssjefen, 2010), as well as in the ensuing guidance paper from the Norwegian Defence Staff (Forsvarsstaben, 2010), it is stated that only one specific method should be used when assessing risk, and that this applies to all activities performed by the Armed Forces both domestically and abroad. According to the guidance paper, the purpose of this requirement is to describe a common method, covering most needs for risk assessment in the Armed Forces, which can be used regardless of department, level and case, including describing the performance of risk assessments to prevent unwanted incidents. It is further stated that other methods for risk assessment can be used if the activity/task requires it, but that the choice of alternative methods in that case must be justified. These instructions are implemented in the different branches of the Armed Forces. For example, the Directive on Safety Management in the Norwegian Air Force (Luftforsvaret, 2017) repeats that the instructions from the Chief of Defence are that, preferably, there should be only one method used for risk management, and that the method to be used within the Norwegian Air Force is Operational Risk Management (ORM), as described in The Norwegian Armed Forces Safety Rules and Regulations (Hæren, 2023). There is, however, a caveat that, in some cases, external requirements can necessitate the use of other methods. The Norwegian Army’s current compendium on risk management (Hæren, 2021) and the corresponding risk management booklet (Hæren, 2020) are both based on an adapted form of ORM. This intent to use ORM as the single method for risk management is also made clear in the introduction of the booklet, where it is stated that an adapted form of ORM is the preferred method used for risk management in the Norwegian Army. It is further stated that, although ORM is not primarily intended to be used to manage risks related to enemy activity, the method *can* be used to manage all types of risk.

The US-originating ORM bears clear resemblance to how the risk management process is described in the already implemented NATO standards and how the risk is visualized with the use of risk matrices (e.g., NATO, 2002, 2013, 2019); the Norwegian Army variation of the ORM is quintessentially a translated copy-paste version of the US ORM instructions already in use by many others (e.g., Department of the Navy, 2010; United States Marine Corps, 2004). There is, however, one particularly noteworthy difference that separates the Norwegian ORM version from its originator: where it is generally stated in the ORM fundamentals that, in situations when time is not a limiting factor and when the right answer is required, the in-depth level of the ORM should be applied. Examples of other situations where the in-depth level should be applied are also listed, and it is specified that the listed examples do not provide a comprehensive list: *"Other examples of application of ORM at the in-depth level include, but are not limited to: long term planning of complex or contingency operations; technical standards and system hazard management applied in engineering design during acquisition and introduction of new equipment and systems; development of tactics and training curricula; and major system overhaul or repair"* (Department of the Navy, 2010). In the Norwegian version, some of the fundamentals seem to be lost in translation, and it appears as if the in-depth level is only applicable to the following four listed situations: "long-term planning of complex training or operations; operations abroad in new countries/environments; the acquisition and implementation of new equipment and documentation; and implementing new tactics and training curricula"[1] (Hæren, 2020). The Armed Forces Safety Rules and Regulations (Hæren, 2023), which are referenced in most other regulations regarding risk management in the Norwegian Armed Forces and which it is mandatory for all branches of the Norwegian Armed Forces to use, further limit the methodology available for risk management, as they declare that risk is to be understood as merely the product of probability times consequence (Risk = P × C). The regulations also cover risk management to a certain degree, compressed into a summary of the ORM process, despite there being no mention of the need for other methodology or what actions to take if the decision is not time critical or if the *right* answer is required.

Whereas neither the ORM nor NATO standard AJP-3 includes any form of uncertainty analysis, on a national strategic level there seems to be a shift, in line with international development trends, from the traditional probability-based risk management towards a broader approach, allowing for both complexity and the uncertainty aspect to be an integral part of the risk management. The national risk assessment report from the Royal Ministry of Justice and Public Security (Justis- og beredskapsdepartementet, 2018) states that Norway has previously been criticized for not appreciating the complexity of risk, in this case not including, to a satisfactory degree, the relevant actors from the government and the private sector. An analysis of national crisis scenarios presented by the Norwegian Directorate for Civil Protection (Direktoratet for samfunnssikkerhet og beredskap, 2019a) states that, as opposed to in previous years, an uncertainty assessment is now also added as an integral part of the risk analysis. This includes that all assumptions and reasonings must be documented, and the inherent uncertainty must be described through a knowledge base assessment. This approach allows for both complexity and uncertainty, as one is forced to assess the strength of knowledge related to every relevant factor. This is further implemented in the first step of the risk analysis process, which requires the involvement and cooperation of all relevant actors, including all relevant subject matter experts, research establishments, responsible authorities, etc.

Consequently, there seem to be several definitions and/or formulations of risk used in official documents, guidelines rules and regulations in Norway. Although risk at a strategic level is defined as being a function of the probability of and a consequence of an event or series of events (e.g., Forsvarsdepartementet, 2016), the Armed Forces still adhere to the traditional risk approach, where the assessments about risk are generally decomposed into quantifiable attributes and portrayed using a form of a risk matrix. It is even specifically mentioned in the Army's Risk Management Booklet that "As of 2020, there has been no so-called paradigm shift in the Army. This means that some of the traditional approach still has value"[2] (Hæren, 2020, p. 7). Consequently, the traditional risk approach (i.e., P × C) is the predominant approach used for risk management in the Norwegian Army today and forms the basis of risk management methodology (i.e., the ORM) employed by all branches of the Norwegian Armed Forces (Hæren, 2020, 2023).

4. Discussion

As demonstrated in the case study of the Norwegian approach, military and operational risk management is often defined within the parameters of the two-factor approach: an expression for the combination of the likelihood and consequences of an unwanted event. As shown, ORM also falls within this category. The same goes for other commonly used methods, such as Military Risk Management, as described in AJP-3 (NATO, 2019), and Security Risk Management, as described in the United Nations Security Management System, UNSMS (United Nations, 2017). Whilst all clearly fall into the category of a two-factor approach, there are, however, some subtle differences. Whereas ORM and AJP-3 describe risk as a combination of frequency, or probability, and the potential consequences, or a relative perceived risk, the UNSMS (as well as the Norwegian Army, as seen in the abovementioned case in Section 3) defines risk as a mere product of a multiplication of an assessed transformed numeric value assigned to factors of probability and consequence (i.e., P × C), thus limiting the assessors' capability to make qualitative overall assessments of the various factors and their internal prioritization. In both cases, facts and assumptions are normally transformed into quantifiable measurable units and expressed in risk matrices or graphs, based on the matrix approach. The ORM does mention, however, that the use of a matrix is not strictly required but is helpful in identifying the risk assessment code (RAC), expressed as a single Arabic number, based on the value assigned to factors of probability and consequence, and therefore recommended.

The prerequisite of using any risk management method is first and foremost that the methodology is included in the orientation and training of all personnel, military and civilian, and that the level of training will be commensurate with rank, experience and leadership position (Department of the Navy, 2004). This is to ensure that all relevant personnel have a common understanding of risk and a common foundation for understanding risk. This approach to risk management provides a logical and systematic means of identifying and controlling risk. It is not a complex process but does require individuals to support and implement the basic principles on a continuing basis, and its intention is to offer individuals and organizations a powerful tool for increasing effectiveness and reducing accidents, as it aims to be accessible to, and usable by, everyone in every conceivable setting or scenario (Namazian and Eslami, 2011). It can certainly be argued that there are many positive aspects and effects of utilizing the two-factor approach to risk management, when it is used correctly and under the right circumstances. Most importantly, it provides the user with a familiar systematic structure to perform risk assessments. It can also be proved to enhance decision-making skills, based on a systematic, reasoned and repeatable process, and it can provide individuals with improved confidence to make informed risk decisions (Department of the Navy, 2010). The assessed risk can easily be communicated in a way that is

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[1] Authors' translation.

[2] Authors' translation.

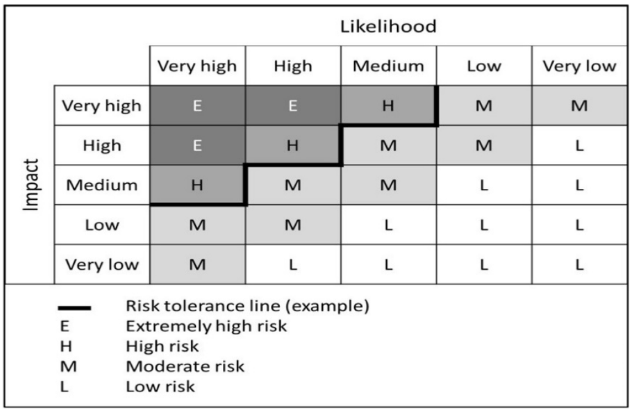
both quick and understandable, as it is built on a risk matrix that is intuitive in appeal and simplicity, as well as easy to construct, explain and score (Thomas et al., 2014). These are all attributes that could prove vital in time-critical situations, given proper attention to common risk assessment pitfalls such as over-optimism, misrepresentation, alarmism, indiscrimination, prejudice, inaccuracy and enumeration (Department of the Navy, 2010).

The limitations and inconsistencies of this approach could, on the other hand, lead to an oversimplification of the risk and a poor decision-making basis (Busmundrud et al., 2015). It is argued that the defined approach as such (i.e., based on a two-factor model) could be regarded as generally unsuitable for managing certain types of risk, unless supplemented by alternative assessments, particularly when addressing risks typically characterized by great uncertainty and complexity, and that the solution is to replace the probability factor with uncertainty (i.e., C, U) (Aven, 2012b). This risk perspective, as also mentioned in Section 3, covers that the activity leads to some consequences but also recognizes the fact that these consequences are not known (Aven, 2012a). From this perspective, the risk description is a subjective measure, and, rather than attempting to reference a correct, objective risk level or description, our understanding of risk is a function of our knowledge and our uncertainties (Khorsandi and Aven, 2013); the underlying thinking for this development path is a pragmatic view regarding which risk perspective is the most suitable (e.g., Aven, 2012b, 2020; Fjaeran and Aven, 2021; SRA, 2018).

4.1. The two-factor approach as the single decision-making tool for risk management of UXO/ERW

Risk matrices, such as the product of an ORM and as exemplified in NATO standard AJP-3 and UN Security Risk Management, are widely used tools for analysing, assessing and visualizing risk in many industries and employed extensively for risk-management purposes (Goerlandt and Reniers, 2016). The main benefits attributed to such matrices are their intuitive appeal and simplicity: they are perceived to be easy to construct, explain and score. They are also used extensively in risk communication, as their graphical displays provide us with an easy to portray focal point, typically free from the distractions of uncertainty and often used as a tool to summarize detailed analyses in lengthy reports that may not always be fully read by decision makers (Abrahamsen et al., 2014).

Risk matrices are, however, also the object of discussion and research in scientific environments, and several serious limitations and problems have been discovered. Just as the method is easy to use, the presentation of the result, the portrayed risk, is equally simple. By simplifying the steps too much, for example by the subjective classification of consequence and probability and defining risk scores and their relation to the scaling of the categories, one is in danger of losing critical elements in the analysis or of these elements being dimmed (Busmundrud et al., 2015). Some of the other issues that are discussed include the consistency between the risk matrix and quantitative measures; the corresponding appropriateness of decisions based on risk matrices; the limited resolution of risk matrices, resulting in “risk ties”; and the aggregation of scenarios and consequences for a single event in different areas of concern and for multiple hazards originating from a single activity (Goerlandt and Reniers, 2016). For example, the use of a two-dimensional risk matrix, often coloured, with probability along one axis and consequence along the other, gives a visually simple expression of the results of the assessment, but one can argue that plotting scenarios into the risk matrix allows the risk analyst – and not the manager – to make the decisions through colour coding (Busmundrud et al., 2015), and, as illustrated by the example in Fig. 1, it is impossible to assess the accuracy of the background data and the level of uncertainty related to the risk assessments based solely on the information presented in the risk matrix, as the matrix is fundamentally indiscriminate regarding data quality. And, although the basis of the matrix should be a thorough and methodical review of values, vulnerabilities, consequences and probabilities, the matrix is often perceived as the decisive result of the analysis, whereas it is really only a summary of far more important results such as the vulnerability assessment and the impact assessment. It is therefore an absolute prerequisite that decision makers familiarize themselves with the entire risk assessment, including assumptions, assessments and uncertainties, and not just settle for looking at the risk matrix (Busmundrud et al., 2015).



		Likelihood				
		Very high	High	Medium	Low	Very low
Impact	Very high	E	E	H	M	M
	High	E	H	M	M	L
	Medium	H	M	M	L	L
	Low	M	M	L	L	L
	Very low	M	L	L	L	L

▬ Risk tolerance line (example)
E Extremely high risk
H High risk
M Moderate risk
L Low risk

Fig. 1. Example of a risk matrix (NATO, 2019).

When discussing the risk management of UXO/ERW, these factors are fundamental, as the complexity and level of uncertainty are inevitably high. There is, for example, little knowledge about the long-term environmental consequences of chemical constituents leaking from the ammunition. The same goes for research on how the properties of the individual pieces of unexploded ordnance or their internal components vary over time, in terms of technical and chemical stability. Some of this information may, however, never be known for certain, as any examined individual object may represent a set of unique properties, rendering the collected data not directly transferrable to similar objects with different properties or to other object categories. These differences in properties could originate from several factors, such as local environmental variations (e.g., temperature, humidity, pressure, salinity, currents, etc.), technical state (i.e., armed or unarmed) and various degrees of the technical and chemical decomposition of materials.

There will also always be individual variations, as a result of the different materials and/or explosive compositions used and their subsequent chemical reactions, their physical environment and numerous other factors, making individual objects more or less sensitive over time. Making a subjective classification of various consequences and probabilities related to unexploded ordnance will, therefore, depend extensively on the available data and the assessors’ background knowledge and their relevance to the individual objects and the environment in which they are located. Without detailed studies at the exact location of interest, such assessments will always carry a high degree of uncertainty.

An additional layer of uncertainty will arise as a result of the assessors’ knowledge about, and the relevance of, the different properties related to the physical conditions under which the ordnance has been stored, the location in which it is situated, its surroundings (i.e., safety/security for people, infrastructure, environment), the situation (i.e., urgency, level of prioritization, etc.) and the latitude and range of possibilities available to the assessor, to mention but a few.

The complexity of the situation will also bring with it a layer of uncertainty, as there is no definitive way of predicting exactly how various EOD methods (ranging from open detonation to neglecting the object) may affect its surroundings from a short-/long-term perspective (including environmental) in each particular situation.

When it comes to risk management for UXO/ERW, it is therefore generally not possible to obtain consistency between quantitative measures and the corresponding appropriateness of decisions based on risk matrices, without a relatively high degree of uncertainty. Based on these factors, the traditional matrix-based two factor approach can be argued to be generally deemed unsuitable when it comes to risk management for UXO/ERW.

4.2. *Criteria for alternative risk assessment methods*

It can be argued that there is a need to emphasize uncertainty in detailed risk assessments, more so than can be visualized by a risk matrix based on the use of a two-factor analysis such as the ORM, AJP-3 or UNSMS. This is not to say that the traditional approach should not be used; it certainly has great value in assessing, managing and communicating risk in time-critical situations, but, as stated in the ORM fundamentals, in "situations when time is not a limiting factor and the right answer is required for a successful mission or task", some of the tools used at the in-depth level include "thorough research and analysis of available data, use of diagrams and analysis tools, formal testing or long term tracking of associated hazards" (Department of the Navy, 2010). Although the AJP-3 states that "Risk analyses can be undertaken with varying degrees of detail, depending on the risk, the purpose of the analysis, and the information, data and resources available", neither the AJP-3 nor the UNSMS mentions situations where more accurate risk assessments are required and where the described methodology may be inadequate. The ORM, on the other hand, states that some detailed risk assessments will require the use of advanced risk assessment tools and that "professional expertise will probably be needed when performing In-Depth ORM" (United States Marine Corps, 2004). In-depth ORM is used to study the hazards and associated risks in a complex operation - in which the hazards are not well understood and which is a long-term application that involves research, various analysis tools and long-term tracking of the associated hazards - typically used for high-visibility risks and requiring a lot of time and resources? (U.S. Air Force, 2021). Contrary to the AJP-3 and the UNSMS, the ORM also endorses the use of other methodology for detailed risk assessments within strategic (in-depth) ORM. It can be argued, however, that because of the inherent limitations of the traditional risk matrices, the ORM risk management process cycle, in which risk matrices are a prerequisite when assessing the hazards, is only applicable in situations in which time is a limiting factor and when the right (best) answer is not absolutely required (i.e., on the deliberate level only). For an example of the ORM risk management levels and process cycle, see Fig. 2.

There are several models that could be applicable in order to support existing methodology when performing detailed (in-depth) risk analyses, including models based on the aforementioned three-factor approach, as described in the NS583-series. However, as reported in a study that examined methods (i.e., US Army) for assessing the risks of UXO and munitions' constituents on former military training land (MacDonald et al., 2004), any single method for assessing risk at such sites will normally not suffice. Rather, different methods must be utilized or developed that are applicable to the unique situations, the different steps in the UXO/ERW risk assessment process and the different elements of risk. What is crucial is that – whatever method is chosen – the results must be documented and communicated in a written report that provides a basis for decisions, and the inherent complexity and uncertainty in UXO risk assessments must be clearly communicated. This will also contribute to creating conditions for building critical trust within both the risk assessment and risk management processes (Fjaeran and Aven, 2021). Based on uncertainty and strength of knowledge analysis, there are several existing models for how this could be visualized in risk matrices, if so desired, including uncertainty boxes and bubble diagrams, as well as matrices with prediction intervals and strength-of-evidence assessments (see e.g., Flage and Aven, 2017; Goerlandt and Reniers, 2016).

