Thematic assessment on

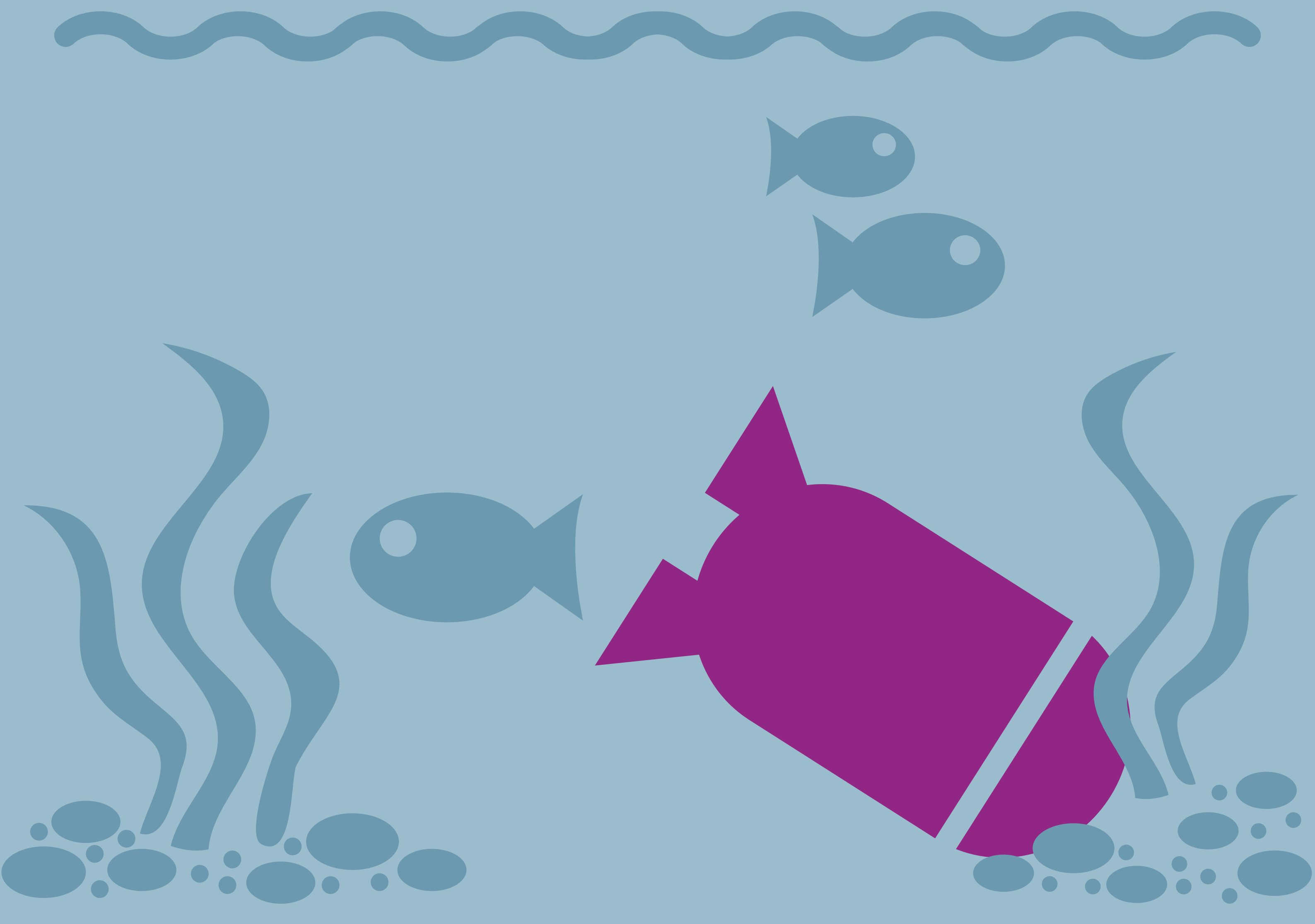
Hazardous Submerged Objects in the Baltic Sea

Warfare Materials in the Baltic Sea

Baltic Marine Environment Protection Commission

Hazardous Submerged Objects

2024



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Content

1. Introduction

1.1 The Warfare Materials Issue in the Baltic Sea

Contemporary society's perception of past wars is almost exclusively driven by historic sources such as film recordings, photographs and written documents that are presented in mass media. However, the legacy of these wars is still present throughout European soil and waters, including the Baltic Sea. The marine waters of every Baltic Sea state contain warfare materials. Resulting risks may be direct and short-term. Fishermen, divers, offshore wind farm constructors and beachgoers can potentially be exposed to their remains while performing their daily work or while collecting objects in the surf. Other potential effects might be indirect and long-term such as the accumulation of carcinogenic toxic substances and their metabolites in the marine food web.

Since 1974 Contracting Parties of the Helsinki Convention are seeking to address the increasing environmental challenges from human activities and that were having a severe impact on the marine environment. This includes the protection of the Baltic Sea from all sources of pollution, and thus munitions in the Baltic Sea are addressed by HELCOM since 1993. The convention commits the signatories to take measures to conserve habitats and biological diversity and for the sustainable use of marine resources. In addition, warfare materials potentially constitute a hazard and an obstacle for the utilization of the sea floor for economic purposes. The global ocean economy is predicted to double in size by 2030, as compared to 2010 (OECD 2016). In the Blue Growth Strategy laid out by the European Commission the economic potential for the extended economic usage of the oceans was recognized and focus was placed on five blue growth sectors. Two of these sectors (ocean energy and seabed mining) require the ability to safely access large areas of the sea floor (European Commission 2017). In order to exploit the economic potential of the ocean energy and seabed resources sectors, the detection and removal of warfare materials in affected areas will become increasingly important (European Parliament 2021).

Recently, numerous HELCOM Contracting Parties supported increasing the knowledge concerning warfare materials in the Baltic Sea and their effects on humans and the marine environment of the Baltic Sea. As a result of national, regional and international scientific research the understanding of the issue grows and consequentially numerous recommendations are published on how the warfare materials challenge can be addressed. However, international coordination is necessary to identify synergies and to avoid a duplication of efforts. This report provides the current state of knowledge on warfare materials in the Baltic sea based on recent research projects.

1.2 Introduction to HELCOM EG Submerged

The Terms of Reference of the HELCOM Expert Group on Hazardous Submerged Objects (HELCOM EG Submerged) were agreed upon by the HELCOM Heads of Delegation meeting HELCOM HOD 43-2013. HELCOM EG Submerged worked under the supervision of the HELCOM

Response Working Group to compile and assess information about all kinds of hazardous objects and assess the associated risks. This compilation and assessment was used to produce the present thematic assessment report on challenges related to warfare materials in the Baltic Sea.

HELCOM EG Submerged was chaired by Jens Sternheim (MELUND – Germany), Jacek Bełdowski (Institute of Oceanology PAN – Poland) and Jorma Rytkönen (Finnish Environment Institute (SYKE) – Finland) during the development of this assessment report. The group convened eight times to arrive at the results presented in this assessment report. While the terms of reference of HELCOM EG Submerged requested an assessment on various submerged hazardous objects, this report only covers the issue of warfare materials. This is because the number of experts on wrecks, lost dangerous goods, cargo and sea-dumped waste joining the preparation of the assessment report has unfortunately remained insufficient. A volume 2 HELCOM Submerged Assessment – Wrecks in the Baltic Sea, is under development by EG Submerged, under the supervision of the HELCOM Working Group Reduction of Pressures from Sea-based Sources (WG Sea-based pressures).

1.3 Objective and Scope of the Report

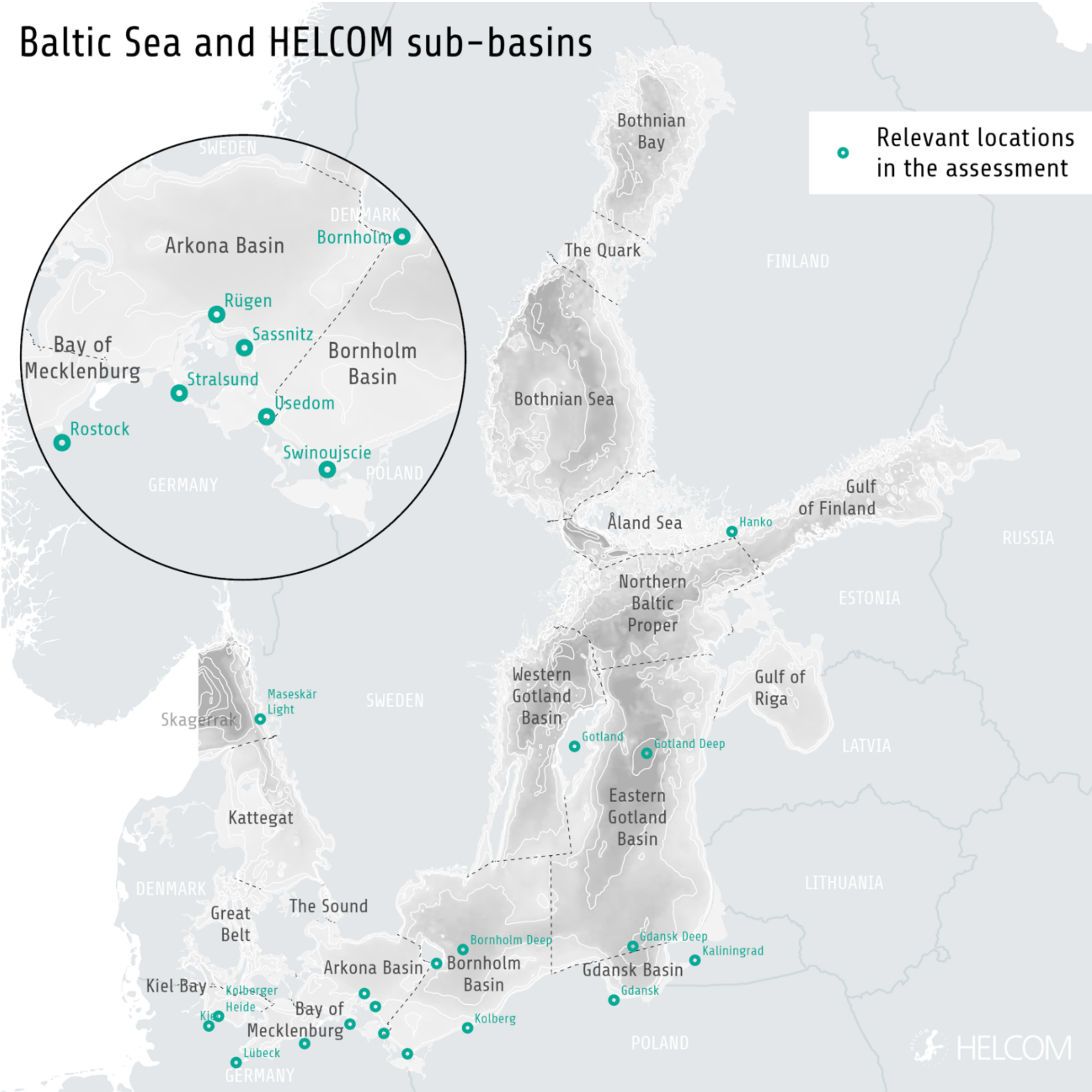
The present assessment report has the following three objectives, which are based on the recent research project findings on chemical and conventional warfare materials in the Baltic Sea:

1. Provide the current scientific state of knowledge about warfare materials in the Baltic Sea (chapters 2, 3 and 4).
2. Compile a comprehensive overview of past and present national and international efforts and activities (chapter 5).
3. Provide a science-based collection of findings and conclusions (chapter 6).

The assessment report focuses on warfare materials in the Baltic Sea. Due to its favourable environmental conditions, research on warfare materials is often less cost- and resource-intensive than in the North Sea. The great majority of research results described in the subsequent chapters were generated here. Nonetheless, many of the results and recommendations presented in this report can be transferred to other European waters, such as the North, Mediterranean and Black Seas.