Although no best practice has been identified, and bearing in mind the fact that cases exist for which conventional techniques of risk assessment and analysis are unable to give any authoritative answers (Alexander, 2019), there are some key characteristics that may enhance and strengthen UXO/ERW risk assessments. In addition to having a structured process that is transparent, traceable and verifiable (Busmundrud et al., 2015), one should have a holistic perspective and, based on the complexity of risks, establish a working group with broad expertise, securing the involvement and cooperation of all relevant subject matter experts, research establishments and authorities, in the risk analysis process. This could prove to be beneficial in several ways. First, cooperation between different subject matter experts could result in recognizing important information, known by the subject matter experts but not necessarily documented in the process so far. In addition, the synergy effect of cooperation could result in the development of new knowledge and a common understanding of risk and risk factors, and, by interacting with others, different views and opinions can be clarified and the number of misconceptions and misunderstandings reduced, thus improving the overall quality of the risk analysis (Direktoratet for samfunnssikkerhet og beredskap, 2019a). As Charles Perrow (1999) described in *Organizing to Reduce the Vulnerabilities of Complexity,* a rich environment of diverse interests could even be prone to paying more attention to security and safety than an organization working in solitude. Moreover, a rich organizational environment, albeit partially adversarial, would also be prone to allowing inputs that could reduce the

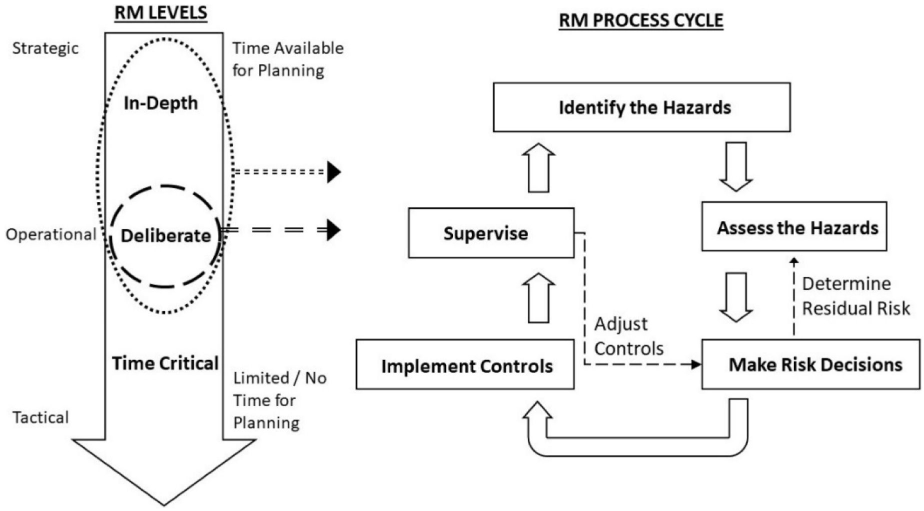


Fig. 2. ORM Risk Management Levels and Process Cycle (based on Department of the Navy, 2010).

self-indulgent fiction of unrealistic assumptions and analyses; without these inputs, false "knowledge" could prevail. Another key characteristic of enhancing and strengthening UXO/ERW risk assessments would be the mapping of the uncertainty and strength of knowledge among the experts in the working group but also regarding the relevant available data (Busmundrud et al., 2015). With respect to how uncertainty is represented in the input parameters, the strength of knowledge assessment is a critical step, as it is directly linked to epistemic uncertainty. For example, in the traditional multi-hazards risk aggregation methods, the aggregation is normally performed by a simple arithmetic summation of risk from different contributors. The final results are then compared to the established quantitative safety goals and acceptance criteria, to support decision-making. However, this simple arithmetic summation does not take into account the fact that the risk estimates from different contributors are based on different degrees of subjective understanding, experience, knowledge and beliefs and, therefore, might have different degrees of realism (Bani-Mustafa et al., 2020). The different experts and contributors would normally also represent different organizations or stakeholders, with their own unique priorities, perspectives and schools of thought regarding risk and risk management.

The importance of assessing the strength of knowledge becomes even more apparent in risk-informed decision-making, where the decision maker needs to choose amongst different alternatives based on the estimated risk, simply choosing the alternative with the lowest risk estimate. As risk assessments are subjective by nature, the background knowledge on which the risk assessment is based needs to be taken into consideration when describing and communicating risk. As knowledge can be more or less strong, with uncertainty hidden within it, all relevant uncertainties cannot be properly reflected simply by addressing the conditional risk description (Langdalen et al., 2020). Without considering the degree of knowledge the assessments are based on, the alternative with a lower risk estimate might not be the right choice. This is partly due to the fact that the risk picture is complex, not only in that it has multiple dimensions (e.g., safety, security, economic, political) but also in that information about each dimension contains a different degree of strength of knowledge and inherent uncertainty. This makes combining information into a unified risk assessment a formidable problem, and such assessments should, therefore, include uncertainty as an integral element, thus accounting for the predecisional state of knowledge and its impact on the incentive to take or avoid risk (Vertzberger, 1998). When assessing or developing a risk mitigating strategy, it is therefore imperative to assess the strength of knowledge of the risk assessment model, as it refers to the level of knowledge that supports the model and in that way directly affects the trust one has in the results obtained by the risk assessment and the decisions that are based on it (Bani-Mustafa et al., 2020). To meet these challenges and to inform the decision maker of the foundation of the risk assessment, it is of vital importance that the risk assessment includes a framework to identify and assess the background knowledge on which risk can be assessed (Direktoratet for samfunnssikkerhet og beredskap, 2019b; Langdalen et al., 2020). Through this increased focus on the knowledge dimension, one can seek to improve the understanding of relevant risk issues, increase risk awareness and avoid potential surprises (Veland and Aven, 2015).

5. Conclusion and recommendations

As the above analysis demonstrates, there are several challenges related to assessing UXO/ERW risk, one in particular being the level of uncertainty as a result of not only complexity but also, typically, the lack of both knowledge and relevant or available data; the elements of surprise and black swans also represent a level of uncertainty. Events that seldom occur and events for which we have very limited historical reference material are particularly difficult to assess in the traditional technical view on risk (e.g., P × C) (Kringen, 2015). In order to make informed decisions, we must therefore map the uncertainty in risk assessments, utilizing applicable and relevant methodology.

Another challenge is how risk is portrayed and communicated. Transforming risk into quantifiable values presented in risk matrices etc. may also result in an oversimplification of the risk, as critical elements (e.g., uncertainty) in the analysis may be dimmed or lost. As the described two-factor approach models (i.e., ORM, AJP-3 and UNSMS) do not have a structure capable of managing or communicating this uncertainty, there is a need to strengthen detailed risk assessments with the means of more relevant methodology. This could, for example, include an uncertainty and strength of knowledge analysis, visualized within a matrix, if applicable.

We have seen from the analysis, as well as from the case in Section 3, that neither the Norwegian national official guidelines nor the international standards for risk assessment are uniform or harmonized, either in addressing the fundamental view on risk or when suggesting an appropriate approach for risk assessment and management. This may result in an increased workload and added complexity, which can in itself introduce risks. Regulatory convergence should therefore be of critical importance, to promote safety and improved operational efficiency.

The case in Section 3 further illustrates the challenges of developing risk management methodology based on (parts of) selected existing methods, adopted to fit into prevailing (traditional) ideas and principles. The case shows that limiting available methodology to any particular method (in this case the ORM) leaves no room for judgements of whether or not this method is applicable or relevant to the exact problem at hand. The case also illustrates how a presumably inattentive or cursory decision, to introduce the P × C perspective in ORM, can result in a potentially unintentional limitation of the assessors' capability to perform qualitative overall assessments of the various factors and their internal prioritization.

Based on this, it is therefore strongly recommended that the current standards and regulations forming the basis for UXO/ERW risk assessments are revised, so that (i) other methodologies to support or complement a risk assessment are made available, ensuring the inclusion of certain identified key factors, such as the high level of complexity and uncertainty that characterizes risk related to UXO/ERW, (ii) risk matrices used in risk communication or decision-making are used with caution and, preferably, adopted to visualize uncertainty where applicable, and (iii) regulatory contradictions and inconsistencies are mitigated.

As it seems, various standards and risk assessment guidelines are not always uniform, either in addressing the fundamental view on risk or when suggesting an appropriate approach for risk assessment and management. Whilst some documents suggest a broader perspective on risk, recommending addressing both strength of knowledge and uncertainty, as well as advising against applying the traditional probability-based risk approach (i.e., P × C) in risk assessments, others state that risk is to be understood as merely the combination of frequency, or probability, and the potential consequences, in which both facts and assumptions are to be quantified and summarized, transforming risk into a definite measurable unit. The conclusion of the paper is that the studied risk assessment methodology urgently needs to be revised, in order to improve the decision-making basis in non-time-critical situations, when assessing risks characterized by a high level of complexity and uncertainty, such as those regarding unexploded ordnance and explosive remnants of war.

CRediT authorship contribution statement

Geir P. Novik: Conceptualization, Writing – original draft. **Eirik B. Abrahamsen:** Validation, Supervision, Conceptualization, Writing - review & editing. **Morten Sommer:** Validation, Supervision, Conceptualization, Writing - review & editing.

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.

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Paper III

Analysis of samples of high explosives extracted from explosive remnants of war

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Analysis of samples of high explosives extracted from explosive remnants of war

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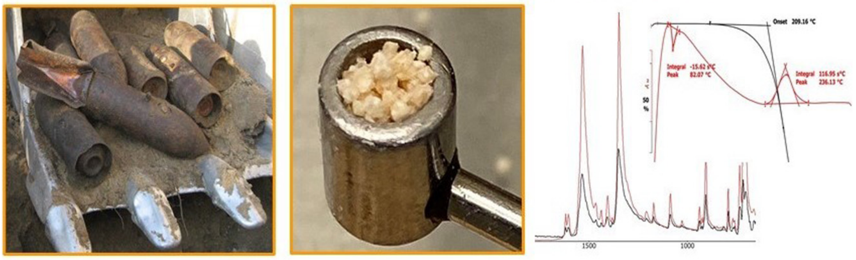
HIGHLIGHTS

- Huge amounts of explosive remnants of war remain in nature.
- The performance and impact sensitivity of WW2 munitions has been studied.
- Analysed high explosives (TNT and PETN) were extracted from live ordnance.
- Explosives were found to be in good condition with no detected decrease in sensitivity.

GRAPHICAL ABSTRACT

Analysing the condition of aging explosives



High explosives extracted from WW2 munitions analysed and tested for impact sensitivity

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ABSTRACT

Millions of tonnes of dumped ammunition and explosive remnants of war remain in nature both on land and at sea. It is well known that the ordnance could represent a definite explosive risk if disturbed, and that some of the constituents in the ammunition could be harmful to humans and the environment. Nevertheless, a tacit assumption by decision makers is that, if left alone, the ammunition will slowly become harmless over time. Explosive remnants of war, however, represent not only an environmental risk but also a security and safety risk, as members of the public could come into contact with them, and fear is growing that ageing munitions could explode and/or be misused. In recent years, several concerns have been raised regarding the presence of dumped ammunition and explosive remnants of war, the potential dangers they represent, and the fact that the deterioration rate of the explosives could be significantly lower than previously assumed. In the present work, thermal and impact sensitivity studies of high explosives extracted from explosive remnants of war were performed, to determine whether or not the explosives have deteriorated to such a degree that a noteworthy decrease in performance and/or impact sensitivity can be recorded. The thermal behaviour of the explosives was studied using thermogravimetry analysis, and the impact sensitivity was determined using a fallhammer machine and the Bruceton test procedure. The thermal and impact sensitivity results obtained in the analysis indicated no deterioration of high explosives in the examined explosive remnants of war that would denote any significant reduction in performance and/or impact sensitivity.

1. Introduction

In the aftermath of war and armed conflict, millions of tonnes of explosive remnants of war (ERW) and unexploded ordnance have been dumped in landfills, lakes and seas (Kampmeier et al., 2020; OSPAR Commission, 2009). It was believed that the ammunition and explosives would deteriorate and slowly become harmless over time. Although the dumpsites are

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acknowledged by the authorities, their real extent and their effect on environmental and societal safety are mostly unknown (Kampmeier et al., 2020). As a result, there has been an assumption that, if left alone, the ammunition will generally not represent any significant risk. Consequently, explosives and ammunition in dumping sites, shipwrecks and ammunition-contaminated land are often ignored (e.g., Alexander, 2019; Long, 2005), and in many cases no effort is made to either survey the sites or clear the ammunition. The munitions do, however, represent a steadily increasing concern regarding both safety and security. Although the societal risk related to ERW has been described as more hypothetical, it is now increasingly clear that simply neglecting the problem is no longer a viable solution, as continuous deterioration of the munitions can lead to an increased risk to societal safety (Craig and Taylor, 2011; NATO, 2010; OSPAR Commission, 2009). Studies show that the leaking and bioaccumulation of toxic constituents from corrosive munitions poses a threat to the ecosystem and that several of the chemicals used in ammunition are highly poisonous and have been proven to contaminate living organisms, as well as the surrounding soil and groundwater (ATSDR, 1995; Koske et al., 2019; Koske et al., 2020; Schuster et al., 2021; Yinon, 1990). Some munitions' constituents may also enter the food chain and directly affect human health upon the consumption of contaminated food (Maser and Strehse, 2021).

The most prominent risk, however, is naturally that of an unplanned explosion. Such an explosion could occur as the result of an intended act of terrorism or crime, utilizing the explosive effect of high explosive munitions or harvested explosives from such, or accidentally as a result of the intentional or unintentional disturbance of the ordnance (e.g., construction work, moving, rendering safe or disposing of ammunition). An increasing number of spontaneous detonations have also been reported in ageing munitions, possibly resulting from deteriorating technical or chemical properties (Ford et al., 2005; Nordaas, 2019), and research indicates that ageing explosive ordnance can become increasingly sensitive to external stress (Albright, 2012; Hamer, 2004; Long, 2005; Pfeiffer, 2012).

There are, however, only a very limited number of studies that analyse the properties of high explosives (HE) retrieved from ageing ERW, but those that do exist suggest that the explosives are in very good condition (e.g., Nawała et al., 2020). The main aspect of this work is to analyse explosives retrieved from a representative number of samples of actual ageing ERW, with particular attention paid to the impact sensitivity of these explosives. Whilst the most sensitive part of HE ordnance generally is the primary explosives, this particular study will focus exclusively on a limited selection of secondary explosives: Trinitrotoluene (TNT) and Pentaerythritol Tetranitrate (PETN), as shown in Fig. 1. This selection was made because these particular types of explosives were widely used throughout World War II (WW2) and can be expected to be encountered wherever WW2 munitions are located. Additionally, there is a much higher frequency of secondary explosives being encountered, partly due to the fact that they represent a much bigger mass in comparison with the incorporated primary explosives but also because much of the discarded ordnance was dumped separately from its initiating sources, in which the primary explosives are located (Bełdowski et al., 2019). Although primary explosives are considerably more sensitive to external stress than secondary explosives and can easily detonate by the action of a relatively weak mechanical shock, heat, spark and/or friction, they are often also easily desensitized by the presence of humidity. Additionally, if the initiating source (e.g., the fuze) is fitted to the ordnance, the main explosive charge is normally protected from the explosive impact of the primary explosives by the means of mechanical safety devices, thus preventing a detonation transfer to the main charge. Although secondary explosives cannot be initiated as easily as primary explosives, and are usually therefore initiated by means of a detonator containing primary explosives, they can in practice also be initiated under the influence of other forms of external energy (thermal, mechanical, etc.) (Suceska, 1995). As all interaction with ERW that introduces sufficient external energy to the explosives can theoretically initiate a chemical reaction resulting in a detonation, it is therefore of vital importance to establish the relevant thresholds.

Consequently, this study focuses on the chemical properties of the most common of explosives originating from WW2 ERW, TNT and PETN, and whether or not the ageing of the explosives has led to any significant changes in respect to thermal properties and impact sensitivity.

2. Materials and methods

2.1. Sample characteristics

TNT is by far the most important explosive for the blasting charges of all weapons (Meyer et al., 2005). It is normally charged by casting or pressing and can be applied pure or mixed with other substances such as ammonium nitrate (e.g., Amatols), aluminium powder (e.g., Trional), RDX (e.g., Cyclonite) and combinations (e.g., Torpex). It is considered one of the least impact- and friction-sensitive of all common explosives, and cast charges of TNT are insensitive to blasting caps and require a booster charge (e.g., PETN) for safe initiation. This, combined with a fairly high explosive power and good chemical and thermal stability, has meant that TNT has been the most widely used military explosive since before World War I (WWI) up to the present time (Kaye and Herman, 1980).

PETN, on the other hand, is a much more sensitive explosive and is considered one of the most powerful and brisant explosives known (Kaye, 1978). It is a very stable explosive but, as it is much more sensitive than TNT, requires very little priming charge. PETN is often used in high-capacity blasting charges and detonation cords and, if phlegmatized, may be used to produce boosters and fillings for smaller-calibre projectiles (Meyer et al., 2005). It can be applied pure or mixed with other substances such as TNT (e.g., Pentolite) or RDX (e.g., Semtex).