Even though the warfare materials issues in the Baltic Sea concerns both conventional and chemical weapons, this report leans towards reporting on conventional material. The reasons are twofold: First, the vast majority of warfare materials are conventional. Second, the HELCOM report *Chemical Munitions Dumped in the Baltic Sea* (2013) already covers the issue of chemical warfare materials. For this reason, the report at hand addresses chemical warfare materials mainly in cases in which more recent knowledge was gained.

The report *Warfare Materials in the Baltic Sea* is structured in the following manner: The next section provides basic and background knowledge on various types of warfare materials that are present in the Baltic Sea and how they got there. Subsequently, the report describes the effects and risks related to these dangerous artefacts to humans, marine infrastructure and the marine environment. The section following thereafter introduces methods for the management of the warfare materials issue. Next, the authors provide an overview of the previous and contemporary national and international efforts and projects. The final section contains a catalogue of potential risk mitigation measures.



2. Warfare Materials – Historic and Geographic Background

2.1 Warfare Materials and their Components

Warfare materials is a term including many different objects intended for military purposes. There are several ways to group and distinguish warfare materials, such as by the intended purpose, by certain properties of construction, by ways of their deployment or by characteristics of typical payloads.

To be able to understand direct hazards, related risks or general challenges that need to be taken into consideration, some very basic knowledge on warfare materials and especially different types of munitions is introduced in this chapter. Regarding "warfare materials in the sea", a very general distinction is commonly made by dividing warfare materials into the following two groups:

1. Conventional weapons, e.g. explosive, incendiary or ballistic munitions.
2. Weapons of mass destruction (WMD), e.g. chemical, biological, radioactive or nuclear payloads (CBRN weapons).

Because HELCOM MUNI (2013) refers in detail to chemical munitions in the Baltic Sea, the report at hand focuses mainly on conventional munitions. Some extraordinarily relevant and new findings on chemical munitions or crucial relations between both groups are also mentioned in this report. At this point, there is no evidence indicating that biological, nuclear or radioactive warfare materials have been introduced to the Baltic Sea.

To distinguish between conventional and chemical warfare materials, the composition of the payload is the critical indicator. Other munitions compounds and parts are usually equal in both groups. Thus, to explain the effects of warfare materials in the marine environment it is necessary to assess the composition of modern warfare materials developed, produced and deployed in the Baltic Sea region after 1840.

2.1.1 Munitions Compounds

A large number of munitions compounds was used to fulfil a relatively small range of tasks. Explosives were designed to provide extraordinarily high energy release rate to enable detonation. Propellants, on the other hand, have a much lower energy release rate and are used to propel missiles, shells or other payloads towards their targets. Incendiary materials are designed to ignite flammable goods in the target area after a hit or to illuminate. Yet other payloads were intended to provide artificial fog or smoke. Finally, chemical warfare agents (CWAs) are physiologically effective chemicals that are subject of the Chemical Weapons Conventions (CWC).

Towards the end of the 19th century explosives development was highly innovative, leading to a variety of new materials. At this time explosive materials were developed in numerous nations simultaneously. In general, these were based on the same basic chemical compounds and nearly all of them contained 2,4,6-trinitrotoluene (TNT). Numerous other materials were intermixed with the aim of creating higher performance explosives.

The development of nitrocellulose and later nitro-glycerine altered the weapon systems but were hazardous to use. The need for more stable solid materials with higher performance and the development of nitration technology was a significant innovation, specifically the addition of nitro groups to organic molecules. Picric acid was one of the first of these nitrated solids but was rapidly replaced in the early twentieth century by TNT. The use of TNT replaced some of the other attempts to produce higher performance materials with ammonium nitrate (AN) mixtures. However, blends such as Amatol (AN/TNT) were also used. Later the synthesis and development of first RDX/Hexogen and then HMX/Octogen in both Germany and the UK enabled armour-piercing ammunition. Most of the materials used in quantities are organic and nitrogen containing, with the nitrogen located in either nitro groups or nitrate ester groups. These chemical bonds release energy rapidly when stimulated.

Over the years, a large number of different explosives were developed. For example, the German military deployed more than 117 types of explosive materials over the course of World War II alone. The German navy utilized nearly 40 substances that were specifically designed for the use in naval weapons, such as naval mines, depth charges and torpedoes.

2.1.1.1 Explosives

Explosives are energetic materials, that undergo a strong exothermic chemical reaction when a mechanical, thermal or shock wave stimulus delivers a sufficient amount of activation energy. The following reaction is self-sustaining and releases significant amounts of gases and thermal energy during a very short time, normally in the scale of microseconds. The energy is released as kinetic energy and the gaseous products expand faster than the surrounding air or matter can respond, so that a pressure wave/shock wave spreads out with devastating effects, accompanied by loud noise and light phenomena. For the use of explosives, different performance aspects are of interest, such as the velocity of detonation, the working capacity, the detonation pressure or the heat of explosion.

As regards the chemistry of explosives, their composition is the key to understanding their specific properties. In contrast to combustion where the fuel, for example petrol, can only be burned in the presence of oxygen as oxidizer, explosives contain both an oxidizing group and the fuel in one molecule or within the same compound. For example, oxidizing groups can be $-ONO_2$, $-NO_2$, $-NF_2$, while $-NH_2$, NH or alkyl groups are fuel contributors. These characteristic chemical groups allow the classification of explosives into the following groups:

- Nitrate esters
- Nitroaromatics
- Aliphatic nitro compounds
- Nitramines
- Heterocyclic compounds
- Energetic salts

For handling safety, the materials have to be stable under expected storage and service conditions and in the environments to which they will be exposed. Factors affecting the stability are different environmental conditions such as temperature, pressure and exposure to water. Possible degradation mechanisms can be the chemical decomposition, phase changes or autocatalytic degradation. This can lead to enhanced sensitivity or even spontaneous auto-ignition (Köhler et al. 2008).

Besides stability, the most important issue affecting the handling safety of explosives is their sensitivity to mechanical, thermal and electric stimuli. The measurement methods are described by various guidelines such as the *Recommendations on the Transport of Dangerous Goods: Model Regulations* by the United Nations, which are summarized in Table 1. Here, based on results of standardized test procedures, substances are divided into different hazard groups These procedures are used to obtain the impact (which is measured in newton-metre [Nm]) and friction sensitivity (which is measured in newton [N]), but also the thermal and electrical sensitivity. The same values are also used to categorize high explosives into primary and secondary explosives. Primary explosives are very or extremely sensitive to friction and impact while secondary explosives range from sensitive to insensitive.

Table 1. Classification of explosives sensitivity according to UN recommendations

	Impact sensitivity [Nm]	**Friction sensitivity [N]**
Insensitive	> 40	> 360
Less sensitive	35 - 40	Appx. 360
Sensitive	4 - 35	80 - 360
Very sensitive	< 4	10 - 80
Extremely sensitive		< 10

A general differentiation of energetic materials can be made according to the safety related parameters described above and according to their intended application. The main categories are high explosives, propellants and pyrotechnics. This is shown in

Figure **1** (Zukas and Walters 1998).

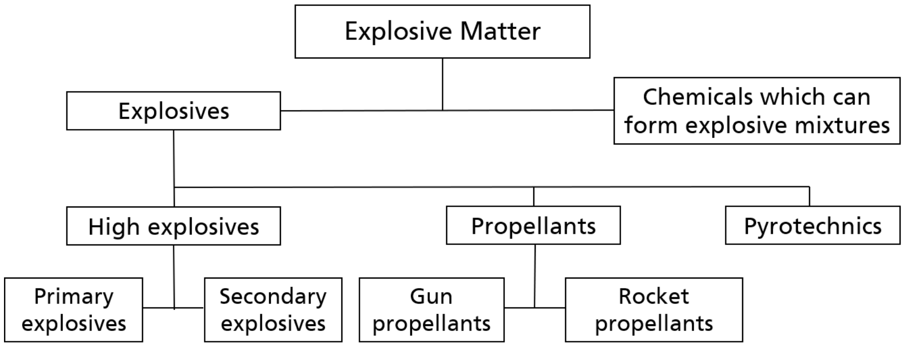


Figure 1. Explosive materials classification

2.1.1.1.1 Primary explosives

Substances belonging to the category of primary explosives are much more sensitive towards heat, impact or friction than secondary explosives and the transition between deflagration and detonation is faster even for very small quantities (Sućeska 1995). They are mostly used as initiating explosives in fuse trains, e.g. in detonators or booster charges (Klapötke 2009). Accordingly, warfare materials in the Baltic Sea will only contain primary explosives if they were fused. That means that the warfare materials were either dumped in a fused state or that it was deployed during combat, mine laying operations or training.

The most common primary explosives and their characteristic values can be seen in Table 2. Usually their performance indicators like detonation velocity and pressure are lower than those of secondary explosives.

Table 2. Common Primary explosives according to (Köhler et al. 2008).

	Impact sensitivity [Nm]	**Friction sensitivity [N]**	**Detonation velocity [m/s]**
Lead azide	2.5 - 4	0.1 - 1	4,630
Lead styphnate	2.5 - 5	< 1	5,200
Mercury fulminate	1 - 2		5,000
Tetrazene	1	8	4,000

2.1.1.1.2 Main charge explosives

Main charge explosives are mixtures of different compounds, some of which are explosive themselves. The mixture of the compounds determines the properties of the resulting explosive. Different mixtures have specific names, e.g. Schießwolle 16, 36, 39 for Germany.

TNT, RDX and HMX represent a major portion of munitions materials present in terrestrial and marine environments (US EPA 2012). The amount of main charge explosivematerial contained in different types of warfare materials varied considerably. While depth charges contain up to 130 kg of explosives, British ground mines contain up to 500 kg and very larges bombs reached up to 4,000 kg. Naval mines, moored mines and ground mines have a weight/charge ratio of 60%. The same is true for unguided rockets. For general purpose air-dropped bombs 50% of the overall weight is explosives. Special constructions, such as armour-piercing bombs, have a total weight that is comparable to other bombs but contain a smaller charge of 10% to 20%. These weight/charge ratios are very similar in the warfare materials across different countries.

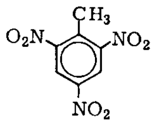
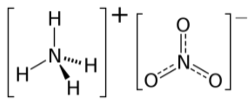
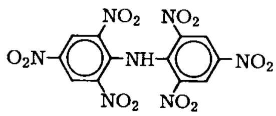
These variations originate from the purpose of the warfare material. Artillery shells are encased with a heavy steel hull that needs to withstand the large compressive force which occurs during the firing of a shell. The shell must only explode when it hits or after it penetrates the target. The destructive force of the shell originates from the combined effects of the kinetic energy and the explosive energy. Hence, a small explosive charge is sufficient. Bombs and mines on the other hand rely heavily on the force of the detonation, resulting in them carrying larger amounts of explosive material.

Main charge explosives, when initiated, are more powerful and thus have a much higher detonation velocity and working capacity than primary explosives. The higher performance is combined with a lower sensitivity. Therefore, they are used as main charges in warfare materials like naval mines, torpedoes or bombs. As a result, every single piece of warfare material that is present in the Baltic Sea can be expected to contain secondary explosives.

In the past, especially during the world wars, one of the most frequently used explosives was TNT. Along with ammonium nitrate (AN), it was the main component in explosive mixtures used in underwater ordnances. AN was often used as a substitute for secondary explosives due to its high availability, low price and detonation behaviour which enables higher bubble energies (Strahle 1988). Depending on the manufacturing country, different formulations for explosive mixtures existed. British naval weapons consisted of Amatol or Minol, while the German mixtures were built up from block fitted Hexanite. An overview of these compositions is shown in the following table.

Aluminium powder was added to formulations to increase the bubble heave energy through reaction with the surrounding water, which resulted in a higher impulse that effected the surroundings (Komissarov 2015). This post-detonation process generally also increases the heat of the explosion and with it the temperature of the reaction products.

Table 3. Explosives and components included in different formulations (Köhler, Meyer, & Homburg 2008).