Both TNT and PETN are considered virtually insoluble in water (Meyer et al., 2005). This property affects their long-term persistence in the aquatic environment; therefore, dependent on a number of factors, the explosive

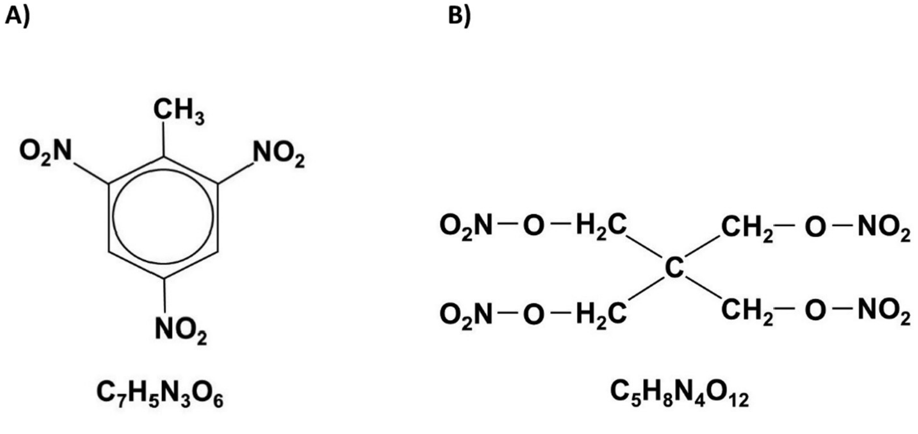

Fig. 1. Chemical formulas of the high explosives extracted from explosive remnants of war in this study; A) TNT and B) PETN.

filler present in munitions could take centuries to dissolve (Craig and Taylor, 2011).

2.2. Sampling location and methodology

To ensure reliable data, all samples have been extracted from live ordnance originating from WW2. Relevant objects were ERW in Norway containing high explosives. Consequently, all explosive objects utilized for the extraction of their high explosives are ERW that have been localized and/or reported to the relevant governmental agencies. All samples of high explosives have been extracted from the relevant objects and analysed within the last three years (i.e., 2020–2022). The author carried out the physical extraction of the high explosives from the ordnance. In situations where it was deemed too unsafe or impracticable to move the explosive objects, the extraction was performed at the location where the object was first discovered. The majority of objects that had to be dismantled in the field were located in areas of heavy fighting during WW2. For the most part, this concentrates around circumpolar Norway, more particularly in Troms and Finnmark county in the northernmost part of Norway. Any required disassembly of the objects in order to access the high explosives was normally carried out with the use of explosives (e.g., shaped charges, etc.), as shown in Fig. 2, and/or with the use of a lightweight, portable and specially customized metal band saw.

Samples that were deemed safe to move and to transport were normally dismantled/disassembled in specialized explosives workshops, belonging to defence agencies under the Norwegian Ministry of Defence, and under the directions and regulations of the Norwegian Armed Forces. Any required disassembly of the objects was normally done mechanically (i.e., reversed engineering), as shown in Fig. 3, with the use of remote-controlled tooling (e.g., lathe, band saw, drill, etc.) or manual dismantling where applicable.

After any required disassembly of the explosive object, an initial sample of the high explosives was retrieved at the point of entry. The explosives were visually examined, and any surface changes in homogeneity (i.e., variations in colour, texture, consistency, etc.) were recorded. Wherever possible, samples were extracted at the central core of the explosives, from any contact surfaces (i.e., where the explosives come into contact with the ammunition body or metal parts), at the entry point, and wherever any fluctuations in homogeneity were observed.

In total, samples of high explosives were extracted from over 60 individual ERW and subjected to analysis and testing. Of these, 50 samples identified as TNT and PETN were included in this study. Analysed samples consisting of other high explosives (e.g., Tetryl, RDX, etc.) or compositions of different explosive substances (e.g., Amatol, Donarit, Pentolite, etc.) are not included in the study, at this time. The preliminary results of the analyses of the explosives omitted from this study indicate, however, that further research should be conducted, as some of the analysed samples demonstrate an impact sensitivity that conflicts with expected values (i.e., a significantly increased impact sensitivity). Of the 50 samples included in this study, 25 were located on land and 25 submerged in water. Twenty-six of the samples were found to be intact, with no exposure of the explosives to the elements, three samples were found to be partially open (i.e., water intrusion to the explosives), and 21 were open (i.e., full exposure of the explosives to the elements). All 50 samples included in this study were extracted at the central core of the explosives. Extracted samples not included in this study (i.e., other than central core) will be subject to further, future analysis.

Fig. 2. German 10.5-cm HE projectile cut with flexible linear-shaped charge.

Fig. 3. German 20-mm HE projectile mechanically disassembled.

2.3. Storage and preparation of samples

Once extracted, the high explosive samples were immediately placed in airtight containers (i.e., 50-ml sterile polypropylene screw-cap tube) and stored in approved ammunition storage facilities. Apart from humidity control (at about ≤50 %), the samples were stored in normal atmospheric conditions, in continuation of the normal temperature fluctuations that would appear in nature, albeit with less violent variations, as the samples were stored under cover, protected from direct sunlight.

Preceding the impact sensitivity analysis, the samples were prepared in accordance with the requirements of NATO STANAG 4489 - Explosives, Impact Sensitivity Tests (NATO, 1999) and the United Nations Manual of Tests and Criteria - Classification Procedures, Test Methods and Criteria Relating to Explosives, Test 3 (a) (ii) (United Nations, 2019): Powdered substances are sieved and only a fraction with a particle size of 0.5 to 1.0 mm is used for testing. Pressed or cast substances are crushed and then sieved. The fraction passing a 1000-μm sieve and retained on a 500-μm sieve is used for the test. Rubbery or composite materials are cut into slices of 3-mm thickness and approximately 4-mm length and width (NATO, 1999), or a cylindrical tube of 40-mm^3 capacity (3.7 mm diameter × 3.7 mm) is inserted into the substance, and, after levelling off the surplus, the sample is removed from the tube by means of a wooden rod (United Nations, 2019).

As several of the objects from which the samples were extracted were damaged (e.g., partially destroyed, corroded, disassembled, etc.), some of the explosives were saturated with water. In preparation of further analyses, explosives positively identified as TNT or PETN (See Section 3.1) were placed in a humidity-controlled environment to reduce the relevant humidity (RH) in the sample to about 20 % RH.

2.4. Description of analysis equipment and methodology

2.4.1. FT-IR spectrometer analysis

Fourier transform infrared spectroscopy (FT-IR) uses a mathematical process (Fourier transform) to translate the raw data into the actual spectrum. The FT-IR method can be used to obtain the infrared spectrum of transmission or absorption of a sample of explosives. FT-IR identifies the presence of organic and inorganic compounds in the sample, and the specific molecular groups prevailing in the sample will be determined through spectrum data in the automated spectroscopy software (Shameer and Nishath, 2019).

In this study, FT-IR has been used to characterize samples of high explosives retrieved from ERW. A Thermo Scientific TruDefender FT and a Smiths Detection HazMatID 360 apparatus were used for this analysis, and the tests were performed in accordance with the requirements described in the applicable test procedures. The technique involves placing a sample on top of a diamond crystal embedded in a stainless steel disk, whilst an infrared beam is passed up from the spectrometer through the crystal, reflected internally in the crystal and back towards the detector, which is housed within the spectrometer (HazMatID 360). The device collects the molecular fingerprint of the sample, compares it against an on-board chemical library and then provides an identification of the substance or mixture of substances, as well as presenting the sample infrared absorption frequency in the spectrum range 600–4000 cm^{-1}, compared with the relevant library hit(s). Explosive samples positively identified by FT-IR as either TNT or PETN were included in this study and selected for further analysis. An example of the analysed samples is shown in Fig. 4.

2.4.2. Thermal analysis

Thermogravimetric analysis (TGA) is an analytical technique used to determine a material's thermal stability and its fraction of volatile components, by monitoring the weight change that occurs as a sample is heated, cooled or held at constant temperature (Rajisha et al., 2011). The record is a thermogravimetric or TG curve. Single Differential Thermal Analysis (SDTA) is a procedure for recording the difference in temperature between a substance and a reference material, against either time or temperature, as the two specimens are subjected to identical temperature regimes in an environment heated at a controlled rate. The record is the single differential thermal or SDTA curve; the temperature difference is usually plotted on the ordinate, with endothermic reactions downwards, and time or temperature on the abscissa, increasing from left to right (Kaye and Herman, 1980). The analyses were carried out on the high explosive samples, in order to identify characteristic temperatures, which are exhibited whilst heating the sample at a constant rate, with the aim of characterizing the materials with regard to their composition.

A Mettler Toledo TGA/SDTA851e apparatus was used to investigate the thermal properties of the samples. Preceding the analysis, the samples were crushed and then sieved where applicable. After calibration of the apparatus (i.e., weigh-in of empty pan), a weighed sample (≈ 3 mg) with particle size <500 μm was placed in a 100-μl aluminium pan and positioned in the sample holder of the instrument. All measurements were performed at a single heating rate of 10 K/min, and the data were recorded as mW versus temperature/time from 40 °C to 400 °C. An inert atmosphere was maintained by using a nitrogen gas purge at a rate of 50 mL/min throughout the experiment.

2.4.3. Impact sensitivity analysis

For the impact sensitivity determination, several types of impact testing apparatus, known also as Fallhammer Apparatus, are used. These apparatuses operate on the same principle: a sample of the tested explosive is subjected to the action of falling weights of different sizes, and the parameter to be determined is the height of fall at which a sufficient amount of impact energy is transmitted to the sample for it to decompose or explode (Meyer et al., 2005). The main difference between the various apparatuses is related to their design and the manner in which the sample is subjected to the drop weight impact via different types of plungers (Suceska, 1995). The fallhammer method was modified by the German Bundesanstalt für Materialprüfung (BAM), in order to obtain more reproducible data (Meyer et al., 2005), and this apparatus (the BAM Impact Machine or the BAM Impact Apparatus) is considered to give reasonably reproducible results (Suceska, 1995).

The BAM Impact Apparatus, OZM BFH 12, was used for this analysis, and the tests were performed in accordance with the requirements of the test procedure described in NATO STANAG 4489 - Explosives, Impact Sensitivity, Annex C; BAM Impact Machine (NATO, 1999). The BAM Impact Machine, which is presented in Fig. 5 A, consists of two coaxially arranged steel cylinders with polished surfaces and rounded edges, held in place by a cylindrical steel guide ring with an inner diameter of 10 mm. The impact device is prepared by partially pushing one of the cylinders into a guide ring and positioning it on the intermediate anvil fitted with a locating ring, as shown in Fig. 5 B. Using a measuring spoon, 40 mm^3 of the prepared (e.g., crushed and sieved to particle size 500 μm to 1000 μm) high explosive samples are placed inside the open impact device, making sure that a central heap is formed. The impact device is then closed with a second steel cylinder, by carefully pressing it into the guide ring until it touches the sample. For the impact sensitivity testing, different drop weights, with a mass of 0.25 to 10 kg, are available. The body of each drop weight has two guide grooves, in which it moves between the guide rails. It is equipped with a suspension spigot, which arrests the weight in the release mechanism, and is further provided with a cylindrical striker, a height marker,

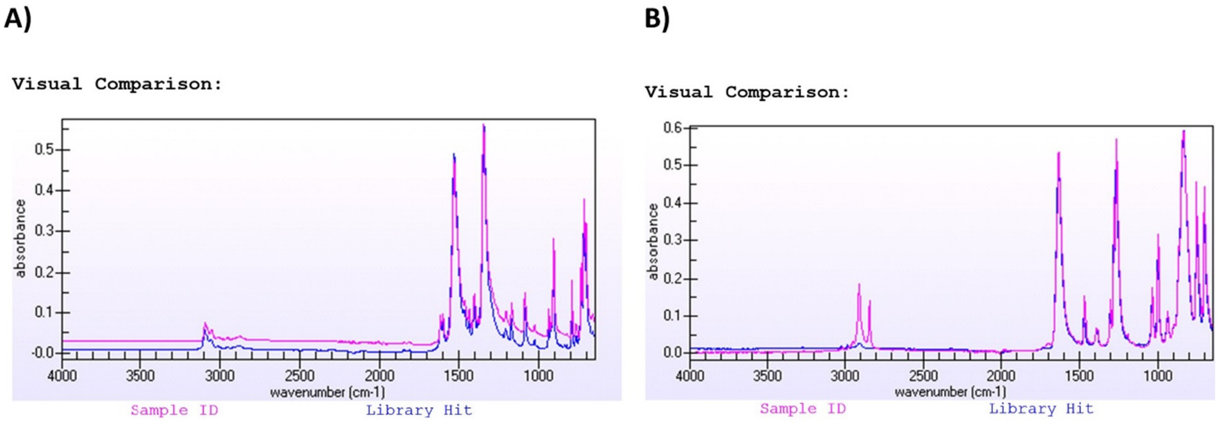

Fig. 4. FT-IR spectra of A) TNT extracted from an intact German 1-Kilogram Sprengbüchse 24 and B) PETN extracted from a partially destroyed German anti-tank mine (booster charge).

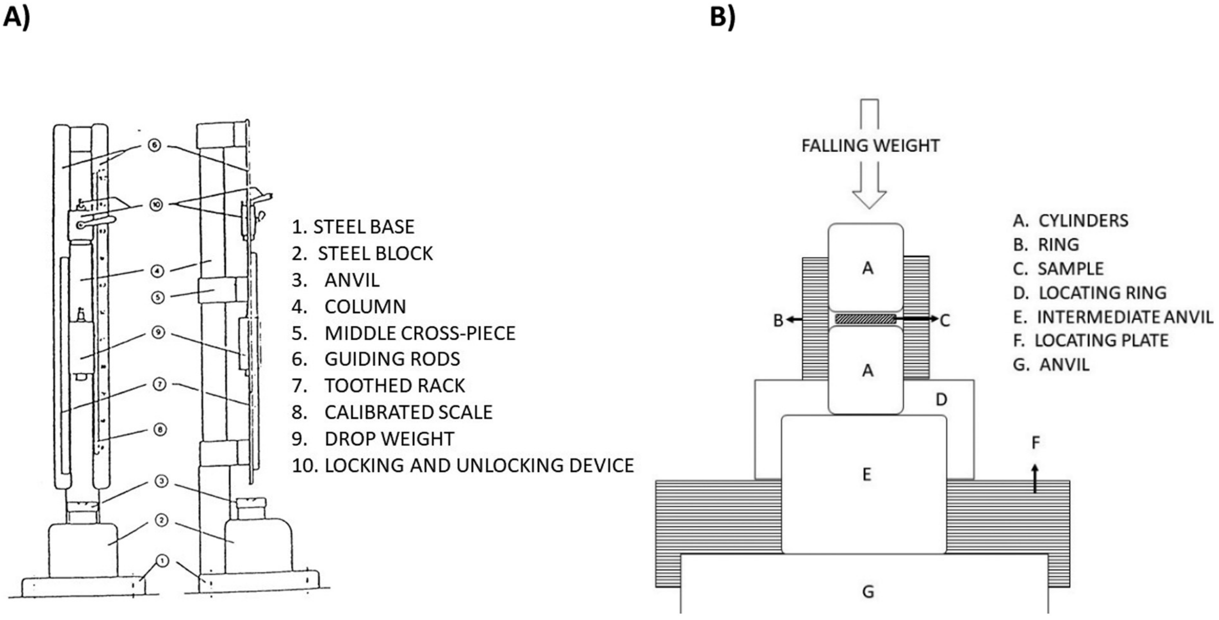

Fig. 5. A) The BAM Impact Machine (NATO, 1999) and B) The fallhammer confinement device (NATO, 1999).

and the rebound catch for stopping the weight after rebounding from the anvil.

When the desired drop weight has been secured in the release mechanism, the weight is then positioned to the desired height. Upon activating the release mechanism, the drop weight is unlocked, consequently impacting the upper roller of the impact device.

Depending on the characteristics of the tested explosive substance, the drop weight mass and the drop height (i.e., impact energy), the initiation of the sample may or may not occur when the weight is dropped. In judging the results, a distinction is made between no reaction, decomposition and explosion, in the sample. Explosion and decomposition can be recognized by several factors, including sound, gas, flame, smoke or by inspection of the impact device for sooty deposits after the upper cylinder has been removed. If none of these effects are noticed, initiation failure (no reaction) is registered. Of the three possible types of reaction, decomposition and explosion are considered positive reactions when testing, according to STANAG test procedures.

The test can be conducted and the test results reported in a number of different ways, including percentage of initiations, relative impact sensitivity with respect to the impact sensitivity of a referent explosive, or as an impact sensitivity curve for a given explosive, i.e., the relation between the percentage of initiations and the drop height of the weight having constant mass. On the basis of the results obtained in the latter, the impact sensitivity can be expressed as the drop height at which 50 % initiations occurred (H_{50}), the minimum drop height at which 100 % initiations occurred (H_{100}) and the maximum drop height at which lack of initiation is observed (H_0). Also, the test results can be expressed by the impact energy (E_1) at which a certain percentage of initiations occurred (Suceska, 1995). According to NATO STANAG 4489, a Bruceton up-and-down procedure shall be applied for the determination of the impact sensitivity of the explosive sample.

In these tests, the impact sensitivity was determined as follows: Beginning at an established starting level, a number of runs was performed to determine the exact drop height which causes 50 % positive reactions of the samples. Every new test was conducted with a new impact device and a new sample. The tests were performed in ambient temperatures (22.5 °C + 2.5 °C). As the scope of the test method is within the range of −30 °C to +80 °C, no particular environmental modification was required. The number of positive reactions and the number of negative reactions during the tests were recorded as either positive (x) or negative (o). In addition to audio-visual observation, a decomposition gas detector (MultiRAE model PGM6208) was used to classify the reactions. The mean (M) and its standard deviation (S) was calculated, and the 50 % drop height (H_{50}) was determined using the formulation $H_{50} = 10^{M} \pm \sigma$, where σ is standard deviation 50 % drop height ($\sigma = 10^{S}$).