	Structural formula	Minol	Amatol	Hexanite
2,4,6-Trinitrotoluene		X	X	X
Ammonium nitrate		X	X	X
2,4,6,2',4',6'-Hexanitrodiphenylamine				X
Aluminium powder	Al	X		X

Another military explosive that was widely used is 1,3,5-Trinitro-1,3,5-triazinane, also known as RDX (Royal Demolition Explosive). It is still in use, for example in C-4 in combination with plasticizers. In the table below the most relevant explosives of the past decades are listed along with their date of invention.

2.1.1.2 Propellants

Some warfare materials contain propellants in addition to explosives. Propellants were designed for high-speed combustion and not for detonation. However, they can detonate and can contribute to any explosive event. Accordingly, for warfare materials containing propellants the amount of explosive material in a given object is complemented by an additional 120 g to 6 kg of propellants.

Propellants are designed to provide thrust, either for a missile or for a projectile. They come in two major varieties: rocket and gun. In both cases the performance is produced by the reaction of an oxidant with a fuel. They have similar ingredients, and there are two main classes: double base or composite. For the former, which has broad applicability, the main ingredients are nitrocellulose and nitro-glycerine. For some systems black powder is employed, which is a form of gunpowder based on carbon (charcoal) sulphur and potassium nitrate. Composite propellants are much more common for high performance missile systems. Here the more common oxidant is ammonium perchlorate with a polymer binder, often hydroxy-terminated polybutadiene as the fuel.

The general use of these in systems means that they are likely to be found where munitions were dumped either actively or as a result of military action. The nature of activity in the Baltic means that all types are likely to be found. Both single base and double base (based on nitrocellulose and nitro-glycerine) were common for all participants and early versions of composite propellants were in use during World War II. Germany experimented with liquid propellants in their missile programmes.

2.1.1.3 Chemical Warfare Agents

Up to this date, the sea-dumped chemical weapons in the Baltic Sea had been a topical issue of two HELCOM reports: CHEMU Report (1994) and HELCOM MUNI report (2013). Both documents confirmed that a total of 40,000 tonnes of chemical warfare materials were dumped. The HELCOM MUNI report indicates that these contained 15,000 tonnes of CWAs and their mixtures.

HELCOM MUNI provides an extensive description of Sulfur mustard, Nitrogen mustard, Lewisite, Adamsite, Clark I, Arsine Oil and Clark II, Phosgene, Diphosgene, Tabun, αChloroacetophenone, Hydrogen cyanide and White phosphorus.

The present HELCOM *Submerged Assessment* focuses on presenting significant updates of the state of knowledge regarding both chemical warfare materials and CWAs that are present in the Baltic Sea.

2.1.1.4 Other Materials

In addition to the above, a multitude of other payload materials were used. These include incendiary materials as well as lighting and signalling pyrotechnics.

A special type of payload was the highly flammable material. During World War II, these were used in all fighting areas in the Baltic Sea. Incendiary shells or bombs contain a small explosive charge and a container that was filled with the main incendiary charge. This charge usually was a liquid flammable blend of gasoline, diesel and rubber. To trigger the ignition, white phosphorus, which ignites when reacting with oxygen, was stored in a separate container. At the moment of impact, the explosive charge would burst open both the container with the main incendiary charge and the container with white phosphorus, resulting in the spread of the incendiary material over a large area. Only a few seconds after the release to oxygen, the white phosphorus would ignite independently and the fire would thereupon spread to the flammable liquid. Another class of incendiary munitions was filled with a charge of thermite. Underwater, the hazard of incendiary warfare materials originates from the fuse, which contains explosive material.

Many of the incendiary bombs were constructed with very thin shells. They broke when hitting the water surface and released their payload. However, as the white phosphorous sunk its contact with oxygen in the air was prevented. It was often broken into multiple small pieces. The risks of white phosphorous are described in chapter 3.2.5.

Yet other material is contained in pyrotechnic signal munitions. Different mixtures were used in the past and are still in use today.

2.1.2 Relevant types of warfare materials

Warfare materials fall into two major categories: conventional and chemical. In addition, munitions compounds and agents of both types were either dumped purposely or are separated due to deterioration. Conventional munitions can be further distinguished into explosive and non-explosive, including incendiary munitions. Finally, ship and plane wrecks are located on the Baltic seafloor. The following chapters describe these categories of warfare materials. They are subdivided into the multitude of types and nations who deployed them.

2.1.2.1 Conventional Explosive

2.1.2.1.1 Bombs

Bombs are weapons that are transported by an aircraft, then dropped on a target and finally detonate when they reach this target. In 1849, the first trials with bombs from balloons were started by the Austrian Army. In 1911, an Italian pilot dropped bombs by hand from an aircraft onto the enemy ground structures. Bombs are streamlined metal cylinders that are filled with an explosive charge and an ignition system. Different systems allow for the detonation of the bomb before impact, on impact or after impact. Professional construction and production started during World War I and the development of bombs is still ongoing.

<u>Germany</u>

The entirety of German airdropped bombs comprises of an extraordinary wide range of different types and sizes. The smallest bomb was the SD 0.5 with an explosive charge 0.031 kg. The biggest was the SA 4000 with a charge of 2,700 kg explosive. Most deployed were the 50, 250, 500 and 1,000 kg bombs. The number corresponds to the total weight of the respective bomb, 40% to 50% of which comprises the weight of the charge.

All of these bombs were used in the Gulf of Finland, the coasts of Estonia, Latvia and Lithuania, in Gdansk Bay and in the dumping grounds along the German coastline.

<u>Soviet Union</u>

The development of Russian bombs progressed in similar fashion as in Germany or other nations. The types of bombs are similar in weight of up to 5,000 kg. However, most produced was the 100 kg class. The form of the casing displays some minor differences to the constructions of other nations during wartime, but the effectiveness was nearly the same.

In addition to Soviet developments, the Allies supported the Soviet Union with warfare materials, including aircrafts, mines and other weapons. Accordingly, Soviet replications of this material can be found in the marine environment as well.

All kinds of the Russian bombs were deployed throughout the majority of the Baltic Sea from the Gulf of Finland all the way along the coastline to Świnoujście and Bornholm.

<u>UK and USA</u>

Bombs from the UK and USA are comparable to German or Russian types in terms of construction and firing systems. Weights were given in pound (lbs.) and not in kilogram (1 lbs. ≈

0.454 kg). Standard sizes were produced in the range from 8 lbs. to 12,000 lbs., but the majority of deployed bombs weigh 100 lbs. to 1,000 lbs.

The distribution area of UK or USA bombs is the western Baltic Sea area, the southern coastline of the central Baltic Sea and the Gdansk Bay. Allied bombers approached Germany via the border to Denmark and then setting course towards Kiel, Rostock, Stettin or other targets. The air defence attacked the bombers with artillery or fighter planes and in case of emergency bombers dropped the explosive cargo into the sea. The areas off the coast from Kiel, Lübeck, Rostock, Sassnitz, Usedom, Świnoujście, Gdańsk and Kaliningrad are affected by a high density of submerged bombs.

2.1.2.1.2 Naval mines

The first trials with naval mines go back to the 18th century. Serious development started later and the first ever minefields were laid by Russian units in the approach to Port Arthur (now Lüshun) in the Russo-Japanese War (1904-1905). From the beginning of World War I, naval mines were essential weapons in naval warfare. Mines were laid out both as offensive minefields to stop the merchant and military ships of the enemy and as defensive minefields to secure the own coastlines, harbours and sea-traffic lanes. The most common mines deployed were contact mines.

The number of mines laid during both World Wars in the Baltic Sea and approaches (including Kattegat) is 160,000. Extensive military mine clearance during the years 1996-2022 show that about 25% of the contact mines remain sunken in the area they were laid and approximately 75% of the ground mines remain in the positions they were laid.

Moored mines were invented prior to ground mines. Their case has a spherical shape, some with an additional belt connecting two hemispheres. Inside the mine casing the charge is stored in a separate container. The explosive charge in a moored mine weighs between 20 kg and 350 kg. This type of naval mines contains ignition systems that are based on different modes of contact ignition: Chemical Horns and switch-horns protruding out of the sphere give moored mines their characteristic look. Chemical horns contain a small glass phial with an electrolyte liquid. Contact of a vessel's hull with the horn breaks the glass and releases the contained electrolyte, resulting in the ignition of the mine. Switch horn systems contain a fully loaded battery in the mine case. As a consequence of direct physical contact with the horn the switch is activated, closing an electrical circuit what initiates the detonation. A contemporary challenge with historical mines is the uncertainty regarding their ignition systems. Intact mines might still have functioning fuses, despite the aging.

By design, the moored mine case is partly filled with air, thereby acting as a floating body and providing buoyancy for the mine. It is moored to the sea floor with the mine chair by wire or chain that maintains the mine's position. A properly deployed mine case floats at a water depth between one and five metres when targeting surface vessels and 100 m when targeting submarines. If mooring gets damaged by natural processes or cut by minesweeping gear, a moored mine will resurface posing a high risk to seafarers. Very often floating moored mines were mistaken as "drifting mines". Minesweepers often used bullets to sink moored mines by breaking the integrity of mine case.

Ground mines were firstly developed at the end of World War I, so only a small number of ground mines could be deployed during that conflict. However, during World War II this new type of naval mine was fully operational.

The explosive charge of ground mines varies between 45 kg and 880 kg. The ignition systems are magnetic, acoustic or pressure influenced. Combinations of two or all three sensors were also developed. The magnetic field of a steel vessel, the noise emanated by the engine and the marine propeller or the pressure change resulting from the displacement of water activate the battery supplied electrical ignition system. However, in order to function, the ground mine requires a sufficiently charged battery. It is possible that some batteries for ground mines still show a small voltage, but the last intended function of a ground mine from World War II was dated to 1972.

Minesweeping against ground mines is intricate, as minesweeping systems need to be able to simulate the magnetic or acoustic fields of a real ship. The pressure displacement cannot be simulated by minesweeping systems.

<u>Germany</u>

The first functioning moored mine from Germany was produced in 1877. With an explosive charge of 40 kg and a simple contact-detonator, the mine served as a defensive mine to defend coastal waters. Later, in 1914, Germany deployed new, improved moored mines with chemical horns, a well-functioning depth setting system and charges of up to 220 kg. An additional development were UC mines, moored mines laid by submarines with a charge of 200 kg explosives. All mines were contact mines and the majority used chemical horns to trigger the ignition system. Between the wars, further efforts towards the development of moored mines were made. The resulting EMC or EMF mines contained explosive charges of 300/350 kg while influence distance firing systems were added to the contact systems.

The development of ground mines started in the 1920's. The development followed two paths: ground mines laid by surface ships or submarines and ground mines laid by aircraft. The LM (Luftmine) an BM (Bombenmine) are typical examples for air-deployed mines and both could also function as a bomb. The explosive charge weighed between 290 kg and 720 kg. Ground mines laid by surface ships and submarines worked solely as mines and contain explosive charges of up to 880 kg.

<u>Russia and Soviet Union</u>

The development of mines by tsarist Russia and later by the Soviet Union was more advanced than in other countries. Part of the mines have similar characteristics as mines used elsewhere, specifically the spherical cases and chemical horns. The mine-anchor has a greater weight, therefore providing better stabilisation on the sea floor. The Russian Navy also developed contact mines without chemical horns. The bottle with the electrolyte liquid was located inside the mine casing and a mechanical gear fixed a hammer. After physical contact by a vessel, the mine case tilted, and the hammer broke the bottle while electrolyte activated the detonation. This pendulum system was installed in a limited numbers of mines in both wars.

The development of ground mines proceeded in similar fashion to that in Germany. Ground mines from the UK were provided to the Soviet Union after it entered the war, resulting in a mix of Russian and UK mines located in the Gulf of Finland.

Finland

Finland produced naval mines during World War II for the Merivoimat (i.e. the Finnish Navy). Most of them were replicas of German, Russian and Swedish mines and own development efforts were very low.

Netherlands and France

After the war against France, the German army and navy captured around 100 mines from both navies. The fully functioning mines were incorporated by the German Navy and deployed in the Nashorn minefield, located between Helsinki and Tallinn, between 1942 and 1944.

Sweden

The Kingdom of Sweden was a neutral state during World War I and World War II. Sweden developed and deployed different types of mines with the purpose of defending and securing Swedish harbours and national waters. The construction principle was the same as that of other countries.