The tests were completed when H_{50} was determined and the test results were considered valid (i.e., $0.5 \leq S/D \leq 2.0$). The final results were recorded as both the drop height in centimetres, which caused 50 % positive reactions of the sample explosives, and its calculated impact energy in Joules. A drop weight with a mass of 5 kg was used for testing the impact sensitivity of TNT and a weight of 2 kg for PETN.

2.5. Quality control

All analysis was undertaken at the Norwegian Defence Research Establishment laboratory. To ensure reliable and comparable datasets, implemented internal Quality Control (QC) procedures, based on ISO standard no. 17025 *General requirements for the competence of testing and calibration laboratories* (International Organization for Standardization, 2017), were observed. Additionally, analyses of bench-mark samples were performed, using recently produced relevant standard explosive samples. These control materials were treated throughout in exactly the same manner as the test materials and subjected to the same analyses (i.e., FT-IR, thermogravimetric analysis and impact sensitivity analysis). The QC TNT sample used in the analyses was “Trinitrotoluene (TNT) Type 1, Flake” with a 0.44 % content of Hexanitrostilbene (HNS), produced by Zaklady Chemiczne “NITRO-CHEM” S.A. in Bydgoszcz, Poland, released for sale following Certification of Compliance / Analysis on 8th September 2017. The QC PETN sample used in the analyses was “PETN Wax NSP452” grains with 7.7 % content of wax, produced by EURENCO Bofors in Karlskoga, Sweden, released for sale following Certification of Compliance / Analysis on 29th November 2018.

3. Results and discussion

3.1. Thermal analysis (TGA/SDTA)

The thermograms for TNT, presented in Fig. 6 A, show a single, gradual weight loss with an average onset temperature at 209 °C. The corresponding SDTA curves typically show an endothermic peak, with its maxima ranging from 81.1 °C to 83.9 °C. This is consistent with the melting point

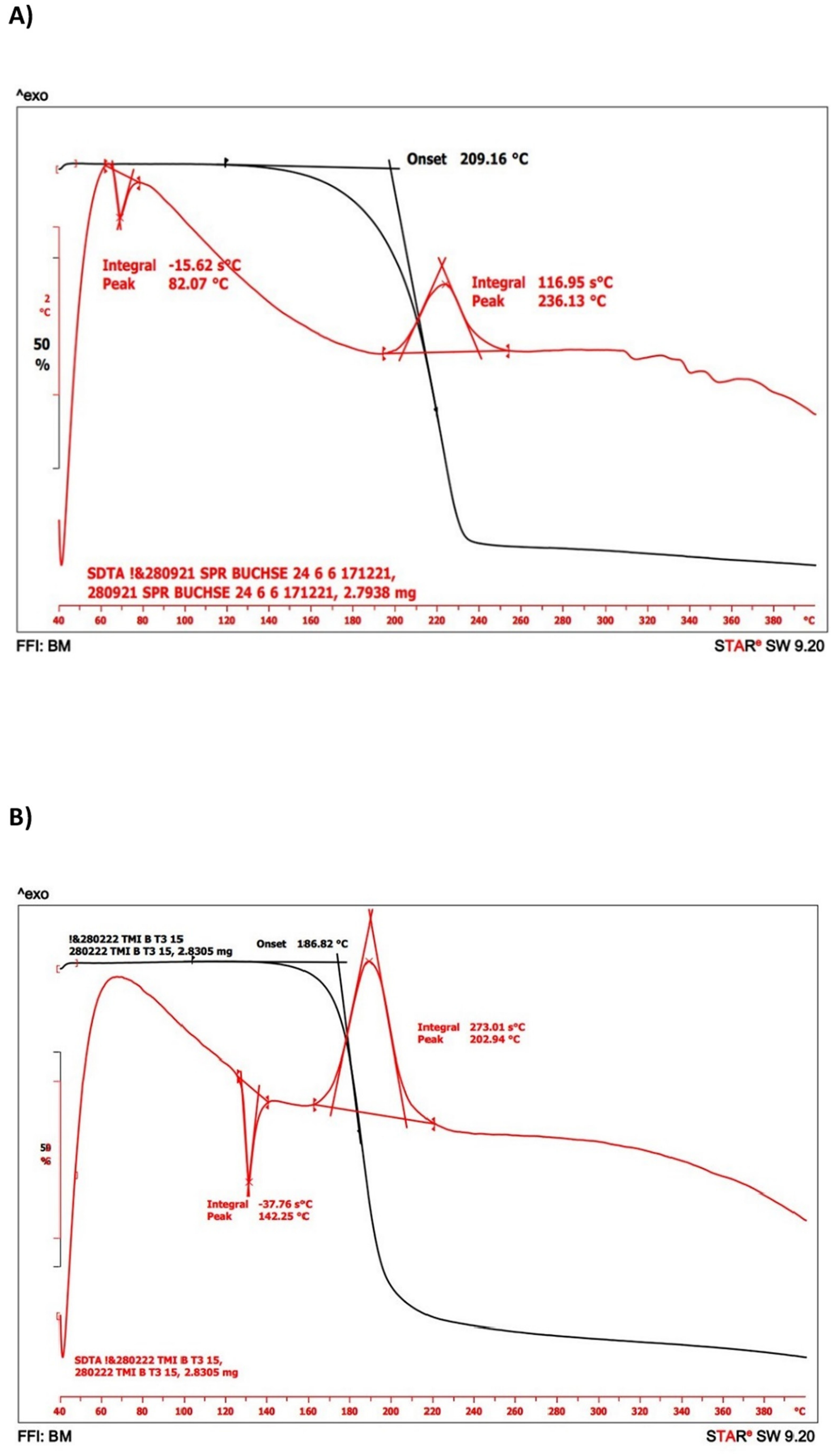

Fig. 6. Examples of TGA (black) and SDTA (red) curves for the thermal decomposition of A) TNT extracted from an intact German 1-Kilogram Sprengbüchse 24 and B) PETN extracted from a partially destroyed German anti-tank mine (booster charge), in N_2 atmosphere at a constant heating rate of 10 °C/min.

of TNT (about 81.0 ± 0.5 °C) (Kaye and Herman, 1980; Tharaldsen, 1950), as the exact melting point of the composite will be dependent on the average heat capacity of its individual elements (e.g., metals, binders, phlegmatizers, other energetic material or compositions thereof, etc.). This heat effect is not accompanied by mass loss. Next, an exothermic peak is observed with maxima at 232.6 °C to 274.9 °C, indicating the decomposition of the TNT, correlating with a decomposition temperature of 250 °C (Meyer et al., 2005).

In the cases of PETN, presented in Fig. 6 B, the thermograms show a single, gradual weight loss with an average onset temperature at 186 °C. The corresponding SDTA curves typically show a sharp endothermic peak, with its maxima ranging from 141.5 °C to 143.1 °C, consistent with the melting point of pure PETN (141.3 °C) (Meyer et al., 2005). This heat effect is not accompanied by mass loss. Next, an exothermic peak is observed with maxima at 194.9 °C to 206.48 °C, indicating the decomposition of the PETN, correlating with a deflagration point of 202 °C (Meyer et al., 2005).

3.2. Impact sensitivity analysis (BAM impact apparatus)

The recorded H_{50} values in centimetres from the impact sensitivity tests using the BAM Impact Apparatus and the Bruceton up-and-down test procedure are presented in Table 1 and Fig. 7. Analyses of bench-mark test samples using recently produced relevant samples of TNT and PETN are listed in Table 1 as BMS-1 (TNT) and BMS-2 (PETN) and visualized in Fig. 7 as red horizontal lines.

It is important to note that drop-weight impact tests are only a screening tool for handling sensitivity, and that interpretation of the results can be difficult (Manner et al., 2020). As measurements can also be affected by test conditions, location and the various analysis methodology, consistency among sample testing is critical (Marrs et al., 2021). As such, the results obtained may vary due to differences in the way the experiments are conducted and reported and with respect to the type of impact sensitivity apparatus used. However, when all influencing factors are considered, it appears

Table 1

Description of ordnance category, country of origin, explosive, condition, location, impact weight and the corresponding drop-height (H_{50}) with standard deviation.

Sample	Object category	Country of origin	Condition	Location	Explosive	Weight (kg)	50 % drop height (cm)
1	Grenade, hand	United Kingdom	Intact	On land	TNT	5	69.4 cm ± 1.187 cm
2	Grenade, hand	United Kingdom	Intact	On land	TNT	5	56.7 cm ± 1.110 cm
3	Grenade, hand	United Kingdom	Intact	On land	TNT	5	59.6 cm ± 1.139 cm
4	Grenade, hand	United Kingdom	Intact	On land	TNT	5	54.5 cm ± 1.101 cm
5	Grenade, hand	Norway	Partially open	On land	TNT	5	66.8 cm ± 1.212 cm
6	Charge, explosive	Germany	Intact	On land	TNT	5	50.5 cm ± 1.110 cm
7	Charge, explosive	Germany	Intact	On land	TNT	5	46.2 cm ± 1.116 cm
8	Charge, explosive	Germany	Intact	On land	TNT	5	66.8 cm ± 1.139 cm
9	Charge, explosive	Germany	Intact	On land	TNT	5	56.2 cm ± 1.156 cm
10	Charge, explosive	Germany	Intact	On land	TNT	5	47.3 cm ± 1.083 cm
11	Charge, explosive	Germany	Intact	On land	TNT	5	61.6 cm ± 1.225 cm
12	Charge, explosive	Germany	Intact	On land	TNT	5	61.3 cm ± 1.143 cm
13	Grenade, hand	Germany	Intact	On land	TNT	5	66.8 cm ± 1.139 cm
14	Projectile	Germany	Intact	On land	TNT	5	56.9 cm ± 1.133 cm
15	Grenade, hand	Russia	Partially open	On land	TNT	5	47.3 cm ± 1.104 cm
16	Grenade, hand	Russia	Partially open	On land	TNT	5	64.9 cm ± 1.255 cm
17	Projectile	Russia	Intact	On land	TNT	5	57.9 cm ± 1.143 cm
18	Grenade, hand	Germany	Intact	On land	TNT	5	68.1 cm ± 1.168 cm
19	Mine	Germany	Open	In water	TNT	5	64.9 cm ± 1.255 cm
20	Mine	Germany	Open	In water	TNT	5	47.3 cm ± 1.139 cm
21	Mine	Germany	Open	In water	TNT	5	59.6 cm ± 1.139 cm
22	Mine	Germany	Open	In water	TNT	5	75.0 cm ± 1.104 cm
23	Mine	Germany	Open	In water	TNT	5	47.3 cm ± 1.139 cm
24	Mine	Germany	Open	In water	TNT	5	66.8 cm ± 1.139 cm
25	Mine	Germany	Open	In water	TNT	5	65.6 cm ± 1.243 cm
26	Projectile	Germany	Intact	In water	PETN	2	32.5 cm ± 1.143 cm
27	Projectile	Germany	Intact	In water	PETN	2	42.2 cm ± 1.139 cm
28	Projectile	Germany	Intact	On land	PETN	2	43.0 cm ± 1.098 cm
29	Grenade, rifle	Germany	Intact	On land	PETN	2	25.0 cm ± 1.166 cm
30	Grenade, rifle	Germany	Intact	On land	PETN	2	32.5 cm ± 1.255 cm
31	Grenade, rifle	Germany	Intact	On land	PETN	2	21.1 cm ± 1.212 cm
32	Grenade, rifle	Germany	Intact	On land	PETN	2	25.9 cm ± 1.143 cm
33	Grenade, rifle	Germany	Intact	On land	PETN	2	26.6 cm ± 1.156 cm
34	Projectile	Germany	Intact	On land	PETN	2	37.6 cm ± 1.139 cm
35	Mine	Germany	Open	In water	PETN	2	23.7 cm ± 1.104 cm
36	Mine	Germany	Open	In water	PETN	2	29.9 cm ± 1.139 cm
37	Mine	Germany	Open	In water	PETN	2	29.9 cm ± 1.212 cm
38	Mine	Germany	Open	In water	PETN	2	30.7 cm ± 1.143 cm
39	Mine	Germany	Open	In water	PETN	2	26.6 cm ± 1.104 cm
40	Mine	Germany	Open	In water	PETN	2	29.0 cm ± 1.143 cm
41	Mine	Germany	Open	In water	PETN	2	26.6 cm ± 1.139 cm
42	Mine	Germany	Open	In water	PETN	2	21.1 cm ± 1.104 cm
43	Mine	Germany	Open	In water	PETN	2	27.8 cm ± 1.100 cm
44	Mine	Germany	Open	In water	PETN	2	21.1 cm ± 1.060 cm
45	Mine	Germany	Open	In water	PETN	2	29.9 cm ± 1.139 cm
46	Mine	Germany	Open	In water	PETN	2	21.1 cm ± 1.139 cm
47	Mine	Germany	Open	In water	PETN	2	27.4 cm ± 1.143 cm
48	Mine	Germany	Open	In water	PETN	2	23.7 cm ± 1.139 cm
49	Projectile	Germany	Intact	In water	PETN	2	27.2 cm ± 1.116 cm
50	Projectile	Germany	Intact	In water	PETN	2	24.8 cm ± 1.179 cm
BMS-1	Bench-mark test sample				TNT	5	59.6 cm ± 1.212 cm
BMS-2	Bench-mark test sample				PETN	2	29.0 cm ± 1.143 cm

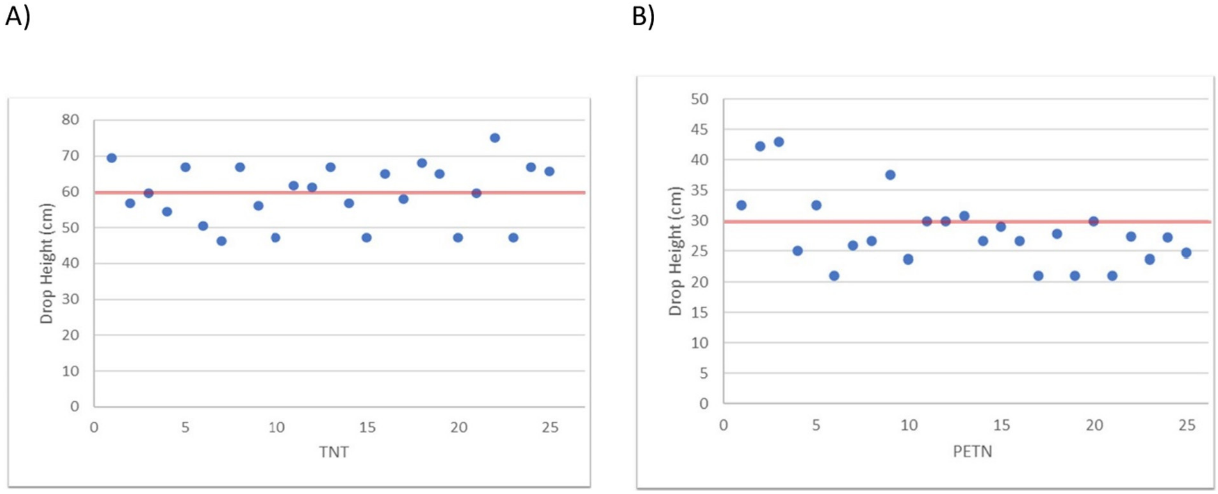

Fig. 7. 50 % drop height (H_{50}) in centimetres for A) TNT and B) PETN. The X-axis represents the sample number, and bench-mark samples of recently produced TNT and PETN are shown as red horizontal lines.

that there is consistency between the results obtained by this test and results in the literature on comparable explosive compositions. For example, NATO STANAG 4489 lists typical anticipated results in Joule for the testing of impact sensitivity of various explosives with the BAM Impact Machine (NATO, 1999). The applicable listed values are: TNT – 30 J and PETN – 5 J. This study demonstrates that the H_{50} impact energy in Joule for the tested explosives is as follows: for TNT, between 23.1 and 37.5 J, with a mean of 29.72 J (the correlating test sample result was 29,8 J), and for PETN, between 4.2 and 8.6 J, with a mean of 5.6 J (the correlating test sample result was 5,8 J). This demonstrates that the test results are consistent with the expected values for comparable explosive compositions, taking into account variations in composition (e.g., the presence and/or percentage of metals, binders, phlegmatizers, other energetic material or compositions thereof, etc.), as well as test conditions and analysis methodology.

4. Summation and discussion

Most recorded incidents of unplanned explosions in ERW come as a result of a sudden unintended incident or external stimuli. This can originate as the result of a “natural” incident, such as a lightning strike, forest fire, structural collapse of shipwrecks or the shifting of ordnance in the tide; as the result of deteriorating containers and packaging, etc.; or as the direct result of human interaction (e.g., touching or moving the ordnance or otherwise subjecting the energetic materials to heat, friction, impact, etc.). Furthermore, ERW are coming into increasing contact with human activities, like development and fishing. Some decades ago, for example, trawlers would rarely trawl below 120 m; now, they can trawl in depths of 1500 m (Monfils, 2005). Increased development and utilization of both land and sea can lead to infrastructure being built in explosive-contaminated areas. Sometimes this is even done knowingly, reassured by an assumption that the ammunition does not pose any significant risk. However, the forces generated by the use of construction equipment, such as excavators, hydraulic hammers, crushing machines and drills, are generally sufficient to detonate most kinds of explosives under certain circumstances and are regularly linked to accidental detonations of undetected explosives (Dahl, 1998). Analyses of some accidental explosions have shown that the most frequent causes of these accidents are subjective in nature, resulting from the disregard of necessary safety precautions (Suceska, 1995). Similarly, at sea, both shipping and construction activity, such as dredging and other seabed interventions (e.g., cable and pipeline installations and piling works), can produce more than enough impact energy to initiate an underwater explosion of high explosives and/or explosive objects, potentially resulting in a sympathetic mass-detonation of dumped ammunition or ammunition confined within a sunken vessel (Zhuang et al., 2016).