UK

UK mines were used in the Baltic Sea during World War II. In April 1940, the Royal Air Force started with so-called “gardenings” using ground mines of the types MK I-IV, MK V, and MK VI-IX. Areas of first targets were the approaches to the Kiel Canal and the Bay of Kiel. Next where the entrances to the harbours with dockyards and the exercise areas for submarines. In total 13,543 mines were deployed to the Baltic Sea and the Kattegat.

A special variant were “lent and leasing” ground mines from 1941. The UK sent hundreds of mines to the Soviet Union. The Soviet Navy in the Eastern Baltic directly used some, but they also copied the British ground mines and introduced the replicas.

2.1.2.1.3 Rockets

Germany

After World War I, Germany was not permitted to own airplanes, submarines and other highly developed warfare material. Civil research and development of rockets was a small, but effective branch. Werner von Braun drove the civil research, contacted with the research division of the German army and was eventually employed by it. The testing ground was established in Peenemünde/Usedom, which was initially out of reach of allied aircraft. It was this test site where the Luftwaffe developed and tested their rocket systems.

The Fieseler Fi 103 (“Vergeltungswaffe 1” or V1) was developed by the German air force and built by Fieseler Werke, an aircraft construction company. The V1 was the first cruise missile, shaped similarly to a small aircraft, with a special jet propulsion and containing a 700 kg explosive charge. The V1 was in service by the Luftwaffe and used in World War II beginning in June 1944 against Great Britain. In March 1945, production was halted and the V1 that were ready for combat were stocked in Schleswig Holstein. The last 200 V1 were dumped in the outer part of Flensburg Fjord on 3 May 1945 by German forces. Parts of them and nearly complete V1 were found near the dumping ground.

The “Aggregat 4” (A4 or Vergeltungswaffe 2 or V2) was a rocket that was produced and built after a long time of development. With a firing range of around 330 km, the V2 was the first ballistic missile. It contained an explosive charge of 738 kg amatol. Germany launched nearly 3,200 A4-missiles during World War II.

Some additional types of rockets were produced and tested in smaller numbers. The types Taifun, Wasserfall and Rheintochter were antiaircraft missiles, Rheinbote was developed for surface-to-surface application.

Several rockets were developed for the Wehrmacht unit Nebelwerfertruppe and put in service. The rockets were unguided and contained a large explosive charge. They were utilized to support the firepower of artillery. After the war, rockets were dumped in the known dumping grounds.

The Luftwaffe used some unguided rockets for air-to-surface attacks, as anti-tank weapons and in air-to-air combat. The diameter of these rockets was 5.5 cm to 21.0 cm and they were in service until 1944. The smaller units from the German Navy used a similar anti-aircraft rocket with the diameter of 8.6 cm.

Allied forces

Similar to the German forces, the allies used rockets in wartime. The unguided Russian missile Katyuscha is a well-known example. The coastline area all the way from Mecklenburg-Western Pommerania to Estonia it is highly probable to encounter rockets that were misfired in wartime or dumped afterwards.

2.1.2.1.4 Torpedoes

The torpedo is a self-propelled weapon, consisting of an explosive charge, a control system, a power source for the engine and a drive unit.

Germany

Already during World War I German torpedoes in different sizes existed. Their diameter ranged from 45 cm to 53.3 cm and in rare cases up to 60 cm on few battleships. The explosive charge had a weight of up to 300 kg and the installed ignition system was initiated by a contact fuse. The propulsion was achieved by releasing pressurized air resulting in the typical bubble trail that can be observed at the rear of a propelled torpedo. The firing range for these World War I torpedoes reached from 600 m to a few kilometres.

In World War II, two standard torpedoes were used by the navy. The torpedo G7a, that was again propelled by pressurized air, contained a charge of 280 kg to 300 kg. Its firing range reached from 6 km at a speed of 44 kn all the way up to 12 km at a speed of 30 kn. The other type was the G7e propelled by an electric engine and batteries. The torpedo contained the same charge as the G7a, but the G7e reached a firing range of 5 km to 7.5 km at a speed of 30 kn.

The Luftwaffe used a large number of airdropped torpedoes. The F5b torpedo had a diameter of 45 cm, propulsion by pressurized air and contained a torpedo head with a 200 kg charge. In the Baltic Sea, two areas are affected by concentrations of F5b torpedoes. One is located close to Gdynia; at former testing site “Hexengrund” many F5b failed and sank. The second area is located in the Gulf of Riga where the Luftwaffe operated a training centre in 1944 and numerous torpedoes were lost as well.

<u>Russia and Soviet Union</u>

The Russian torpedo development started with three torpedo calibres: 37.5 cm, 45 cm and 53.3 cm. All torpedoes were wet-heaters, meaning that they were propelled by injecting a liquid fuel into the pressure air chamber, further supported by the steam resulting from cooling the combustion chamber. They contained main charges ranging from 200 kg to 300 kg. In World War II the 45 cm version and a series of 53.3 cm torpedoes was used by the Soviet Union. By then, the torpedo head could carry an explosive charge of up to 400 kg.

2.1.2.1.5 Depth Charges

The depth charge is a weapon developed for combat against submarines. After the beginning of the submarine war in World War I, escort units required an antisubmarine weapon. The depth charge was the solution. Explosives were filled in a metal container. A clockwork or a pressure sensor (i.e. membrane switch) initiated the detonation after a certain amount of time passed or the device reached the desired depth. The underwater detonation results in damage to or destruction of submarines' outer layers.

<u>Germany</u>

The German depth charge carried an explosive charge between 60 kg and 130 kg. A special type was the depth charge with floating aid. The explosive charge weighed 60 kg and the floating aid reduced the speed of sinking.

<u>Russia and Soviet Union</u>

The Russian and Soviet depth charges are similar to the German ones in terms of explosives utilized, shape and firing system installed.

2.1.2.1.6 Artillery Shells

The history of artillery shells goes back to the Middle Ages. Originating from a hollow sphere filled with black powder and using a burning fuse, development over the centuries has resulted in the development of a high-technology warfare material.

Armed forces used many kinds of artillery shells. The small calibres of 2 cm to 5.7 cm serve two purposes. The main purpose is defence against aircraft attacks from low and medium altitude. The second application is combat against surface targets over short and medium distances. These calibres were mostly deployed as main weapons of small vessels.

The calibres from 7.5 cm to 15 cm were installed as the main gun of vessels for use against surface targets. Antiaircraft artillery with calibres from 7.5 cm to 12.8 cm could work in a double role of antiaircraft and artillery firing support against surface targets. The larger calibres from 15 cm up to 40.5 cm were used in regular sea-sea and sea-land artillery roles.

Up to a calibre of 12.7 cm naval and antiaircraft artillery munitions consisted of two main components: the artillery shell or grenade, containing payload and fuse, and a cartridge with propellant and primer/ignition device, that remained at the launcher position. For bigger calibres shell and propellant charge were separate components provided independently from each other to howitzer barrel and lock.

Some artillery shells had specific effects. The variety encompasses exploding, hollowed, antitank, illumination, smoke and CWA grenades. In terms of the amount of main charge and booster charge explosives, artillery shells are quite specific. For example, the charge of an anti-tank grenade is about 30% of the explosive mass of a regular high explosive (HE) artillery shell.

2.1.2.2 Conventional Incendiary

Incendiary munitions like shells or bombs are used to inflict damage by starting fires in targeted areas. The payload is an incendiary mixture, e.g. thermite, and sometimes a small charge is included to open the case and scatter the incendiary mix. The mixture starts to burn after the ignitor, often white phosphorus, gets in contact with air. The fillings include thermite and burning fluids.

Germany

Two types of incendiary bombs were employed by the Luftwaffe. The smaller type, called Elektron-Brandbombe, weighed 1 kg to 2.2 kg and contained a small explosive charge of 0.008 kg to 0.015 kg and a thermite charge. The other type was filled with a mixture of oil and fuel and the ignitor was white phosphorus. The biggest of this type was the C 500 bomb containing a mixed liquid charge of 157 kg.

Bombs similar to incendiary bombs were used to release smoke for the purposes of camouflaging or target marking.

UK and USA

Incendiary bombs were of high priority both tactically and strategically. Similar to Germany, the Allies utilized small bombs containing thermite charges and bigger ones containing both a combustible liquid and a phosphorus charge. Up to 30% of 30 lbs incendiary MK III bombs with 1 lbs white phosphorus failed to detonate or ignite.

2.1.2.3 Chemical

While conventional munitions contain explosives or incendiary agents and their effect is characterized accordingly by detonation or burning, chemical munitions are distinguished by a payload of CWAs. Their purpose is not the physical destruction of infrastructure, but rather directly or indirectly, a temporary or permanent incapacitation of humans due to the respective toxic effects of the compounds used. In addition, a strong psychological component exists, that is associated with the type of external injuries and the delay before their appearance (e.g. blisters on the skin). In contrast to the substances contained in conventional munitions, the hazards posed by CWAs for people and the environment appear obvious. Hence, researching this kind of munitions has received special attention in the past.

An extensive description of CWAs and the corresponding warfare materials types is already listed in the HELCOM MUNI report (2013).

The majority of chemical warfare munitions dumped are aircraft bombs. More than half of the chemical munitions dumped (in tonnes) were aircraft bombs containing Sulfur mustard. However, not all CWAs were dumped as payload of munitions. A considerable amount was dumped in encasements and containers.

2.1.2.4 Other warfare material

Many, if not all types of munitions are available as live and as practice munitions. Practice munitions are of the same size and weight as live munitions. Currently, practice munitions of NATO forces always appear in light blue colour.

Each year practice munitions encountered in the Baltic Sea region cause an alarm for responders of explosive ordnance disposal units (EOD). These objects might have lost any indications of their initial purpose, so they are initially treated as live munitions, with all recommended precautionary measures, until they are concluded to be practice munitions.

The payload of practice munitions is usually filled with environmentally harmless mineral materials (concrete, dry clay) and the fuse is a dummy.

2.2 Historic Overview

The Baltic Sea is an inland sea with a long coastline proportionally to its area. Due to this fact the Baltic Sea was and still is of strategic importance to its neighbouring countries. Numerous wars have been fought over territories adjacent to the Baltic Sea. Those conflicts often had a naval warfare component. Because of the rare use of gunpowder-based ordnance, the wars of medieval and early modern history are of no interest to the scope of this report. Since the vast majority of warfare materials were entered during and in the aftermath of World Wars I and II this report focuses on warfare materials from that era.

In the 19th century, weapons, warfare materials and equipment for army and navy advanced significantly. Guns for army and navy increasingly used grenades instead of cannon balls. In 1848, the introduction of mines in the Baltic Sea took place. A minefield was placed in the Bay of Kiel to prevent the entering of Danish warships. Werner von Siemens had constructed a waterproofed container that was filled with gunpowder and a simple firing system, which was activated by two land-based controllers. The knowledge about the minefield discouraged the Danish ships from entering the bay. Later, during the Crimean War (1853-1856), Russia laid mines in the Black Sea but also in the Baltic Sea off the coast of Kronstadt and St. Petersburg. In 1864, during the Second Schleswig War between Germany and Denmark, the first modern naval gunfire exchange was reported.

The first war in the Baltic Sea utilizing modern explosives (TNT) was World War I (1914 – 1918). At the dawn of this war four countries were adjacent to the Baltic Sea, namely Denmark, Germany, Russia and Sweden. Of those Denmark and Sweden remained neutral during the conflict. Even though Germany and Russia were at war, the active warfare was limited to smaller scale operations without the commitment of the main battle fleets. Because of its shallow bathymetry the Baltic Sea was an ideal area for military operations using light vessels, submarines and minefields. Both opponents laid numerous minefields in order to close certain sea areas, sea lanes or ports to their adversary or to defend their own ports. However, the use of naval mines was not limited to the parties at war. Neutral Denmark laid extensive minefields in the Belts and the Sound in order to deny their use to all warring parties. (Jentzsch 2018)

Following the rise of the Nazi Party in Germany in 1933, World War II began with the German invasion of Poland on 1 September 1939. The southern exits of the Great Belt and the Sound had been mined by Germany in early September 1939. On 30 November 1939 the Soviet invasion of Finland marked the start of the Finnish Winter War which lasted about three and a half months and comprised almost no naval warfare. In 1940 Germany invaded neutral Denmark and Norway during Operation Weserübung. With Denmark and Norway occupied, all maritime approaches to the Baltic Sea were controlled by Germany. The same year brought the annexation of the Baltic states Estonia, Latvia and Lithuania by the Soviet Union, thus increasing the strategic flexibility of the Soviet Baltic Fleet. With Operation Barbarossa Germany invaded the Soviet Union, beginning on 22 June 1941. After the quick fall of the Baltic states and extensive mine laying operations by the German Navy in the Gulf of Finland, the Soviet Baltic Fleet was trapped in Leningrad until summer 1944. For the time between summer 1941 and 1944 Allied warfare in the Baltic Sea was mostly limited to aerial operations, such as air-deployed mine laying which was conducted by the RAF starting May 1940. The German Navy used the Baltic Sea primarily as a training area. When the German Army was pushed back from the eastern occupied territories by the Red Army in the summer of 1944, Soviet naval and aerial activity in the Baltic Sea increased.

Losing the war on all fronts Germany capitulated on 8 May 1945. The military occupation and reconstruction of Germany after World War II were negotiated in Potsdam in 1945 by Joseph Stalin, Premier of the Soviet Union, Harry S. Truman, President of the United States of America, and two Prime Ministers of the United Kingdom, Sir Winston Churchill and Clement Attlee. Even though there were numerous disagreements, the three leaders agreed on the disarmament and demilitarisation of Germany. In the resulting Potsdam agreement, the parties made terms that "The complete disarmament and demilitarization of Germany and the elimination or control of all German industry that could be used for military production" should be achieved and that "All arms, ammunition and implements of war and all specialized facilities for their production shall be held at the disposal of the Allies or destroyed. The maintenance and production of all aircraft and all arms, ammunition and implements of war shall be prevented."

With Germany divided into four zones (American, British, French and Soviet), the parties were individually responsible for tending to existing warfare materials within their respective area of oversight, either by adding them to their own arsenals or by destroying them by any means they found to be suitable. This was primarily done by submerging them in oceans and seas.

2.3 Modes of Entry into the Marine Environment

The modes of entry of warfare materials into the Baltic Sea can be roughly categorized into three categories: warfare, military practice (including various test sites) and dumping.

Warfare

During both world wars, the Baltic Sea was an area of conflict. Due to the strategic importance of the Baltic Sea, innumerable combat actions of great variety took place, all of them causing the entry of warfare materials into the marine environment. The following list provides an overview of these actions, all of which (with the exception of the final point) were geographically widely spread:

- Naval battles between surface warships using artillery and torpedoes.
- Submarine torpedo attacks against military and civilian vessels using torpedoes and sometimes light artillery.
- Anti-submarine warfare using depth charges deployed by naval vessels or aircraft, as well as artillery and bombs in a lesser degree.
- Air raids against military and civilian vessels as well as coastal installations using cannon armament, bombs, air-to-surface missiles and torpedoes.
- Mine laying operations usually deploying moored and ground mines by surface vessel, submarine or aircraft.
- Military aircraft conducting emergency dumps of their loads or being shot down with their loads still on board as a result of aerial combat action or anti-aircraft fire.
- A rare type of naval engagement in the Baltic Sea was coastal bombardment by surface warships using artillery (including counter fire from coastal artillery batteries).

Military Practice

In peacetime military live-fire training was and is conducted in dedicated training areas. Those training areas are bound to contain warfare materials. Training with non-explosive training ordnance can lead to misidentification in geophysical surveys. Training ordnance may have been non-explosive, but it may also contain propellant or residues thereof.

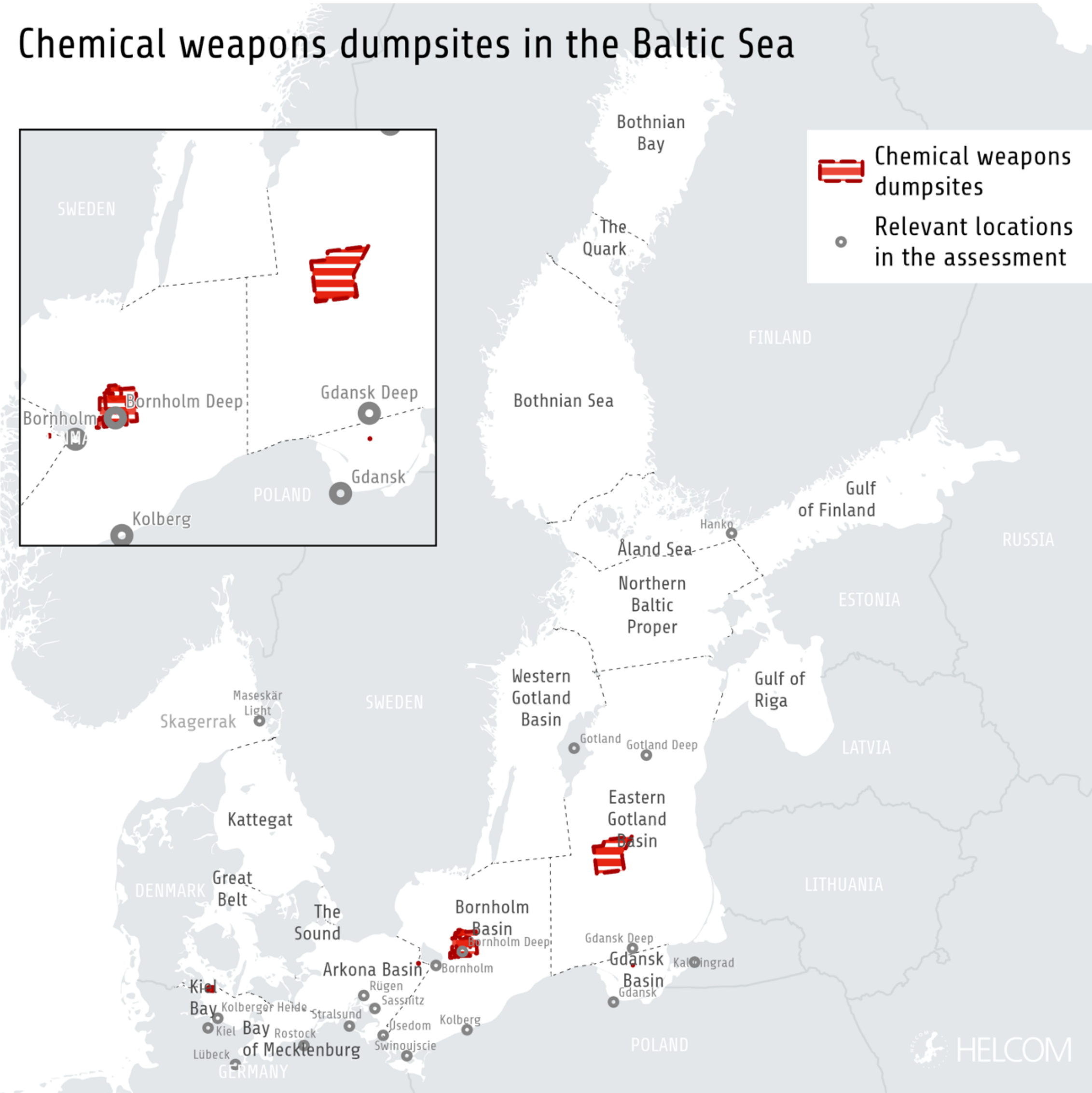
The training areas used today are bound to their geographical borders to ensure the safety of civilian shipping. During wartime, however, military practice was usually not restricted to dedicated training areas. It was instead conducted wherever possible, with the exception of the warring parties' civilian shipping lanes. During World War II the German Navy used large areas in the Baltic Sea for military practice, as it was relatively secure from allied attacks for the majority of the time. In principle all of the modes of entry mentioned in the previous section on naval warfare apply to military practice.

In addition, test sites and firing ranges for weapon prototypes were established, e.g. in Peenemünde and along the Baltic Sea coast of Mecklenburg-Western Pomerania. Tests included air-dropped weapons, which means that the entry was not limited to coastal waters. Weapon prototypes in later stages of development often contained an explosive charge. Rocket type prototypes may contain propellants or their residues.

Dumping

Immediately before and after the armistice of World War II in the European theatre (May 1945), the dumping of warfare materials constituted an additional mode of entry into the Baltic. Dumping of warfare materials was carried out for a multitude of reasons. With the end of the war drawing closer, they were dumped by the German Armed Forces to remove them from areas subjected to imminent occupation by the Allies. The aim was to prevent warfare materials from being seized by the advancing Allied troops and to demilitarize before the impending surrender. In the immediate post-war period, the Allies chose dumping at sea as modus operandi to conduct swift demilitarization and removal of warfare materials. Sea-dumping was considered to be an inexpensive and safe alternative to land-based disassembly and a responsible disposal procedure.

Both conventional and chemical warfare materials were dumped at sea. While conventional munitions may have entered the sea as a direct result of military actions, the chemical warfare materials in the Baltic Sea originate exclusively from intentional dumping. At that time, it was believed that the vast amounts of water would neutralize the CWA. During dumping operations in Skagerrak (NOR), off Måseskär (SWE) and southern Little Belt (DNK), complete ships and semi-finished hulls were filled with munitions objects and scuttled. On the other hand, dumping grounds in German waters contain individual warfare materials and crates filled with smaller calibre objects. The vast majority of chemical warfare materials was dumped piece by piece into the central Baltic Sea.



2.4 Geographic Distribution

Disclaimer: The following sections were generated by performing an interview with Mr. Uwe Wichert, who has been doing archival work on the matter of warfare materials in the Baltic Sea for over ten years.

Mine Laying Operations

Mine laying operations were conducted both during WWI and WWII. Some of the mines that were laid in 1914 (BArch-MA RM 60 II/v 39) may still be present in the Baltic Sea today. In the areas of all mine barriers and gardening described in the following subsections, mines in different conditions must be expected. During WWII English mine laying operations in the Baltic Sea was performed all the way to Kaliningrad. It is well-documented and information down to each individual mine can be retrieved from the archives.

2.4.1 Denmark

Dumping

Numerous dumpsites that were established post-WWII are present in Danish waters. These were briefly addressed in the HELCOM MUNI report (2013). The primary dumpsite is located in the Bornholm deep.

About 32,000 tonnes of chemical munitions (HELCOM MUNI 2013) found in German depots in the Soviet occupation zone were dumped, containing approximately 11,000 tonnes of active CWAs (Sanderson et al. 2010). Vessels departed from Wolgast (BArch-MA BM 1/2392; BArch-MA BM 1/8922) where only CWAs were loaded. In the dumpsite, S-Lost, N-Lost, Winter-Lost, Adamsite and Clark I & II were dumped. It is likely that the Soviet Union also dumped part of its own CWAs in the same area. Furthermore, reports indicate that additional material was dumped on the initiative of the UK and US administrations, but this has not been confirmed so far.

Dumping of Tabun and Phosgene was executed by the German navy in the Little Belt (BArch-MA BW 1/25453). Ships were loaded in Flensburg and eyewitnesses reported that en-route dumping started on the level of Okseøerne, which could mean that this material is now located in German waters or in Danish waters. The speed at which vessels steamed and the amount of time it took them for one trip suggests that en-route dumping is likely to have taken place. However, so far no warfare materials that would originate from these en-route dumping activities was found. In the early 1970s a clearance campaign in the Little Belt dumpsite proper was executed. Grenades that were cleared still contained amounts of Tabun.

Anti-aircraft and Artillery Batteries

During WWII, anti-aircraft batteries were stationed on Bornholm.

Bombing Hotspots

Denmark was not heavily bombed during either of the world wars. However, due to the flight trajectory of British and American bombers during WWII, some emergency-jettisoned bombs must be expected in Danish waters.