This study demonstrates that all analysed high explosives extracted from ERW are still in good condition, and that impact sensitivity does not seem to have been significantly reduced over the last eight decades. In fact, the study shows that the impact sensitivity of the ageing explosives generally correlates with what is recorded in the literature. The study does, however, also demonstrate that the impact sensitivity (H_{50}) of the tested explosives in some cases could be over 20 % greater, compared to both what are considered standard values for equivalent explosives and the results obtained from the relevant quality control sample (see Table 1).

As the explosives remain in nature, special concern is raised regarding the leaking and bioaccumulation of toxic constituents and their potential to contaminate living organisms, as well as the surrounding soil and groundwater. Unlike other contaminants, they cannot be reduced by land measures, and only removal of the source can reduce the contamination (Bełdowski et al., 2020). Furthermore, as corrosion of munitions persists, the increased deterioration of the munitions' casings may lead to a greater emission of harmful constituents in the future, leading to ecological consequences of yet unknown proportions (Beck et al., 2022). Concern is also raised that dumped munitions are open to terrorist access and potential misuse (NATO, 2010). Some agencies and organizations therefore advocate that all ERW should be cleared, as far as practically feasible (OSPAR Commission, 2009). A prerequisite for this would in any case be that the risks involved are identified to a satisfactory degree, and that the subsequent risk assessments are based on strong background knowledge. This would require comprehensive research into relevant ERW, including potential variations in the ageing of explosives as a result of environmental, chemical or technical differences, etc.

5. Conclusions

The thermal and impact sensitivity results obtained in the analysis showed no indications of deterioration of high explosives in explosive remnants of war that could denote any significant reduction in performance and/or decreased impact sensitivity. Consequently, there is no evidence in this study to support a claim that, if left alone, the ammunition will slowly become harmless over time. The study did show that the high explosives are still in good condition, and that impact sensitivity does not seem to have been reduced over the last eight decades. Further research into possible variations, as a result of environmental, chemical or technical differences, will be required, in order to gain further knowledge on ageing ERW.

It is important to note that this study is limited to only the analysis of TNT and PETN and does not include either primary explosives or other high explosives or explosive compositions, some of which could be expected to be significantly more impact-sensitive than the explosives included within this study.

CRediT authorship contribution statement

Geir P Novik performed writing - original draft and conceptualization.

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Paper IV

On the importance of systems thinking in ERW risk management

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On the Importance of Systems Thinking in ERW (Explosive Remnants of War) Risk Management

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Abstract

One of the legacies of armed conflict is that of unexploded ordnance and abandoned ammunition. This legacy will, in many cases, have a severe impact on society and daily life, even for years or decades after hostilities have ended. The millions of tonnes of explosive remnants that remain in nature represent a grave threat in many ways, and, if left in place, the human, societal and environmental impact could prove to be severe. Clearing the ERW represent a serious and complex risk in itself, a risk that could prove to increase if mismanaged. Furthermore, the accumulations of munition contamination hinder and severely endanger areal development, both on land and offshore. However, vast amounts of explosives and accumulations of munitions, such as those in dumping areas and shipwrecks, are systematically neglected. An unintentional detonation at such a site could prove to have disastrous societal and environmental consequences. In the present work, we show that systems thinking could be used as a tool to gain better insight into the complexity of managing the risk related to explosive remnants of war, and to better prioritize resources allocated to mitigating this threat, resulting in an optimalisation of resource allocation and a reduced societal risk.

1. Introduction

Nearly every conflict in modern times has left behind large amounts of explosive remnants of war (ERW). These are the thousands and sometimes millions of pieces of explosive ordnance that have been fired, dropped or otherwise delivered during the fighting but have failed to explode as intended, as well as ammunition that has been abandoned by the warring parties on the battlefield. The clearing of these weapons has often taken years or even decades, depending on the scale of the challenge. It represents a persistent problem and deadly threat that could kill and injure large numbers of men, women and children who subsequently disturb or tamper with them (Maresca, 2004).

In the aftermath of war and armed conflict, it is therefore essential that unexploded ordnance (UXO) and abandoned ammunition are handled properly, to prevent accidents, illicit recovery, proliferation and misuse. In most circumstances, both time and resources are limiting factors that strongly reduce the possible actions taken to secure the ammunition.

Due to the sheer number of obsolete and unserviceable explosives and ammunition components, it can often be both impracticable and hazardous to store and properly manage the ammunition, and often the only viable choice is the various means of disposal. Often, the burning or detonation of explosives is regarded as the most practical solution for disposing of ammunition, but, when faced with larger quantities, the dumping of ammunition has historically been considered a relevant disposal technique. Although this practice has generally ceased and is now subject to international agreements that ban the dumping at sea of hazardous or industrial waste, millions of tonnes of explosives and ammunition components still remain in dumping areas at sea, on shores, in lakes, waste places, pits, streams and landfills. In addition to the dumped ammunition, there also remain at sea thousands of sunken military and merchant vessels, containing large quantities of live ammunition, shells, mines, depth charges and other explosives, as well as some chemical warfare agents (Monfils, 2005). Large quantities of UXO from war fighting also remain in nature. These still have not been cleared, because they have not been located, are not considered a threat, clearing of them has not been prioritized or because there is a lack of funding and/or available resources.

In many countries, whenever munitions or munition components are discovered by the public and reported to the authorities, specially trained personnel (in explosive ordnance disposal) are generally tasked with assessing the situation, and, if the object is considered a threat to personnel or property, it is disposed of (e.g. removed, rendered safe, detonated, etc.). Sometimes this involves evacuating a great number of people and closing venues until the object is considered safe. However, normally this only applies to those cases where clearance and remediation are urgently needed due to acute safety risk. Measured by the amount of ERW, remediation of all munitions is quite unrealistic in the near future, and the cost of such a plan is an important factor as to why this has not been seriously addressed to date (Kampmeier, Lee, Wichert, & Greinert, 2020). Many countries have therefore taken a passive monitoring approach to large accumulations of ERW, as in the case of known munition dumping sites and some areas heavily contaminated with UXO, such as partially destroyed ammunition stores and the thousands of sunken World War Two (WWII) vessels. Whilst some of these sites are monitored for leaking constituents and their environmental effects (Craig & Taylor, 2011), the vast majority are not. Additionally, it is frequently the case that complete archives regarding what exactly has been dumped do not even exist, nor are there any complete records on where it was dumped. Moreover, those tasked with carrying out the dumping did not always stick to the rules (Ross, 2017).

Despite the knowledge about potential harmful effects, as well as strict dumping restrictions, ammunition was still being dumped on an industrial scale several decades after WWII. It is a timely question to ask whether or not one would do the same today, given the updated knowledge on potential consequences. Given today’s knowledge on potential harmful environmental effects and their impact on communal safety and security, as well as the restrictions it would place on future areal development, it seems safe to say that dumping of ammunition would be avoided to the greatest extent. If dumping were still considered, one should expect strict restrictions in regard to both location (depth, distance to shore, local conditions, etc.) and record keeping (number, type, condition, contents, etc.).

A relevant question to ask ourselves today could therefore be whether there are any aspects of our current practices that would seem reprehensible in the future. As far as ERW are concerned, this criticism could embody both how we assess the risk and how we dispose of ammunition today, but also how we choose to handle the legacy of dumped ammunition and ERW. For many decades now, this ammunition has for the most part been left undisturbed. It is clear that dumped ammunition can survive fully intact and in a pristine condition for over one hundred years, but it can also rust so thoroughly in a few decades that only non-soluble explosive filler and a few metal fragments remain (Barton & Pollack, 2017), causing munitions' constituents to leak into the ground and water. These toxic substances from the explosives can contaminate living organisms, as well as the surrounding soil and groundwater (ATSDR, 1995; Koske, Goldenstein, & Kammann, 2019; Koske et al., 2020; Schuster et al., 2021; Yinon, 1990), and may also enter the food chain and directly affect human health upon the consumption of contaminated food (E Maser & Strehse, 2021). It is also clear that, as time passes, the objects will become less and less identifiable, and their chemical and technical condition will become increasingly indeterminate, thus dramatically limiting the number of potentially available risk-reducing actions. Whilst analysis of some highly explosive substances extracted from WWII ERW shows the explosives to be in generally good condition (Novik, 2022), there is also evidence that some explosives can become increasingly sensitive to external stress (Albright, 2012; OSPAR Commission, 2009). Some ammunition has also proved to explode spontaneously, even without human interaction (Ford, Ottemöller, & Bapite, 2005). Our window of opportunity is therefore diminishing rapidly. In a matter of decades, the ammunition could have become too corroded to handle;, it could be further buried in sediments, making it even harder to locate, identify and retrieve, and, depending on the material, chemical and technical condition and environmental exposure, it could become more unstable and unpredictable in its behaviour – and more dangerous to deal with than normal munitions (Long, 2005). In addition, shipwrecks containing ammunition will continue to deteriorate and eventually collapse, greatly increasing both the unfeasibility and the risks of retrieving the munitions.

This passive approach towards known dumping sites, sunken vessels and areas heavily contaminated with UXO stands, however, in glaring contrast to the measures usually taken to neutralize individual ERW, whenever they are discovered (Alexander, 2019). But, as societies' environmental, safety and security standards are increasing, so are their demands to politicians and governments to take preventive action to avoid unnecessary loss of life and environmental damage. The time for a passive policy of ignorance/negligence has long passed, and, for most countries, decision-makers will, at some time, be forced to make active policy choices regarding ammunition-contaminated areas (e.g. United States General Accounting Office, 2003). This is also confirmed by the United Nations in the "Protocol on Explosive Remnants of War to the Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons (CCW) which may be deemed to be Excessively Injurious or to have Indiscriminate Effects (Protocol V)" (United Nations, 2003), which states that each High Contracting Party and party to an armed conflict shall survey and assess the threat, assess and prioritize needs and practicability, mark, clear, remove and destroy ERW and "take steps to mobilise resources to carry out these activities". The protocol further states that areas affected by ERW which are posing a serious humanitarian risk “shall be accorded priority status for clearance, removal and destruction”.

In this paper, we address how systems thinking can be used both as a tool to gain better insight into the complexity of ERW risk management and as a way of seeing the whole and interactions, enabling us to see beyond snapshots of isolated parts of the system (Langdalen, Abrahamsen, & Selvik, 2020). With the use of this skill set, we hope to better understand the deep roots of complex behaviours, in order to better predict them and, ultimately, adjust their outcomes (Arnold & Wade, 2015). We believe that systems thinking can be beneficial when addressing the complexity and uncertainty of ERW risk and prove to be an important decision-making aid in prioritizing and conducting risk mitigation actions in the future. It is acknowledged, however, that this paper does not offer any ultimate solutions on how to handle the ERW threat but provides a guide for how to address the complexity of ERW risk and an example of how systems thinking could be utilized in the prioritization of risk mitigation actions. This article is primarily directed at countries that are affected with ERW to such an extent that ample protection of personnel, property and environment could represent a challenge.

The aim of this paper is to apply systems thinking, in order to advance the identification and assessment of potential risks related to ERW that may affect complex risk management in the present and the future. This is achieved through the creation of an analytical framework for identifying the network structure in which ERW risk management is embedded. Through a literature review and a causal loop diagram (CLD), we identify and visualize how certain risk mitigating actions can cancel each other out and even enhance the overall societal risk. This type of an approach accounts for the complexity and interconnectivity between and within different systems, by identifying relations and connections that have previously been considered in isolation (Groundstroem & Juhola, 2021).

2. Challenges in ERW risk perception

2.1 Identifying the totality of the risk

Based on the variety and severity of potential consequences related to energetic material such as explosives, it is evident that the risk picture related to the problem of ERW is multifaceted, with several dimensions needing to be considered. Applying a more traditional risk management model to this problem would entail significant shortcomings and sub-optimal solutions, as the traditional approach is simply too narrow (Olsen, Juhl, Engen, & Lindøe, 2020). When addressing the complexity and uncertainty of ERW risk, we therefore need other tools, in order to gain better insight into its risk management.

When dealing with ERW, most countries that are affected naturally tend to prioritize objects that are regarded as an immediate and direct threat to their population. This could, for example, be munitions accidentally discovered in a former military training area or UXO exposed whilst excavating land that could have served as a battlefield or bomb target (e.g. city, industry, military, critical infrastructure, etc.) in wartime. In such cases, the risk assessment is generally straightforward: the object represents an undesired or intolerable risk, and the risk can be mitigated by (relatively) easy terms, normally by destruction, removal or by rendering it safe. There are normally established routines and contingency plans to follow, and, as this is usually a frequent occurrence, there could also be a separate budget set aside for clearing accidentally discovered ERW. The potential explosive risk and the subsequent threat to personnel and property are easily identified and will often overshadow other forms of risk associated with the object. Whenever ordnance is discovered or accidentally detonates, the focus will generally be on its potential explosive capacity and/or the potential damage a detonation could have caused. For decades, therefore, the predominant public view of risks related to ERW has been the potential explosive effect related to accidentally discovered explosive objects (Novik, Sommer, & Abrahamsen, 2022).

But what if we look at the bigger picture and focus not only on the specific ERW that are accidentally discovered but, instead, focus on the risk ERW in general represent? To do that, we have to be able to step back and, based on knowledge-based information on ERW, evaluate the societal risk each ERW object, location or situation represents. First of all, this means that, in addition to accidentally discovered ERW, we also have to take into account all explosive objects that could represent a societal threat, whether it is an object that is discovered and reported by the general public or is a known location for dumped ammunition or accumulations of explosive objects, such as shipwrecks etc. We also have to investigate historical data and statistics, to determine the probability and types of ERW present in the ground, lakes, sea, harbours, etc., as a result of war fighting and/or training, illustrated by the *threat perception iceberg* in Fig. 1. In this illustration, the tip of the iceberg represents the visual threat (i.e. ERW brought to media attention when accidentally discovered or when an unintentional detonation occurs), whilst the main body of the iceberg represents the millions of tonnes of ERW and dumped ammunition that in fact remain in nature today, unknown (or at least unfamiliar) to the general population.

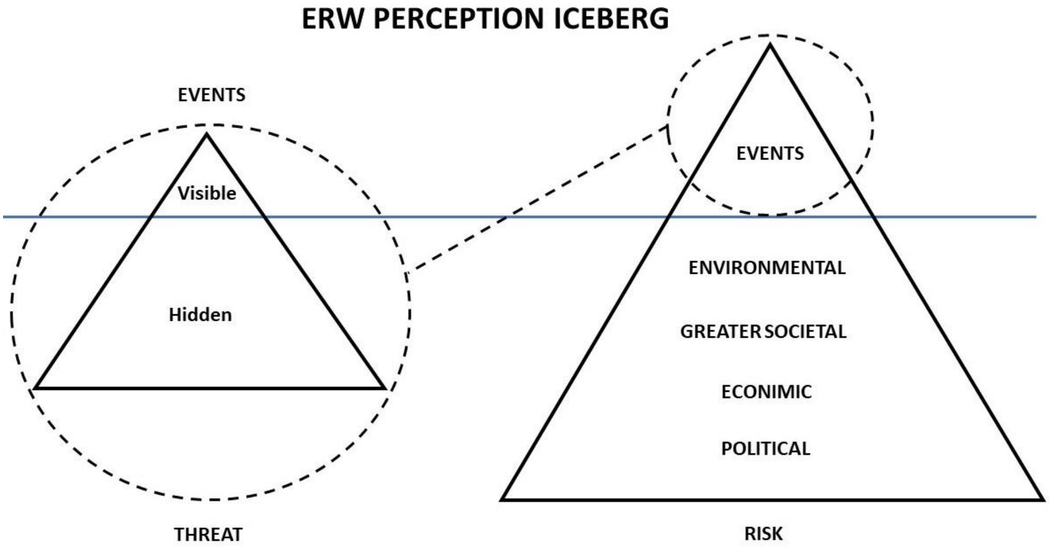

Fig. 1. ERW perception iceberg

Secondly, we need to evaluate the potential risks the ERW represent to societal safety and security, including the potential direct and indirect risk to life and health in the case of an intentional or unintentional fire or detonation, as well as the environmental, economic and political risk, as illustrated by the *risk perception iceberg* in Fig. 1. In this illustration, the tip of the iceberg denotes the potential explosive risk represented by ERW, and the main body characterizes the hidden risks, often disregarded and/or overshadowed by the explosive risk.

A direct risk to life and health could occur if the object were to function, for example detonate or initiate a pyrotechnical charge that could cause a fire or an explosion which could result in injuries or casualties among the public. This could be the result of the object being subjected to sufficient force (accidental or otherwise) to cause it to function as intended (e.g. impact, friction, heat) or the ERW spontaneously exploding due to technical or chemical degradation, etc. An indirect risk could be a potential fire or explosion damaging critical infrastructure, such as a hospital, water/gas mains, etc., which in turn could represent a threat to life and health. A challenge in this regard is the common misconception that explosives in ERW become less sensitive and/or that their explosive potential reduces over time (Novik, 2022).