Mine Laying Operations

During WWI, Denmark laid 215 mines in their own waters for defensive purposes.

German mine fields are well-documented for WWII. Records specify the exact number of mines laid and cleared in the Great Belt and South of the Sound (BArch-MA RM 7/1952).

2.4.2 Germany

Dumping

In the German Baltic Sea, there are six dumpsites that were established after the end of WWII: Kolberger Heide at the entrance of Kiel Bay, Pelzerhaken and Haffkrug in Lübeck Bay, Flensburg Triangle, Schönhagener Grund and suspected area Adlergrund. Dumping was terminated in 1949 (TNA ADM 228-24).

Reportedly at least 35,000 tonnes of warfare materials were dumped in the Kolberger Heide area. Most of the dumped material is of German origin but some of it originated from the UK. In the years from 1949/50 to 1953, an estimated 5,000 tonnes were salvaged by the company Porr leaving around 30,000 tonnes in the area. It is known that explosive material is lying openly on the seabed. This may be partially due to the ongoing corrosion of the materials housings (see 3.1.2). However, it is also possible that explosive material was dumped loosely without any containment. In the post-war years, steel was a rare commodity and thus it is possible that explosive material was removed from its casings before dumping it. For such cases it is impossible to determine which type of warfare materials the explosives belonged to originally.

Further eastward, at Strande Bay, loose explosive material was found as well. Occurrences of loose explosives continue along the coastline all the way to Eckernförde, albeit to a lesser degree. Until around 1965 2-3 tonnes explosive material was cleared at Strande Bay on a weekly basis. Warfare materials dumped here may originate from nearby research facilities and was not shipped to official dumpsites.

In the Lübeck Bay area two individual dumpsites were used. Initially, the Pelzerhaken site was intended to be the only site in Lubeck Bay with Haffkrug being added later. It is possible that further dumping at the Pelzerhaken site was at one point considered too hazardous, with 50,000 tonnes of warfare materials dumped. An additional 15,000 tonnes were brought into the Haffkrug area, leading to a total of 65,000 tonnes in Lubeck Bay. These numbers were provided during “Sicherheitskonferenzen” (i.e. security conferences) (LASH Abt 617 188) of the State of Schleswig-Holstein in the years 1957 to 1960. It should be noted that multibeam echosounder investigations at both sites do not support the presence of such an amount of warfare materials, hinting towards a significant amount of buried material. In addition, a mount of furnace slag was dumped in the area as well, making it impossible to investigate what is underneath. It is also known that en-route dumping occurred, leading to a situation in which a significant amount of warfare materials was dumped under way and is thus not located in the dedicated dumpsites. Dumped materials include both munitions from existing German depots located in the British occupation zone as well as from the UK stockpile. Dumping was terminated in 1949 with 700 tonnes of British 20 mmm and 30 mm shells. Much of the material in the area is packaged in crates and boxes. It is unclear whether these boxes contain the types of munitions they were originally designed for. Crates for artillery munitions, tank munition, hand grenades 15 cm rockets, grenade thrower 28 and 32 cm (both conventional and incendiary) and V1 warheads were found. According to historic documents smoke munitions were loaded aboard a vessel in Schlutup to be dumped in the area. However, the vessel returned to shore without completing its mission since the British authorities decided not to dump this type of ordnance.

Another dumpsite is located east of the town of Falshöft. This area was labelled as Flensburg Triangle by the British authorities. It was originally intended to dump all munitions aboard all vessels located in Schlei Fjord, in Flensburg Fjord and in Gelting Bay at the end of WW II in this area. It is not clear whether this actually happened. According to figures from the "Sicherheitskonferenz" in 1960 (LASH Abt 617 188), 120 tonnes were dumped. If the original plan was executed, around 1,400 tonnes of materials would have been present on vessels located on the river Schlei, if they were fully equipped. Assuming, they only had 30% of warfare materials on stock would still lead to 420 tonnes originating from the Schlei vessels alone. Munitions and torpedoes from Flensburg Fjord, Gelting Bay and from army and air force troops concentrated in the area between river Schlei and Flensburg Fjord would need to be added to this figure. Regarding the Falshöft area it should also be noted that according to witness accounts an estimated 80 tonnes (seven overloaded railway waggons) of leaking chemical warfare materials were loaded on two barges in September/October 1945. It is unclear whether these 80 tonnes of chemical warfare materials were dumped in the Falshöft site or in the Little Belt area (see HELCOM MUNI 2013).

Further south lies the area of of Schönhagener Grund, otherwise known as Kabbeln Triangle. Here, 4,000 tonnes of grenades, bombs, torpedoes, depth charges and Hedgehog anti-submarine projectors were dumped.

One witness reported that warfare materials (including CWAs) were dumped in the Adlergrund area to the north-east of the island of Rügen in the years from 1945 to 1962. Vessels reportedly steamed from Wolgast. Cases of munitions that may contain CWAs appear to confirm this claim. In addition, reports of en-route dumping exist. Furthermore, it is possible that the former GDR scuttled boats in the Adlergrund area. Of five mine clearance boats that were available to the Kasernierte Volkspolizei (the predecessor to the GDR armed forces), at least one was scuttled with up to 100 tonnes of – potentially chemical – warfare material. It is also possible that the boat was scuttled at the Bornholm dumpsite. So far, none of the boats were detected in either of the areas.

<u>Research Facilities</u>

In areas of former military research facilities an increased presence of warfare materials must be expected due to experiments with weapons systems and explosives, as well as due to them constituting a prioritized target for bombing and post-war destruction.

During WWII, a torpedo testing facility was operated in Eckernförde. After the war, it was detonated using explosives of the allied forces. Leftover explosives that were not use may have been dumped directly into the sea. The towns of Strande and Schilksee stored warfare materials from a torpedo research facility and a marine artillery arsenal. In Dänisch Nienhagen there was a physical testing centre for explosives, rockets as well as torpedo propellants and potential CWAs.

Another torpedo research facility – in this case operated by the German air force – existed in Travemünde near Lübeck. It is thus possible that both practice and live torpedoes are present in in the surroundings of Lübeck Bay.

In Lubmin guided bombs type Fritz X and Hentschel HS 293 were developed. All pilots who used this type of bomb needed to successfully conduct seven training bombings, potentially some with live munition. Accordingly, bombs must be expected in the area around Lubmin.

Finally, the testing facility for V1, V2 and other types of rockets (mainly anti-aircraft) on the island of Usedom is worth mentioning.

<u>Anti-aircraft and Artillery Batteries</u>

Anti-aircraft batteries were present thoughout Northern Germany. The impact areas for munitions that missed their target or did not detonate are thus spread along the German coast and overlap with other hotspot areas, such as the dumpsites. Army, navy and air force all operated anti-aircraft batteries with ranges of up to 17 km. Munitions of all sizes from 2 cm to 12.7 cm must be expected in the impact areas. Fail rates at the beginning of WW II amounted to 2% to 3% of the fired grenades. In 1944 and 1945, figures of 5% and 10% respectively appear more realistic. Accordingly, a great amount of undetonated anti-aircraft grenades is present in German waters (BArch-MA RM 45 I/189).

Training Facilities

The German navy operated a training facility in the Adlergrund area north of Kap Arkona on the island of Rügen. The same area would later become a dumpsite. However, until 1944, it was used for target practice, water bomb deployment and submarine hunting, also including the use of live munitions. Furthermore, guns were adjusted and tested for maximum range. The area has been searched by mine clearance units several times, but it is unclear how much warfare materials remains.

Another training hotspot was the area north of the Darß, which was used by the German air force and navy. Different types of bombs must be expected in the region.

In addition, an exercise area was established in the area of Schönhagener. After the war, this area changed into the dumpsite Schönhagener Grund.

Bombing Hotspots

Bombing hotspots along the German Baltic Sea coast include Kiel, Stralsund and Sassnitz. Kiel alone was subjected to over 90 bombing raids. Roughly 2,000 bombs are still expected to be present in Kiel both at land and at sea. Due to it being particularly well-defended by anti-aircraft batteries, Kiel could only be raided by a large number of planes simultaneously, leading to particularly devastating attacks.

Another hotspot was Peenemünde on the island of Rügen. It was heavily bombed due to the V1 and V2 testing on the island. Bombing by the British air force started in the night of 17-18 August 1943, with 596 bombers dropping nearly 1,800 tonnes of bombs. The third wave of the attack was intercepted by the German air force which lead the British to drop around 50% of their bombs into the sea. The fourth wave was intercepted as well, leading to the jettisoning of most of their bombs to the east of the island. About 80% of used incendiary bombs each contained 450 g of white phosphorus as incendiary material. With an expected failure rate of 30%, a significant amount of white phosphorous (and other incendiary and explosive material) was introduced into the area. Subsequently, another five raids by the US air force targeted the island.

In the vicinity of all bombing hotspots a strong presence of anti-aircraft munitions must be expected as well.

Mine Laying Operations

Starting in April 1940, the entire German Baltic Sea coast was mined with so called gardens by the British air force. In addition, German forces performed mine laying operations as a defensive measure, e.g. with a mine field between Falster (Denmark) and Darß. The area around Rügen was even mined by a Soviet submarine, which may have placed between 20 and 40 mines (BArch-MA RM 7/1486).

2.4.3 Poland

Dumping

It is expected that the Soviet Union dumped at least part of the munitions it captured from the withdrawing German forces after WWII. The Soviet Red Army had no use for the captured

German army munitions due to differences in calibre. Since the Soviet Union also delivered its weapons systems to the states of the Warsaw Pact, there was no possibility to use the captured munitions there. All this makes dumping activities in Polish waters probable, but it remains unclear what happened to the captured ordnance in detail.

It is furthermore likely that warfare materials were dumped during the 1992 withdrawal of the Russian Forces. However, additional research on this matter is required.

Research Facilities

A subsidiary of the torpedo research facility Eckernförde was operated in Gdynia until 1944.

Training Facilities

A German training facility for anti-aircraft units was stationed in Kołobrzeg. Its exact location is not known today but its three batteries (twelve guns each) were operational until 1944. The batteries could fire at planes on their way to bombing raids on Berlin or Kaliningrad. To combat such raids, they were used like any regular anti-aircraft battery that was not part of a training facility. Over the course of WWII calibres of 2 cm, 3.7 cm, 8.8 cm 10.5 cm and 12.7 cm were fired. It remains unclear what happened to the leftover munitions that were present at the site when the Soviet army conquered Kołobrzeg.

In Ustka, the German army operated field artillery school 13 until the end of 1944. At least three heavy batteries were operated here, with different calibres being used over the course of the war. These batteries also fired at bombers on their way to Kaliningrad.

A submarine training facility was operated in Gdynia, since Gdansk Bay was out of range of bombers for the majority of WWII. Exercise was probably often executed with training torpedoes (BArch-MA RL 4/16).

Bombing Hotspots

Numerous bombing hotspots are located along the Polish coast. The German vessel *Lützow* was bombed in Swinoujscie, where a tallboy bomb was cleared in 2020 in the river Odra. The neighbouring Szczecin was a hotspot for incendiary bombs.

Gdynia was a Polish navy harbour before WWII and was thus bombed by the German air force during the Invasion of Poland. During these attacks a Polish destroyer and a Polish mine layer were sunk in the harbour. In 1945, heavy bombing by the British, US and Soviet air forces took place in Gdansk and Gdynia. During a Soviet raid the replenishment oiler *Franken* was sunk in Gdansk Bay with munitions and fuel on board. A British air raid resulted in the sinking of the hospital ship *Stuttgart*, which was loaded with synthetic fuel.

Another bombing hotspot was the shipyard in the town of Elblag.

Mine Laying Operations

Poland had established mine barriers in its waters (i.e. Polish waters as of 1939) before the invasion by Germany. These barriers were at least partially cleared during the invasion.

In addition, the allies mined Gdansk Bay and its surroundings in an effort to prevent the activities of the submarine training facility that was located there. Beginning in 1940, the area was constantly mined with 1,200 British airdropped ground mines which the Germans tried to clear. This leaves us with a relatively unclear picture of the mine threat in the region (BArch-MA RM 70/1).