It is known that ERW contain substances that are considered poisonous to humans, and that they can pollute the soil and ground water, as well as biological life (Koske et al., 2019; Koske et al., 2020; E Maser & Strehse, 2021; Schuster et al., 2021). This means they represent not only a risk to life and health but also a broader environmental risk. As ammunition casings slowly deteriorate, harmful substances will start to leak, resulting in contamination of the surrounding land and waters. Some of these could be trapped in the sediments, whilst others could be spread by wind or water, potentially contaminating a large area. Any disturbance of the ERW (i.e. salvaging/moving) could have the potential to release substances caught in the sediments, not to mention the potential environmental consequences of an unintended accidental detonation. Even a planned and controlled detonation could, depending on the characteristics of the ammunition, result in the dispersal of harmful substances, both from the object itself and from the release of trapped substances in the sediments, as well as/or the potential for sympathetic detonations of yet undiscovered explosives and ammunition.

In addition to the explosive and environmental risk, ERW also represent a broader societal risk. In one respect, this hampers or delays development projects, as land and sea contaminated with munitions or munitions' constituents need comprehensive survey and monitoring before any work can be done. This often demands vast resources, and the risk and economic costs will often require project plans to be altered or a project to be terminated. This could affect not only domestic and industrial development (e.g. Sabbagh, 2020) but also, to a greater respect, the global effort towards green change. Examples of this could be how munitions' contamination affects projected underwater power lines / gas pipelines, the development of hydroelectric power plants, wind parks or other projects required to make the change towards more sustainable energy sources. Accidental or spontaneous detonations could also damage critical infrastructure, and ammunition contamination could also hinder the investigation, repair and rebuilding of such (e.g.

Coogan, 2022). Additionally, knowledge of the extent and potential of risks related to ERW could have an impact on the societal sense of safety and security. Raised public awareness of potential risks related to ERW could increase safety and security concerns in terms of the misuse of explosives (e.g. criminal or terrorist), accidental detonations, food or groundwater contamination, etc.

Any severe incidents involving ERW, for example accidental detonations, confirmation of harmful munitions' constituents in drinking water or food (aquaculture industry), etc., will inevitably have economic and sometimes even political consequences. The latter is especially relevant if the government's elected officials have been proved to neglect their responsibilities to protect the population from the considerable risks that ERW represent.

2.2 ERW Risk management

There are several challenges related to assessing and managing ERW risk that are particularly difficult to assess in the traditional technical view of risk, such as complexity, lack of knowledge, uncertainty and the elements of surprises and black swans (Kringen, 2015). We believe that systems thinking can be beneficial when addressing ERW risk and prove to be both an important decision-making aid in prioritizing and conducting risk mitigation actions in the future and a way of seeing the whole and interactions, enabling us to see beyond snapshots of isolated parts of the system (Langdalen et al., 2020). Additionally, systems thinking can be beneficial for identifying the real roots of problems, instead of applying "end of pipe" solutions that fix only symptoms, not causes (Haraldsson, 2004).

Systems thinking can be characterized as a conceptual framework for seeing the whole and interactions, rather than isolated parts of the system (Langdalen et al., 2020). The basic idea is that the understanding of the *why* and *how* of something requires an understanding of the system or context. Specifically, to understand the particularities of an element or an event, we first need to understand the general (Bennett, 2019). It is a science, based on understanding connections and relations between seemingly isolated things, and can be used to discover organizational structures in systems, creating insights into the organization of causalities (Haraldsson, 2004). Through system analysis, it is possible to identify and define critical areas and/or areas of concern and to analyse them, in order to understand their components and feedback relationships. In this analysis, a mental model structure is often created, using Causal Loop Diagrams (CLD), to reflect problem areas. CLDs are also helpful for mapping out the structure of a system and its networks and revealing causalities and feedbacks within the system (Haraldsson, 2004); they are commonly used alongside systems thinking to see the interrelationships among all system components (Monat & Gannon, 2015) and to facilitate understanding and analysis of the system under investigation (Sanches-Pereira & Gómez, 2015). An example of a CLD on the system of ERW action could therefore offer an opportunity to identify feedback effects in the system, which may point to potential future trajectories of change. Feedback effects, as visualized in the CLD, will arise when variables affect each other in a cascading manner, ultimately leading back to a previous variable, creating a feedback loop (Groundstroem & Juhola, 2021). To illustrate how

CLDs can be helpful in identifying causalities and feedback within a system, we developed a simplified example of the system for ERW action, as shown in Fig. 2. In this example, there are six feedback loops, with R1 referring to the reinforcing feedback loop between available explosive ordnance disposal (EOD) methodology (Options) and viable choices available to the decision-maker (Choices). In this loop, more choices will result in more options and vice versa, making it a reinforcing feedback loop, as events or behaviours created by the variables in the loop amplify each other, leading to unbounded growth or decline (Groundstroem & Juhola, 2021). There are also two other reinforcing feedback loops in the example: R2, where knowledge and (the quality of) threat assessments affect each other, and R3, where knowledge and (quality of) training affect each other in a reinforcing manner. In the visualized example, there are also three feedback loops where the variables create counteracting changes, resulting in equilibrium. B1 refers to the feedback loop of limitations and choices, where we can see that the more choices available to the decision-maker, the more limitations are likely to be imposed, thus reducing the number of viable choices. We see, in B2, how (the quality of) threat assessments affect the choices available to the decision-maker and vice versa, and, in B3, how available EOD methodology is affected by their potential negative consequences, and how this limits the feasibility of the relevant methodology. Such negative consequences would include both potential undesired collateral damage as a result of EOD action, the potential residual societal risk after action has been taken, as well as the coherent level of risk and amount of resources the various EOD methodology options embody.

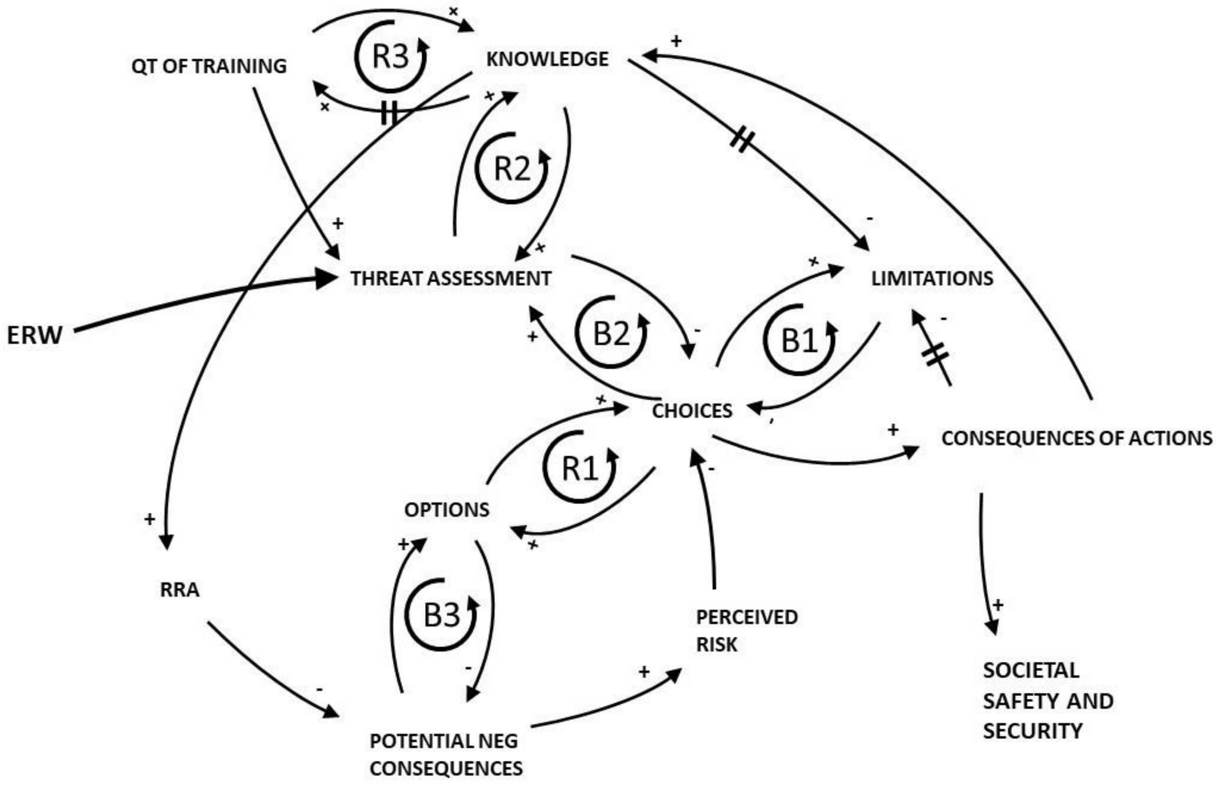

Fig. 2. Simplified CLD example, showing the system for ERW action and the potential for unrecognized influences to affect the system.

In this analysis, it is apparent that both the quality of training and the knowledge are critical system elements that affect both the threat assessment and the possible risk-reducing actions (RRA), both having an effect on the choices available to the decision-maker and ultimately the consequences of actions. The potential consequences (positive) will result in the desired outcome of any ERW action: increased societal safety and security. It should be mentioned, however, that both positive and negative consequences of actions would equally lead to increased knowledge. Information of consequences (both negative and positive) to decision-makers at a strategic level could also prove to affect limitations, as restrictions (e.g. economic, regulatory, etc.) could be altered. In this respect, even information and/or publicity on the negative consequences of actions (e.g. undesired detonations, collateral damage, economic, political or environmental implications, etc.) could bring attention onto the severity of the problem and how imposed limitations restrict the availability of EOD methodology and available choices, thus motivating a review of the limitations in the existing regulations, structure, framework, etc.

The analysis reveals a number of connections and feedback loops, of which only one will receive further scrutiny in this example. It seems that one of the factors that has the most profound potential impact on the system is that of limitations. Whilst some limitations can be relatively constant, such as constraints related to location, weather or time, others can be modifiable, such as regulatory, structural and economic restraints, etc. Some of the imposed limitations are also implemented for the purpose of acting as risk mitigators or safety measures in a specific area. Examples of these could be blast/frag limitations at a specific location, as high-order detonations could damage fixed critical infrastructure (e.g. gas pipelines, etc.); there could be noise regulations, as noise could be harmful to marine aquaculture or wildlife; there could be limitations in order to preserve evidence in a criminal case, etc.; or there could be limitations to preserve cultural heritage sites, etc. For such examples, it is imperative to investigate how these limitations, which are specifically designed to mitigate a defined risk, affect and interact with other parts of the system.

2.3 Potential implications

Taking a closer look at the complex network of connections reveals many counteracting forces in the system, as well as several links and potential cascading impacts that are not perhaps obvious but still highly relevant for the desired end state (i.e. increased societal safety and security). For instance, if we look further into the factors that limit the selection of viable choices available to the decision-maker (limitations), we see that some are permanent, such as environmental implications, and that others may be variable, such as framework (resources) and regulatory restrictions. Whilst permanent limitations, by definition, are unchangeable (e.g. location, chemical, technical and environmental conditions), the variable conditions can be altered. As for framework conditions, these can be altered by regulating the level and quality of training, funding, personnel, etc. Regulatory restrictions can normally be altered by adding, removing, changing or amending relevant statutes, legislation and regulations. In many cases, the more formal regulatory restrictions are also supplemented by codes of conduct, policies and procedures that enforce further restrictions. These often also consist of several individual safety measurements put in place to reduce a specific risk.

Any change in these restrictions would have an effect on the system and, depending on its interconnection with other parts of the system, could have unintended implications for the system output. Examples of this are implications for resources and risk. Experience tells us that that the implementation of restrictions such as safety measures is not always consistent with already existing safety measures. The consequence of this can be that some safety measures may lead to the reduction of other measures already implemented, resulting in the expected effects being less than intended or there being no effects at all. In a worst-case scenario, they can even prove to have a negative effect (Abrahamsen et al., 2018). As the resources spent on safety measures are normally limited, investments in new safety measures may also lead to reductions in investments in other safety measures planned for implementation. This is particularly significant, as it could result in less important safety measures being prioritized over more important (e.g. more cost-effective) measures in terms of effect. Additionally, continuous implementation of uncoordinated safety measures could also mean that, by the time the safety measure is implemented, the risk has already been mitigated by other means (e.g. revised procedures, training, etc.) or by other recently implemented safety measures, leaving the implementation with little or no effect, risking the needless use of resources and introducing even more restrictions/limitations. In this respect, the order in which safety measures are implemented in a complex system would also have an effect on both risk- and resource management.

One example of this is the (often unintended) reduction of the space of possibilities in which the freedom to choose work strategy is very important as a means to resolve resource-demand conflicts met during performance. To determine the “space” in which the human can navigate freely, the constraints which must be respected by the actors for the work performance to be acceptable need to be determined (Rasmussen, 2003). One of these boundaries is given by the control requirements posed by the system and the other by the human resource profile, which depends on individual characteristics such as competence, mental capacity, etc. Navigation within the envelope specified by these boundaries will depend on subjective criteria for choice, such as the aim to save time and money, to spare resources, to reduce risk, to increase the cost-benefit ratio, etc. If, however, these boundaries are too stringent, the space of possibilities (i.e. the freedom to make decisions according to personal preferences) could be considerably reduced. The continuous implementation of uncoordinated restrictions (e.g. safety measures) would result in a systematic migration towards the boundary of the acceptable state of affairs and, if crossing the boundary is irreversible, an error or an accident may occur (Rasmussen, 1997). Such an error or accident could, for example, be that there is an unacceptable impact on human safety or security, on the environment or that the residual risk is considered too high. In Fig. 3, we see Rasmussen’s (2003) model used to illustrate the likely systematic migration towards the boundary of the acceptable state of affairs upon the continuous introduction of uncoordinated restrictions. In this figure, we show how the alternative acceptable work activities are shaped by the work environment, which defines the boundaries of the range of possibilities, and that stricter boundaries reduce the selection of acceptable work strategies.

As presented in Fig. 2, the implementation of limitations could have a cascading effect on the system, especially if the potential undesired effects of these limitations have not been sufficiently analysed.

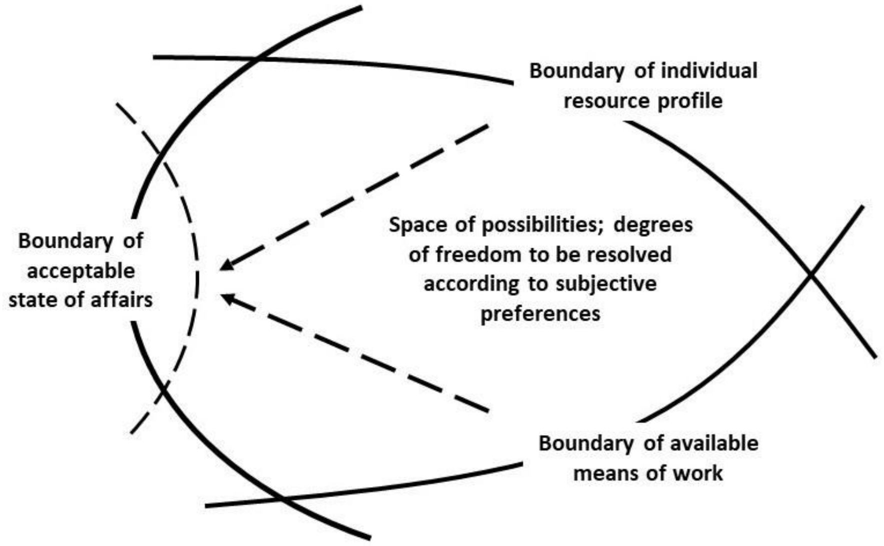

Fig. 3. Rasmussen's (2003) model, identifying the "space" in which the human can navigate freely, adjusted to exemplify the migration of the gradients as a result of the continuous introduction of uncoordinated restrictions.

In addition to the potential consequences of crossing the boundary of the acceptable state of affairs, an unintended restriction of the space of possibilities could also result in a too narrow selection of available work strategies, excluding the only viable options that would result in a successful result with an acceptable risk and an optimal cost-benefit ratio. The inadvertent elimination of viable options in handling a specific ERW threat, as a result of unsynchronized restrictions, could therefore lead to not only significantly increased costs and resources but ultimately also a risk increment to both the operator and the entire society, as the probability and potential consequences of collateral damage and residual risk are likely to increase. As the resources spent on reducing the ERW threat (i.e. EOD action) are normally limited, excessive use of resources due to unsynchronized restrictions may also lead to reductions in planned EOD operations. This is particularly significant, as it could result in less resource-demanding operations being prioritized over more important operations in terms of the reduction of overall societal risk.

2.3.1 The implementation of uncoordinated safety measures: an example

A lack of overall understanding (systems thinking) means that one does not see the totality of the system, and that one therefore focuses exclusively on a limited area (e.g. one's area of responsibility / subject area). In an effort to improve results in this limited area, requirements are introduced (e.g. in terms of resources, efficiency, quality, etc.). Without the required overall understanding, such requirements may be implemented without regard for any impact within other parts of the system and for the system as a whole. Such uncoordinated requirements may limit both the variety of viable actions and the available space of possibilities in which an operator can operate freely.

In this example, we focus on EOD clearance of underwater ERW in Norwegian waters. Norway is one of the largest seafood net exporters in the world, and fish farming or aquaculture is the world's fastest growing food production technology (Smith et al., 2010). It is therefore a concern that ERW in the ocean could affect the quality or sustainability of marine life. ERW are also considered a threat to offshore infrastructure (e.g. oil production and transportation), as well as to offshore development projects (e.g. wind parks, power lines, etc.). With their potentially devastating impact on offshore infrastructure, human safety and marine life, the munitions that still exist in Norwegian waters could have a severe impact on the environment and the world's food and energy supply. There are still hundreds of thousands of tons of ERW in Norwegian waters, making them a considerable environmental concern, as the ammunition casings deteriorate and their harmful constituents constantly leak into the water. In many cases, the locations of the munitions or their types or quantity mean that they represent not only an environmental risk but also a threat to societal safety and security. Clearance of these objects should therefore be a prioritized task of the Norwegian Government. However, as resources are limited, a strict prioritization must be made, to determine what objects/areas should be cleared in what order. Given the current level of resources, it is evident at this stage that only a small fraction of the amount of ERW can be expected to be cleared within the next decades, and that, after a certain point in time, munitions casings have deteriorated to such a degree that they could be virtually impossible to clear.