Naval Warfare

One instance of naval warfare is specifically noteworthy regarding the entry of warfare materials into Polish waters. During the invasion of Poland, the German battleship *Schleswig-Holstein* fired at the Westerplatte, a military compound in Gdansk. It used 15 cm and 28 cm artillery for its naval gunfire support. The 28 cm shells were specifically prone to fail to detonate when hitting the water surface because they were intended to explode when hitting harder targets. Overall, heavy naval combat with many different types of munitions took place in Gdansk Bay, with vessels shelling land positions, which returned artillery fire towards the ships (BArch-MA RM 54/28).

Land Warfare

In general, the Blitzkrieg strategy by the German invaders led to relatively few deployments of heavy weapons along what is now the coast of eastern Poland. A notable exception was the city of Gdynia and the Hel peninsula, which withstood the German advance meaning that more and heavier artillery was used there. Gdansk Bay would again become an area of heavy combat during the Soviet advance and German withdrawal in 1945.

2.4.4 Lithuania

Bombing Hotspots

Klaipeda was bombed by the Soviet Union and thus an elevated occurrence of aerial bombs must be expected in the waters surrounding the city.

Mine Laying Operations

A noteworthy incident occurred close to Klaipeda in 1999 when a small Russian mine with no more than 10 kg of explosive material was found. Historical research indicated that the type of mine found here (a small fish mine) was last used in 1916. This type of moored mine was intended for use in bodies of flowing water but was also deployed to protect mine barriers from demining. This incident demonstrates that types of warfare materials may have been used in different ways than originally intended. Thus, the occurrence of even more improbable types of ordnance is a realistic scenario all throughout the Baltic Sea.

Later during WWII, the mine barrier Wartburgsperre (BArch-MA RM 7/1486) was established by the German navy. It was supposed to block the western Baltic Sea for Soviet vessels coming from the Gulf of Finland. Initially 600 EMC mines were laid, but as the Soviet Union started demining, an overall number of around 1,300 mines were laid. The barrier was supposed to run from Klaipeda to the island of Gotland, but due to the presence of a Soviet cruiser in the area, it was redirected towards the southern tip of the island of Öland in Swedish waters.

Land Warfare

Soviet artillery took positions north of Klaipeda in autumn 1944 and started intensively firing at the German coastal traffic.

2.4.5 Latvia

Dumping

The city of Liepāja has long been a naval harbour. During the withdrawal of the Russian Army in 1992, at least two ships – a corvette and a frigate – were scuttled in the harbour. It is furthermore possible that during the withdrawal warfare materials were dumped around the harbour and is now still present in the waters of the area.

Anti-aircraft and Artillery Batteries

After Latvia was occupied by the Soviet Union in 1940, artillery batteries calibres 130 mm and 180 mm with a range of up to 32 km were established in Liepāja, Courland and Ventspils. However, not all of them could be finalized before the German invasion of the Soviet Union. The positions were later fully established after the area had been reconquered in the late years of WWII (BArch-MA RM 7/1587; Melkonov 2003; Melkonov 2005).

Training Facilities

An airfield in Spilve was operated as a training facility by the Russian army and navy until 1917. It was again used in 1940 and 1941. In 1944, the Germans operated an airfield in Spilve, Riga. This facility was only active for a few months, since it was transferred here due to the advance of allied forces in Italy. For a while the airfield was used by a German aviation school to train the use of airborne torpedoes. It operated until 27 September 1944, when it was abandoned due to the approaching Soviet army. After the war, both live and training torpedoes were found in the waters surrounding Riga. It is possible that target practice was executed by using a wreck that was present in the area. After the airfield was conquered by the Soviet Union, it was again used for training until the Russian withdrawal in 1992.

Bombing Hotspots

During WWII, Liepāja was bombed by the Soviet Union.

Mine Laying Operations

During WWI, Russian-operated military harbour of Liepāja was mined by the German navy so that the Russian navy could not leave port. After WWI, the barrier was cleared and no focus was placed on the harbour during WWII.

Overall, the coast of Latvia was heavily mined by German and Soviet forces during WWII, and wrecks from the mines are present. Among these are wrecks of mine laying ships. Limitations to Soviet intelligence may have led to the laying of Soviet mines into German barriers, thereby resulting in mixed mine fields.

The Irbe Strait, i.e. the western entry into the Gulf of Riga, was mined during WWI and WWII. Overall, between 14,000 and 15,000 moored and ground mines were laid by German and Russian/Soviet forces along and across the strait. The mine barriers were only partially cleared during the war and roughly 30% can be expected to remain in the area until today. Air deployed mines that were laid as early as 1917 were detected in good condition in 2018.

Naval Warfare

In addition to the mine laying operations mentioned above, the Irbe Strait was also the scene of heavy aerial and naval combat during WWII.

In March 1945, the vessel *Ilmenau*, which was loaded with 1,100 tonnes of warfare materials, were sunk close to Liepāja. The cargo did not fully detonate and much of it was cleared. However, about 500 tonnes of 2 cm shells remain submerged.

Land Warfare

The city of Liepāja was subjected to heavy combat during WWI. The entire region of Courland was struck heavily by artillery both during the German advance and retreat in WWII.

2.4.6 Estonia

Dumping

In Estonia there are two main dumpsites. Around the island of Osmussaar dumping took place in a shallow crater. While it is not known what type of warfare materials were dumped here, live and fused Russian torpedoes were found at the site. Another dumpsite is located to the north of the island of Naisaar. A Soviet artillery and mine depot (with up to 10,000 mines) was stationed on the island. While it is unknown whether all of these warfare materials were transported back to Russia after the collapse of the Soviet Union, it is certain that hundreds of mines which were developed after WWII are present at the site.

Anti-aircraft and Artillery Batteries

At the beginning of WWI, the Russian army prepared a 30.5 cm artillery battery at the southern tip of Saarema island (Melkonov 2003; Melkonov 2005). However, the invasion by the advancing German troops prevented its use during WWI. The battery was, however, used in combat during WWII and for training with live and inert munitions until the 1960s. Further artillery was stationed on Hiiumaa, which covered the entry to the Gulf of Finland. The easternmost Soviet defence artillery was located on Osmussaar. After Estonia was occupied by the Germans in WWII, 17 cm artillery was stationed in Juminda, firing northward to support the Juminda mine barrier. Finally, a shooting range existed on Naisaar, which also fired towards the northern direction.

Training areas

The Kurassaaree Bay was used for training activities until after WWII. Numerous ship-based anti-submarine rockets that were built after the 1960s, were found in the area. They may have been dumped during the Russian withdrawal in 1992 or sunk to the seabed during training.

Furthermore, a Soviet submarine school existed in Paldiski, where training with irritants and other chemicals took place.

Mine Laying Operations

The Estonian coast was mined heavily by German and Russian/Soviet forces during WWI and WWII. Accordingly, wrecks of minelayers with active mines aboard may be found in Estonian waters. As discussed in the chapter on Lativa, the Irbe Strait was heavily mined. Furthermore, during WWI, the area north of Saarema was mined by Russian forces. The German navy established another WWI barrier at Moon-Suur, where wrecks of a German torpedo boat were found. The strait was mined again during WWII, leading to the sinking of a Soviet submarine in 1941. In addition, intermixed mine barriers can be found to the northwest of Osmussar. The situation here is further complicated by the presence of a Soviet submarine and an airplane wreck.

Numerous larger German WWII mine barriers blocked the entry to the eastern Baltic Sea. The Juminda mine barrier was established in 1941 to prevent the passing of evacuation convoys from Tallinn, Osmussaar and Hanko. These convoys ran into the mine barrier, leading to a high density of shipwrecks, some of which are loaded with warfare materials. While the mine barrier was not re-established afterwards, around 30% of the mines may remain. Another barrier – the Nilhornsperre – was laid to the north of Naisaar. Two German were sunk here, one of which detonated after it was hit by a mine destroyers (BArch-MA RM 94/232; destroyers (BArch-MA RM 94/143). The other vessel remained in good shape and has roughly 310 tonnes of synthetic oil, 12 torpedoes and its artillery munitions on board. Further to the east, Nashornsperre was established between Tallinn and Helsinki and was remined until September 1941. Finally, Seeigelsperre blocked the southern half of the Gulf of Finland from Narva Bay towards the north. Overall around 25,000 mines were laid here, and it consisted of 17 large and 15 small barriers which partially exist to this day. EMC, EMD and EMF mines with a charge weight of up to 350 kg of explosive material are still fused and attached to their mooring in the water column. In addition, cleared moored mines are present at the seabed (BArch-MA RM 7/1489; BArch-MA RM 70/6).

Naval Warfare

Saarema and Suur Strait were hotspots of naval combat during WWI. Irbe Strait was a core area of warfare during WWII.

2.4.7 Russian Federation

Due to limited access to Russian archives and an absence of representatives of the Russian Federation to the EG Submerged group, the information presented in this section is certainly incomplete. More warfare materials than are mentioned here must be expected.

Dumping

During WWII, German chemical warfare materials were stationed in Königsberg (now Kaliningrad). Most of the warfare materials were transported to St. Georgen in Bavaria, Germany. However, it is possible that a small amount was dumped in the EEZ of Kaliningrad. The same is true for conventional warfare materials.

Training Facilities

The German field artillery school 15 was located in Majak, Kaliningrad. In 1938, the school operated at least six artillery batteries, three of which fired 8.8 cm shells. After WWII, wide parts of the Baltic Sea were used for Soviet training with inert and live munitions, among them Ch-55 cruise missiles.

Bombing Hotspots

Due to the presence of a shipyard, Königsberg was bombed by American, British and Soviet air forces. Leningrad (now St. Petersburg) was bombed by German forces while under siege.

Mine Laying Operations

During WWII, numerous mine barriers were established by the Soviet Union and Germany in the Gulf of Finland. The remnants of these will also be present in the waters and EEZ of Finland. Germany established the so-called Seeigelsperre at Narva Bay to block Soviet vessels on their way from St. Petersburg. Another mine barrier existed in the area of Vyborg, in which both Finish and Soviet mines must be expected.

Land Warfare

The city of Leningrad was heavily attacked during the siege by the German army and misfired warfare materials are likely present in Neva Bay.

2.4.8 Finland

Dumping

A Soviet naval base existed in an exclave at Porkkala after Soviet troops had to evacuate from the Hanko naval base. It is possible that minor dumping events occurred after the war in the Porkkala area.

Anti-aircraft and Artillery Batteries

During WWI, an artillery battery was supposed to be established at Hanko. However, this never materialized due to the fast advance of German troops. During WWII, batteries of 130 mm and 180 mm artillery were present. Since Hanko was a Soviet exclave, the batteries were initially used by the Soviet Union, to cover the entry to the Gulf of Finland. Training at the batteries continued until the 1960s. Furthermore, Finnish 30.5 mm artillery existed in Helsinki and fired towards the Gulf of Finland.

Training Facilities

Soviet training facilities were operated in Porkkala and (to a lesser degree) in Hanko. The Finnish army maintained a training facility in Turku.

Mine Laying Operations

The Nashornsperre is the most notable WWII mine barrier that existed in what are modern day Finnish waters. It led from Tallinn to Helsinki (see 2.4.6).

2.4.9 Sweden

Dumping

Numerous dumpsites that were established post-WWII are present in Swedish waters. These were briefly addressed in the HELCOM MUNI report (2013). Two of them are located in the Skagerrak and Kattegat. CWAs were dumped at both sites. Warfare agents originated from German depots in the British and American occupation zones. They were loaded aboard ships in Lübeck, Kiel and Flensburg and scuttled in the dumpsites. Due to the scuttling, i.e. sinking of the entire vessel, it can be assumed that no en-route dumping was executed from these ships. In order to accelerate the process of sinking, ships were further loaded with unfused conventional munitions in an effort to increase the weight of the cargo.