In this context, it should be evident that the government and all involved parties must work systematically and interactively towards a common shared goal: to reduce the societal risk as much as possible, within the given framework of regulatory restraints and (limited) resources. This is especially so in the light of Norway being a High Contracting Party of Protocol V of the United Nations CCW Convention (United Nations, 2022), which states that ERW in affected territories under its control shall be marked and cleared, removed or destroyed as soon as is feasible (United Nations, 2003). Consequently, all involved governmental agencies should work together on developing and maintaining both a risk assessment and a prioritization-and-action plan for how to deal with the ERW. This is, unfortunately, not the case. There is, at this time, no official national policy on ERW and no coordinated systems approach for how to deal with this grave problem. Consequently, the involved governmental agencies do not have the required systems knowledge to make the optimal risk-reducing choices. This is evident not only from the lack of a national risk assessment and prioritizing plan but also when it comes to routine EOD clearance operations.

For example, underwater EOD operations may take months in the planning and can be extremely resource-demanding in both planning and execution, as (uncoordinated) environmental restrictions are imposed. Examples of such requirements could be to map and survey any vulnerable environmental values in the area and, through a comprehensive and time-consuming research and surveillance process, develop a detailed risk assessment of any potential consequences an underwater detonation and/or uncontrolled release of related hazardous components could have on these values. There could also be additional requirements, such as detailed instructions on how the operation is to be conducted, as well as what methodology is to be used, in order to, as far as they know, reduce any undesired environmental impact from the operation.

The consequence of these restrictions could very well be that some objects/locations, which are otherwise highly prioritized due to the level of assessed risk they pose to societal safety and security, are deprioritized, as, due to imposed restrictions, they become too resource-demanding compared with other, lower-prioritized objects/locations. Other consequences would be that, with an increase in the resources needed for each operation, the number of operations per year would be drastically reduced and/or only low resource-demanding objects/locations would be cleared. Such unintended consequences would mean that the reduction of societal risk is non-optimal from both a cost-benefit ratio perspective and a moral perspective. As uncoordinated restrictions have a direct effect on the prioritizing and execution of EOD operations, they will also have an impact, either directly or by implications of other parts of the system, within the area in which it was intended to mitigate the risk. In this example, the restrictions were implemented in order to reduce the environmental impact of EOD clearance operations. The consequences of the restrictions may, however, have a counteracting effect. For instance, a requirement that the object must be moved to a new location before it is rendered safe (e.g. by low-order deflagration or high-order detonation) could increase the risk of accidental detonation, thus increasing the risk, both towards involved personnel and to that of uncontrolled pollution. Similarly, the relocation of an object could also result in the disintegration of the munitions' casings, potentially spreading harmful substances over a large area.

Another example is the requirement to use a certain disposal technique, like low-order deflagration techniques. Low-order has the potential to mitigate the acute blast effects by over 90 percent of those associated with conventional procedures (i.e. high-order) (Pedersen, Nokes, & Wardlaw, 2002) and is often lobbied as an environmentally friendly, less damaging, less disruptive alternative to conventional detonations (e.g. Robinson et al., 2020). Therefore, it is often suggested as the default method of munitions' disposal (Randall, 2022; UK Government, 2022). Some countries and organisations even prohibit the use of high-order detonation as a suitable technique for disposing of ERW, and others are now working towards a permanent ban (Cottrell & Dupuy, 2021; Koschinski & Kock, 2015). While fairly under-communicated by lobbyists, these low-order techniques often result in an incomplete deflagration, leaving substantial quantities of the explosive material in the environment, resulting in contamination of marine life and an environmental hazard, which can ultimately even endanger human seafood consumers (Edmund Maser & Strehse, 2020). Whilst there is no question that, under the right circumstances, these actions may indeed achieve the intended effect (i.e. risk mitigation), a lack of coordination and systems thinking in the development and implementation of the requirements may ultimately lead to the imposed safety measures having the opposite effect. Other requirements, such as environmental mapping and surveillance, are, generally speaking, both achievable and reasonable, but if the requirements are disproportionately high and very cost- and resource-demanding, the consequence could be that the operation is cancelled, due to limited resources, leaving the societal risk unchanged. In this case, the extent of requirements put in place to mitigate the environmental risk involving EOD action may result in the munitions not being cleared, thus leaving them to further deteriorate and pollute the surrounding environment. In this example, it is also evident that the process itself, of securing permission from the relevant environmental authority to perform underwater EOD, is both impractical and time-consuming, with unclear responsibilities, and suffers from a lack of intergovernmental coordination. An unclear and time-consuming application process, in which the responsible governmental agency also has to pay a service fee to the issuing authority, would by itself act as a demotivating factor for increasing the effectiveness and the number of ERW cleared from Norwegian waters.

As the example illustrates, there is currently no political strategy or guidelines in place regarding how to handle the thousands of tons of ERW in Norwegian waters. The relevant governmental agencies play their role as best they see fit, often acting upon their own uncoordinated perception of the problem. Their immediate response, understandably, is to resolve the most visible symptoms of the problems in their relevant area of responsibility, by applying some sort of quick-fix method (i.e. implementation of safety measures) that is expected to give swift results. This sort of complex problem solving is, however, impossible to deal with in the absence of all of the alternative stakeholders and without adequate system knowledge, and, as illustrated in Fig. 4, there is a tendency to become overly focused on treating the symptoms rather than dealing with the underlying cause (Haraldsson, 2004). This is not done intentionally by policymakers but, rather, stems from the absence of systems thinking and a lack of understanding of how the symptoms manifest themselves. The example further illustrates that a lack of systems thinking can lead to both an inexpedient process, as well as the uncoordinated implementation of restrictions. The pressure towards increased environmental safety reduces the space of possibilities to a point that only a strict number of choices is viable for the operator. The most severe consequence of this is that the only remaining viable choices could then represent an increase in the overall societal risk. Another unfortunate consequence is that any choice would normally represent a high cost- and capacity-demanding option and an inefficient use of governmental funds. In a time of limited resources, the EOD operators’ choices will also be limited, and there will be a pressure towards a methodology that involves a heightened overall risk (Rasmussen, 1997).

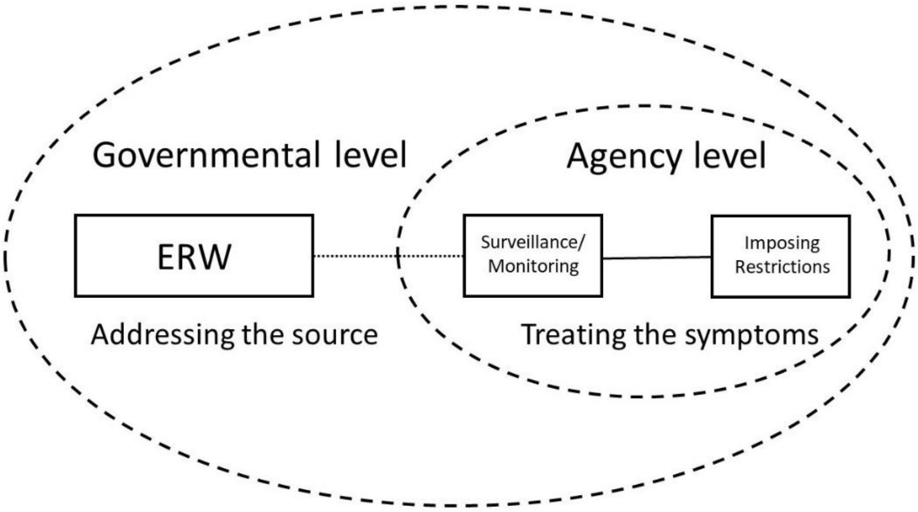

Fig. 4. In order to deal effectively with the dilemma of ERW, all relevant actors need to be included (model based on Haraldsson's (2004) acid rain example).

3. Discussion

In a world of progressively complex systems, interconnections and technological advancements, each increasing the interdependence on other systems, we strive to understand the deep roots of these complex behaviours, in order to better predict them and, ultimately, adjust their outcomes. The need for systems thinking, therefore, stretches far beyond the science and engineering disciplines, encompassing, in truth, every aspect of life (Arnold & Wade, 2015).

The idea of systems thinking is frequently used in accident analysis, organizational theories and quality discourse (Langdalen et al., 2020). As incidents, accidents and near misses most often originate in a complex combination of factors, both technical and social, systems thinking can help tease out the decisions and actions that caused a system to fail (Bennett, 2019). Based on this reasoning, systems thinking should, therefore, also be a necessity in risk analysis for dealing with complexity (Langdalen et al., 2020). It could, therefore, be strongly argued that all people in decision-making roles should have a solid grasp of systems thinking (Arnold & Wade, 2015).

In ERW risk management, systems thinking seems crucial. As both the risks and the risk management systems are complex, we see that a lack of systems thinking can result in a sub-optimal use of resources and a heightened societal risk. More precisely, we see that the lack of a systems approach results in an overcomplicated and bureaucratic intergovernmental process, unclear responsibilities and absent strategic guidance, resulting in a sub-optimal use of both human and economic resources. Additionally, a lack of overall understanding can lead to an over-focus on areas that seem manageable (i.e. the symptoms) and an under-prioritization of fundamentals (i.e. the source of the symptoms). This results in short-term fixes that are adaptive at the time but could impede the development of longer-term solutions (Amalberti & Vincent, 2019). For instance, in an attempt to manage the risks at an agency level, several regulatory restrictions are put in place to govern how a specific part of the ERW risk should be managed. Isolated, such restrictions would not necessarily have any undesirable effects and could very well prove to reduce accidents and increase safety as intended, but, as a part of a complex system, they could also prove to have unintended implications for other parts of the system, possibly even reducing the overall quality and efficiency of the system. In the exemplified CLD for ERW action (Fig. 2), uncoordinated safety measures could act as a restriction (limitation) on the selection of viable choices available to the decision-maker (choices), potentially affecting the consequences of the ERW action and, ultimately, its effect on societal safety and security. The implementation of restrictions, without exploring their effect and potentially cascading impacts, would therefore have the potential to have unintended negative consequences, resulting in an increased overall societal risk. One such unintended consequence could be depriving the decision-makers at the operational and tactical levels of their privilege of choice between the applicable methodologies. This will not only increase the societal risk but also significantly increase the risk for the EOD operator and deprive him/her of the means to resolve resource-demand conflicts (Rasmussen, 2003), making an already difficult job much harder.

The example illustrates that complex problem solving is challenging to deal with without systems thinking and in the absence of all the alternative stakeholders. We also see that adequate ERW risk assessment and management is dependent upon a conceptual framework for seeing the whole and interactions, rather than isolated parts of the system. It is our belief that the implementation of systems thinking can advance the identification and assessment of potential risks related to ERW that may affect complex risk management in both the present and the future, as well as better enabling us to fulfil our requirements according to the United Nations (2003) Protocol on Explosive Remnants of War.

Several existing models for systems thinking could relatively easily be implemented as is or adopted to the specifics of ERW risk, potentially providing us with a new and improved approach to safety. A well-known example of a model that could be implemented is Leveson's (2011) Systems-Theoretic Accident Model and Processes (STAMP), one of the most widely used models for predictive applications in the literature (Düzgün & Leveson, 2018). STAMP is an accident causality model, based on systems theory and created as a response to the limitations of traditional causality models in the analysis of modern complex systems (N. G. Leveson, 2011). It covers accidents linked to both component failures and the interactions of system components (Chaal et al., 2020; Fleming, Spencer, Thomas, Leveson, & Wilkinson, 2013; N. Leveson, 2015). This approach views the hierarchical organization, a model in which feedback loops enable a higher level (the controller) to initiate proper (re-)actions, to maintain the system in a state of equilibrium and within safety limits (Lunde & Njå, 2021). Through its implementation, it could be possible to better depict and review the function of safety from a systemic perspective, to increase the ability to learn from experience and particularly to deal with the complexity from the interaction among diverse system components (Banda & Goerlandt, 2018).

4. Concluding remarks

In this paper, we point out the importance of having a systems approach in ERW risk management, especially when introducing factors that could act as limitations in the system, such as regulations, procedures and instructions. Without adopting a systems thinking approach, we may end up implementing safety measures and requirements with less effect than intended; in the worst cases, the effect can even prove to be negative, due to some unforeseen negative side effects.

Our main goal when addressing ERW must first and foremost be risk mitigation: preventing unnecessary accidents, environmental contamination and illicit misuse of ERW, thus increasing communal and environmental safety. But, if we continuously perform actions that have no significant effect on our overall goal as well as implementing safety measures without exploring their effect and the potentially cascading impacts within a complex system, it could result in a sub-optimal use of already limited resources, as well as an increased overall societal risk.

Based on this reasoning, systems thinking should, therefore, be a necessity in ERW risk analysis and risk management, as well as an integral part of the continuous evaluation of existing and proposed new safety measures. It is our opinion that the adoption of a system-theoretic approach to safety would be an effective way to integrate safety in a complex system such as ERW risk management.

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Paper V

When a safety measure becomes a risk accelerant: Removing the option to blast-in-place when clearing explosive remnants of war

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WHEN A SAFETY MEASURE BECOMES A RISK ACCELERANT:

Removing the Option to Blast-In-Place When Clearing Explosive Remnants of War

By Lieutenant Colonel Geir P. Novik [Norwegian Defence Research Establishment]

The legacy of unexploded ordnance (UXO) and abandoned ammunition following armed conflict will, in many cases, have a severe impact on society and daily life, even for years or decades after hostilities end. These explosive remnants of war (ERW) represent a grave threat in many aspects, and the human, societal, and environmental impact can be severe. These explosive objects must therefore be located and disposed of—a job in itself that involves serious risks. Therefore, various safety measures are implemented to mitigate these risks. Some safety measures, however, could prove to have less than the desired effect, and in the worst cases, could even increase the risk.

Unearthing vast quantities of explosive remnants of war (ERW). More than eighty unexploded German WW2 aircraft bombs were discovered in the center of a Norwegian village.
Image courtesy of Geir P. Novik.

Introduction

ERW contamination is a major problem in many countries, especially those that have experienced armed conflict in recent years. Munitions can remain intact and functional for decades, and even centuries, after the end of hostilities, resulting in a great number of countries where they still represent a severe threat.

Clearance of ERW is therefore a prioritized task in many affected countries and is recognized as a vital risk-reduction tool. ERW—UXO and abandoned ammunition—represent serious risks in several aspects, both humanitarian and societal, as well as economic and political. We need only look at the numerous unintentional explosions and accidents involving ERW all over the world each year to recognize how this can affect human life and societal values. Furthermore, there is increasing concern that the leaking and bioaccumulation of toxic constituents from corrosive munitions threaten ecosystems, as several of the chemicals used in ammunition are known to be highly poisonous and carcinogenic and have been proven to contaminate living organisms and the surrounding soil and groundwater. To deal with these risks, the majority of countries that deal with ordnance put in place legislation, regulations, and provide detailed instructions, as well as implement safety measures that regulate what can and must be done in order to mitigate the risk of explosions.

Safety measures can be implemented for a variety of reasons. First and foremost, there is a desire to protect against danger, risk, and injury. We also seek to further develop existing good practices to ensure that our efforts not only do no harm but also, to the greatest extent possible, to consider and reduce any environmental impacts as a result of our actions. There could also be safety measures that are implemented for legal, economic, or political reasons. Consequently, there are a great number of possible standards that can regulate ERW clearance, as well as several local, self-imposed restrictions. We see, however, that several of the implemented safety measures do not always have the intended effect and can, in fact, have the opposite effect to what was originally intended.[1,2]

One of the ERW-related safety measures that is being discussed and that has already been implemented in several countries is to reduce the environmental hazards related to underwater high-order detonation (i.e., an exothermic reaction wave which follows, and also maintains, a supersonic shock front in an explosive)[3] techniques by effectively banning the procedure. As environmental concern is increasing in society in general, so are the demands for and expectations of environmentally friendly ERW-clearance processes, and rightfully so. However, many contributors to the debate do not differentiate between various disposal techniques when discussing potential environmental consequences, and it seems obvious that there could be unidentified and unintended consequences of eliminating one of the most used ERW-disposal procedures. Moreover, alternative procedures are often presented as quick fixes, not taking into consideration all the potential unintended negative effects these techniques would entail. Undoubtedly, there are various inherent disadvantages and limitations related to all relevant disposal procedures, and in order to make informed decisions, we need to increase our depth of knowledge of what these are and how they can be feasibly mitigated by introducing specific actions.

Choosing the Right Disposal Technique

When clearing ERW, the use of high-order detonations remains the primary disposal method, since it is cost-effective, can be used across a diverse range of munitions and does not require sophisticated infrastructure and equipment.[4] It is not particularly resource-demanding in terms of time, cost, and training, and for blow-in-place operations, it normally does not require the use of any specialized tool, equipment apart from basic explosives, or initiators for donor charges. The major disadvantages of employing this methodology, however, are the explosive effects, such as the blast, fragmentation, earth shock, and the generation of flying debris.[5] Underwater, the detonations generate low-frequency shock waves and subsequent pulsations of the bubble sphere at high pressure, which can propagate for long distances.[6] A high level of impulsive noise poses a serious risk of injury or death to marine mammals and other fauna.[7,8,9] As the potential negative effects of high-order detonations are well documented, there is pressure toward discontinuing the use of this methodology in favor of more environmentally friendly techniques.[10] Some countries and international organizations already prohibit the use of high-order detonation as a suitable technique for disposing of ERW,[11,12] as the environmental impact of this technique is considered too severe.

There are some potential alternative techniques to clear ERW without the need for detonation, such as freezing techniques, the use of robotic equipment, water abrasive suspension cutting, the photolytic destruction of explosive substances, etc.[13,14] However, these are all relatively resource-demanding and normally require the object to be moved, either remotely or manually, with the subsequent risk of unintentional detonation.

While high explosives are designed for detonation, they can also deflagrate in the absence of shock initiation, provided that the combustion initiates and proceeds under minimal clearance volume so that rapid and localized pressure rise is avoided.[15] By employing deflagration techniques (i.e., low-order), the explosive materials often decompose at a rate much below the sonic velocity of the material without requiring any input of heat from another source[16] or the introduction of atmospheric oxygen.[17] Low-order techniques (i.e., the incomplete initiation of an explosive or one which has detonated at a velocity well below the maximum stable velocity of detonation for a system, being more nearly combustion than an explosion)[18,19] has the potential to mitigate the acute blast effects by over ninety percent of those associated with conventional high-order procedures,[20] thus reducing the environmental impact

A German SC50 (fifty kg) aircraft bomb following a low-order procedure. Only a small amount of the explosive component was consumed by the deflagration.
Image courtesy of Geir-P. Novik.

through a lower acoustic output.[21] Low-order can normally be accomplished by applying a sufficient temperature (e.g., with the use of thermite, a laser, etc.) or by detonating a specially designed small explosive charge (not always feasible due to the specific design features of certain types of munitions or the type or composition of their main filling).

In addition to reducing the explosive effect (i.e., blast, fragmentation, pressure, etc.), low-order techniques would potentially also reduce the amount of metallic debris that a high-order detonation of ERW would produce,[22] as well as reduce the disturbance of the sediments and the consequent spreading of harmful substances trapped within the sediments or in their immediate surroundings. As explosive effects are reduced substantially, so is the risk of unintentional sympathetic detonations of undiscovered munitions in the ground or in sediments that could otherwise detonate through detonation transfer. Consequently, this technique would not be suitable for intentional sympathetic detonations. Using low-order techniques, with their significantly reduced probability of high-order detonation-level effects, would also mean that some ERW do not have to be relocated, thereby preventing the potential damage resulting from an unintentional detonation during relocation.[23] Nonetheless, as low-order techniques are not one hundred percent reliable, all relevant measures (e.g., safety, surveillance, etc.) would still be required in the same ranges expected for high-order detonation. Consequently, if a high-order detonation is not acceptable at a specific location, the ordnance is still required to be relocated, even if a low-order technique is being conducted due to the possibility of a deflagration-to-detonation transfer.[24] This is especially relevant whenever aging and deteriorating ERW are encountered, as positive identification is not always possible and the technical condition of the munitions—e.g., the thickness of the munition casings—could vary from object to object due to individual and local properties, such as metallurgic composition, main filling composition and condition, environmental conditions (e.g., salinity, temperature, current, etc.), and others. Therefore, low-order techniques should be used with caution, as relatively small individual variables could result in not only deflagration but also high-order detonation or no reaction.[25]

Simultaneous operations on multiple objects in close proximity would also be challenging, as there is a risk of high detonation in some objects and no-reaction results in others, potentially resulting in some objects being moved or covered in sediments and left undetected. The possibility for the undesired effects involved with low-order techniques entails that one must plan not only for a possible high-order detonation but also for repeated actions on individual objects in case of no reaction. Therefore, it could be expected that using low-order techniques on ERW would be more time-consuming compared to employing high-order detonations. Furthermore, depending on how the technique is employed, it could also require specific training and a high level of personnel specialization,[26] and care has to be taken to ensure that the low-order charges are placed correctly according to the specifics of the individual object design (i.e., the location of vital internal components). As the low-order technique regularly consumes (deflagrates) only parts of the explosive filling in the munitions, sufficient time should be added for the cleanup of unconsumed residual explosives for each object. It must be expected, however, that the majority of particles—which range from micrometers to centimeters in diameter—are unsalvageable and will be deposited in the environment. Therefore, the unconsumed residual explosive constitutes a potentially significant source of explosives for environmental receptors[27] and could pose a great environmental threat.[28] Explosive chemicals, such as RDX, TNT, and its derivatives, are known for their toxicity and carcinogenicity[29] and have been proven to contaminate living organisms, as well as the surrounding soil and groundwater.[30] Dispersed granular particles are easily ingested,[31] and several recent studies have raised concerns about increasing levels of poisonous chemicals used in ammunition being detected in marine life.[32,33,34] Therefore, these chemicals may also enter the marine food chain and directly affect human health upon the consumption of contaminated seafood.[35] Furthermore, there is a risk that some fuzes, boosters, and/or parts of more sensitive primary explosives could be separated from the munitions, leaving the most sensitive part of the ERW behind. This would increase not only the risk for the operator when removing all debris from the low-order procedure but also the risk of leaving behind potentially deadly explosive objects.

In contrast, a high-order detonation of ordnance will also normally leave some energetic residue in the impact area, but this is generally very little.[36] High-order detonation as a result of live fire operations will consume virtually all energetic material in the ordnance, while high-order detonation as a result of blow-in-place operations using a donor charge is normally expected to consume about 99–99.9 percent of the main charge.[37,38,39] As a rule of thumb, it normally takes 10,000 to 100,000 high-order detonations to deposit the same amount of explosives as one low-order deflagration.[40] This is especially vital, as some ERW are cleared not because they pose an immediate explosive risk but because of the potential environmental threat the dispersal of explosives would represent in case of present or future deterioration of munitions casings. Furthermore, it is imperative to recognize the dissimilarities of the techniques in terms of explosive residue, as many, specifically those who are not part of the EOD profession or experts in the field, do not differentiate between the techniques when discussing potential environmental consequences.[41,42]

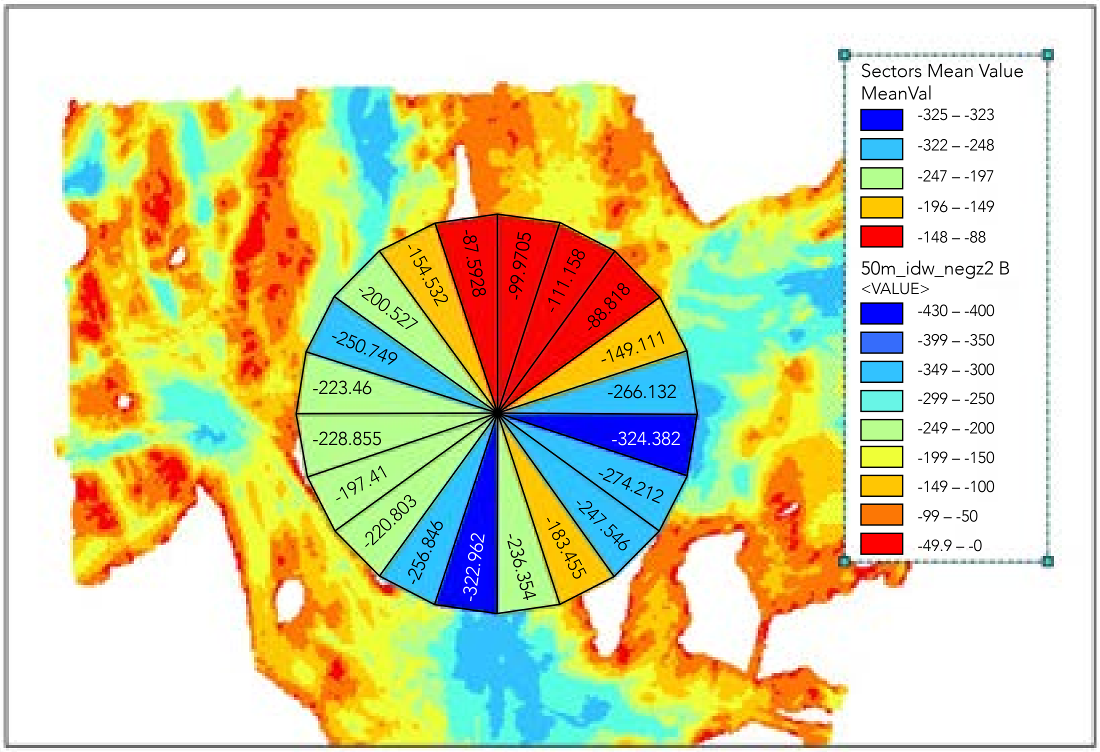

Figure 1. Example of an interactive decision tool based on shock wave propagation and a geographic information systems program that contains updated information on fisheries activities, environmentally protected areas, aquaculture sites, etc.
Figure courtesy of P.H. Kvadsheim (Norwegian Defence Research Establishment).

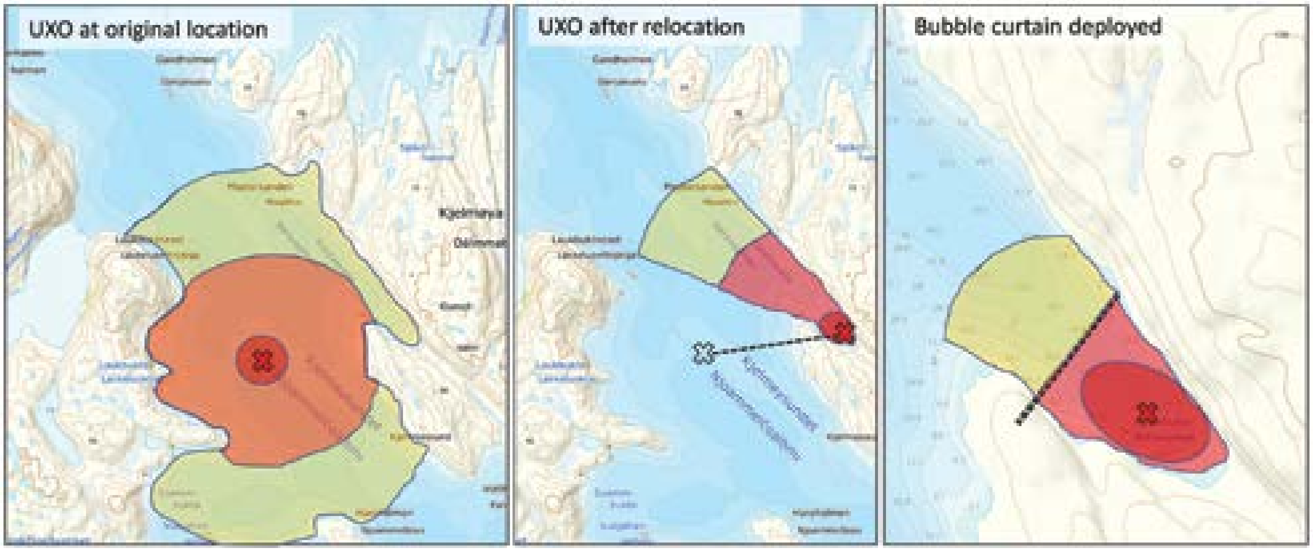

Figure 2. Illustration of how the ERW effect zones (i.e., mortality, injury, and stress/flight) could be reduced by relocation and the use of bubble curtains.
Image courtesy of Geir P. Novik.

Identifying Solutions

First, we should recognize the advantages of using low-order techniques, especially their potential to mitigate many of the negative effects related to high-order detonations, such as the possibility of causing severe injury or death to marine mammals and other fauna. However, we must also acknowledge the most serious limitations and negative effects of the low-order technique: the dispersion of substantial quantities of toxic material into the environment. This risk can be mitigated a great deal by removing all identifiable pieces of unconsumed residual explosives following a low-order operation; still, a substantial part of the explosives will be dispersed in the water and sediments. If the object can be moved without unacceptable risk, it can be relocated to a more suitable location prior to the low-order operation to reduce the time needed to clean up the explosive residues and lighten the burden of locating the explosives. This can be achieved by relocating the object to shallower water and/or to a location where the residues can be more easily observed and collected. When selecting the location, attention should also be paid to the fact that explosives will be dispersed and that some deflagration-to-detonation transfers will probably occur, resulting in high-order detonations. Moreover, we need to acknowledge that the use of low-order techniques will involve a degree of uncertainty, as they are not wholly reliable and that the use of these techniques will require more time and resources spent on each individual object compared to high-order detonations.

Next, we should study how high-order detonations are conducted and how their negative effects can be mitigated. As stated, some low-order operations will most likely result in high-order detonations, although a somewhat reduced effect can be expected, as some of the explosives could already be consumed by the preceding deflagration. Therefore some, if not all, of the safety measures for high-order detonations should also be observed for low-order operations. There are several relevant safety measures for mitigating the negative effects of high-order detonations. First, if possible, the object could be relocated to a suitable location in which the explosive effects are reduced. Several factors need to be observed, including depth, natural obstructions to reduce shock waves and noise, environmental conditions, infrastructure, safety distances, type of sediment, etc. The utilization of electronic mapping tools that include relevant information (e.g., environmental, infrastructure, etc.) could be helpful in calculating and assessing the potential explosive effects of high-order detonations in various locations. Bubble curtains, which consist of pumping compressed air through hoses laid on the seafloor, have proven to cushion underwater detonations by absorbing much of the energy of the blast and sound wave and effectively reducing the sound pressure and shock wave, thus substantially reducing the danger zone for marine organisms.[43] Bubble curtains and natural physical barriers have been successfully used for many years as efficient tools for noise mitigation in several countries (e.g., Norway, Denmark, and the United States).

Nevertheless, the use of bubble curtains does have some major disadvantages and limitations, such as water depth and prevailing currents.[44] They also require specialized training and sufficient time and resources to set up and run. Additionally, bubble curtains can be quite costly, which could deter a potential user from acquiring them, although increased adaptation of the system would play a key role in driving down costs, demonstrating reliability and fitness-for-purpose, increasing technical capacity, and addressing capability gaps.[45] If there are multiple locations where high-order detonations will occur, the bubble curtains will need to be repositioned between locations. However, if the detonations take place in a favorable location, such as a bay, the entire strait could be covered by a bubble curtain, thus effectively eliminating most of the sound and shock waves resulting from underwater high-order detonations. So-called soft-start charges, or scare charges, are also regularly used in order to deter marine mammals and other marine life from the area before blast-in-place operations using high-order detonations are commenced in order to reduce the level of noise exposure and risk of injury.[46] However, the soft-start procedure assumes that animals have an avoidance response and will move away from the source, but this has not yet been proven experimentally.[47] Some mammals are known to ignore soft-start devices, and some may also be attracted by the initial weak sound and thus exposed to potential fatal explosive effects as the detonation commences. There is also concern that soft-start procedures may prolong the total duration of operations, possibly increasing the total amount of acoustic energy transmitted into the environment.[48]

In many countries, it is still common practice to use a range of different techniques, including both low-order deflagration and high-order detonation, to clear ERW as safely as possible while ensuring the utmost protection of the personnel, environment, infrastructure, and material. The risk is complex and multifaceted and includes a great number of unknowns that are dependent on several unique factors.[49] The risks involved are made clear by the numerous unintentional explosions and accidents involving ERW all over the world each year.[50] While the number of ERW seems limitless, unfortunately, the same is not the case when it comes to the available resources for clearing the munitions. Arguably, the most cost-effective disposal technique, high-order detonation, is an important tool in clearing ERW; however, with its inherent negative environmental impact in terms of explosive effects, it is quite clear that using the technique uncritically could do more harm than good. Nevertheless, relevant alternative techniques also have their limitations, such as increased demands in time and cost, increased risk of unintentional detonation, and a potentially devastating environmental impact in terms of the dispersal of toxic chemicals (i.e., low-order).

The obvious solution is to allow for a combination of various techniques. Based on the assessment of the unique locations, objects, environmental condition, available resources, and individual preferences (e.g., training and knowledge), and given the necessary space of possibilities, it would be possible to dispose of every object according to each individual case. Only by allowing for a certain degree of freedom is it possible to assess every object individually and to dispose of it utilizing a safe and practically feasible disposal technique with the least possible negative societal and environmental impacts. Sometimes, the only viable option could be to employ a low-order technique; other times, it could be to do a high-order detonation, even according to the environmental precautionary principle. In any case, great effort should be made to mitigate the inherent risks.

Conclusion

The first priority when dealing with ERW should be their recovery and safe disposal. In doing so, we should also make every effort to minimize the potentially negative societal and environmental impact while also prioritizing resources allocated to mitigating this threat. Only then would we be able to effectively reduce the societal risks related to ERW while also gaining more economic efficiency and a more favorable cost-to-benefit ratio.

While some countries and organizations already prohibit the use of high-order detonation as a suitable technique for disposing of ERW, and others are working toward a permanent ban, we must be cautious not to implement safety measures that could have less than the intended effect, no effect at all, or in the worst case, a negative effect. The priority should not be deciding whether we should use low-order or high-order techniques but assessing what would be the safest and most environmentally friendly option for every unique situation, given proper risk-mitigating actions. We must therefore take caution not to make good the enemy of the best.

A legal obligation not to employ, or even a regulation strongly recommending against, high-order detonation techniques while clearing ERW would effectively eliminate an option that could prove to be the safest, quickest, least resource-demanding and most environmentally friendly, which could ultimately result in an increased societal and environmental risk.

See endnotes page 66

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When a Safety Measure Becomes a Risk Accelerant: Removing the Option to Blast-In-Place When Clearing Explosive Remnants of War by Lieutenant Colonel Geir P. Novik

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