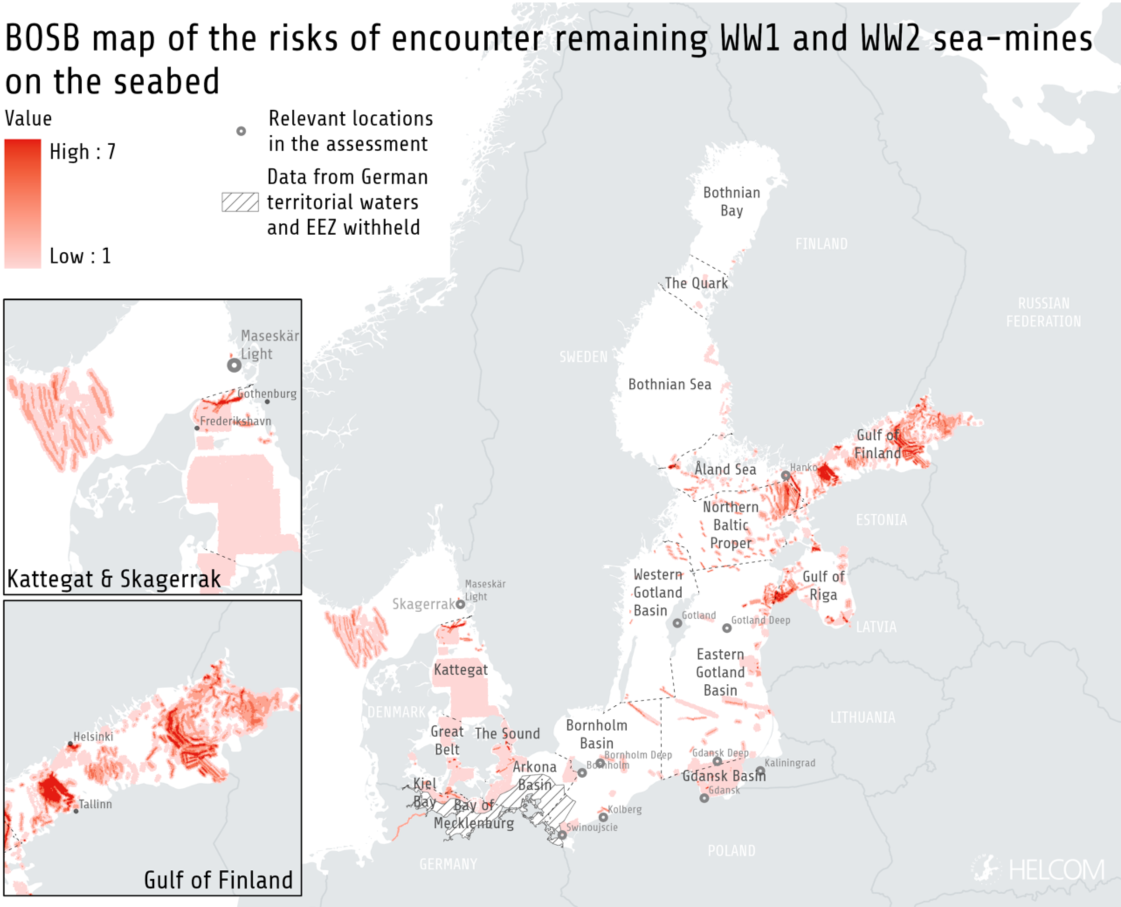
Initially, ships were scuttled by firing at them with artillery. Later, detonators were installed inside the hull to be detonated once the vessels were in position for the scuttling. One vessel did not sink as planned, with an additional explosion taking place approximately 300 m below sea level. It is unclear to what degree this additional detonation lead to a spread of CWAs in the area.

Another prominent site in Swedish waters is the Gotland dumpsite. According to Soviet sources 2,000 tonnes of CWAs were dumped here. Considering the amount of warfare materials that must have been present in German depots of the Soviet occupied zone, 5,000 tonnes appears to be a more realistic figure. It is furthermore possible that the Soviet Union dumped additional Soviet CWAs at the site.

Mine Laying Operations

During WWI, mine barriers were established between the north of Gotland and Gotska Sandön.

The German WWII mine barrier Wartburgsperre ran from the southern tip of the island of Öland to Klaipeda, Lithuania, (see 2.4.4). It happens to overlap with the Gotland dumpsite. To deviate Soviet attention away from the Wartburgsperre, a fake mine barrier, which consisted of depth charges and other warfare materials were established at the south of Gotland.



2.5 Relocation of Objects

Human and natural modes of relocation of warfare materials differ in magnitude and type of force. Natural modes of relocation are mostly driven by currents and extreme weather events. However, when it comes to human modes of relocation only trawled fishing nets, dredgers or other large machinery moving along the seabed (e.g. for laying pipes or power lines) are recognized as being able to relocate large objects along the seafloor of the Baltic Sea.

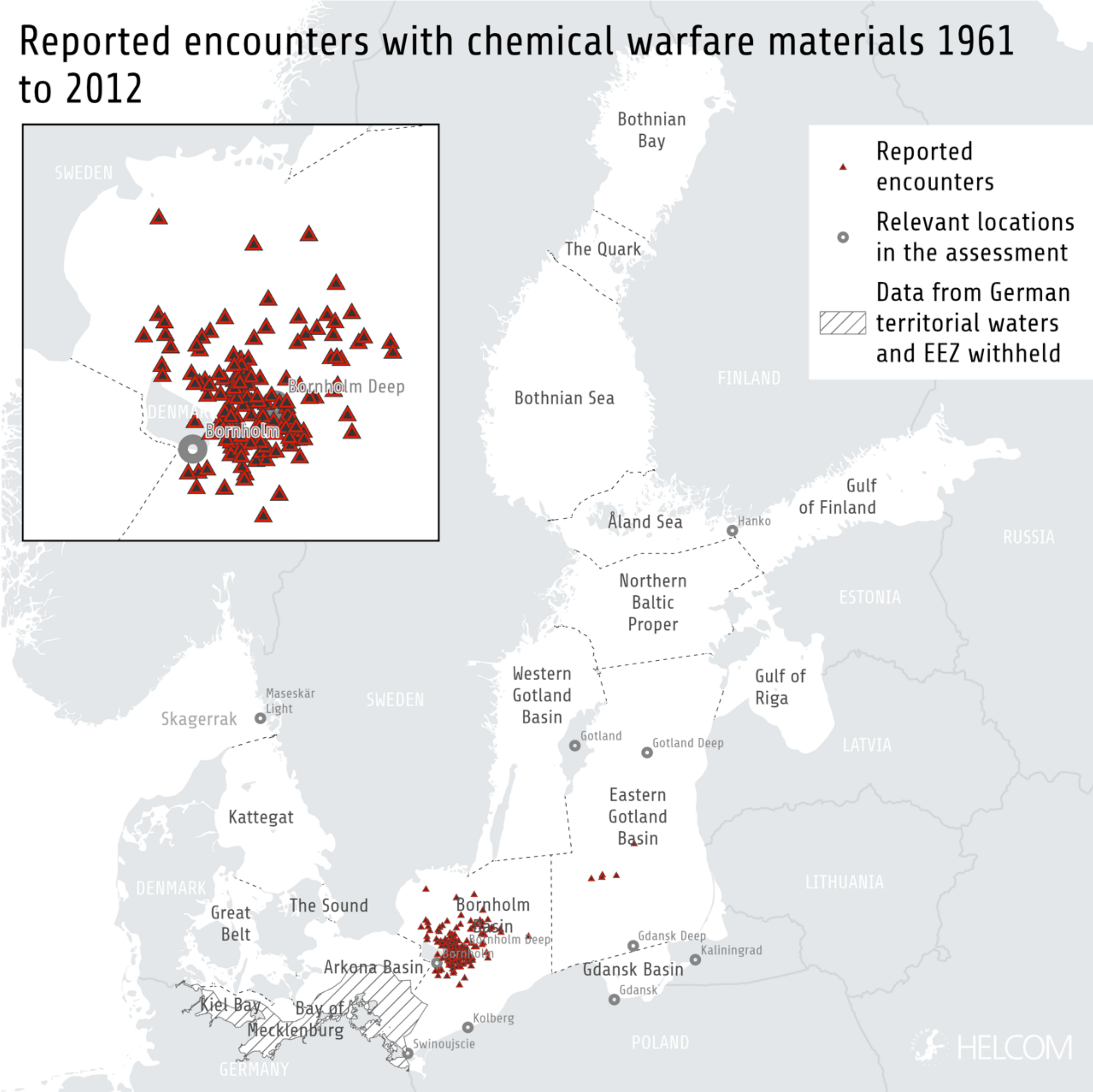
2.5.1 Natural modes of Relocation

Natural water currents can move munitions on the seafloor. The mobility of submerged objects depends on physical parameters such as currents, waves and tides, while high-energy storm events may have a particularly strong effect. The deeper munitions are buried, the stronger currents must be to move them (Menzel et al. 2017), so unburied munitions are more easily transported and redistributed. Sediment scour around munitions during subcritical current conditions can promote burial (Menzel et al. 2018), and small, tapered warfare materials tend to bury more easily than other shapes (Rennie et al. 2017). The movement of underwater munitions depends on drag and lifting forces, and due to different designs, some munitions may have a higher likelihood of being moved than others (Menzel et al. 2017). Relocation by currents occurred more often in the years after dumping took place. This was the result of two factors. First, air in munitions casings reduced their weight. Second, sometimes munitions were dumped in wooden crates. This was especially noticeable in the washing up of chemical munitions in southern Sweden, the eastern coast of Bornholm and central Polish coast (HELCOM MUNI 2013).

2.5.2 Human modes of Relocation

Although many munitions dumpsites were by design far from shore and usually in deep waters, there remains a concern that warfare materials may be transported to locations where it poses a greater risk, e.g., to beachgoers. Relocation by fishing activities is a major concern (HELCOM CHEMU 1994; HELCOM MUNI 2013; Glasby 1997; Missiaen et al. 2010), and chemical munitions recovered during dredging have occasionally been unwittingly brought to port. There are a number of reports of fishermen who were exposed to chemical munitions at sea during fishing operations, and munitions have also been found on beaches (Fabisiak and Olejnik 2012). Furthermore, some purposeful relocation of warfare materials happens in order to keep waterways free or to enable the construction of offshore infrastructure.

Chemical munitions fragments have been reported on beaches in Poland (e.g., Fabisiak et al. 2018), and chemical munitions have washed ashore elsewhere as well (Missiaen and Henriet 2002). Sulfur mustard is one of the primary CWAs of concern because the surface polymerizes in seawater, creating elastic lumps which are protected from further decomposition or dilution (Granbom 1994; Missiaen et al. 2010). These lumps can be transported farther by natural and anthropogenic mechanisms, or recovered in fishing nets, posing a risk when handled by humans.


Reported encounters with chemical warfare materials 1961 to 2012
Reported encounters
Relevant locations in the assessment
Data from German territorial waters and EEZ withheld
SWEDEN
Bornholm Deep
DENMARK
Bornholm
Bothnian Bay
The Quark
Bothnian Sea
FINLAND
Åland Sea
Hanko
Gulf of Finland
RUSSIA
Northern Baltic Proper
ESTONIA
Western Gotland Basin
Gulf of Riga
Maseskär Light
Skagerrak
SWEDEN
Gotland
Gotland Deep
LATVIA
Kattegat
Eastern Gotland Basin
LITHUANIA
DENMARK
Great Belt
The Sound
Bornholm Basin
Bornholm Deep
Gdansk Deep
Kaliningrad
Arkona Basin
Gdansk Basin
Gdansk
Kiel Bay
Bay of Mecklenburg
Kolberg
Swinoujscie
POLAND
GERMANY
HELCOM

3. Warfare Materials – Effects and Risks

3.1 Known and Potential Effects

3.1.1 Detonation

Understanding of the physical theory of detonation and its impacts is important for the successful management of risks to human lives, infrastructure and the marine environment. Detonation is defined as a reaction of an energetic material after a stimulus. Such a chemical reaction consists of a conversion of a material into gaseous reaction products and leads to an instantaneous pressure increase and subsequent expansion in volume.

The detonation velocity and the detonation pressure are therefore important indicators for the overall energy and force of the detonation in general and for the shattering effect of an explosive in particular. The velocity of a detonation depends on the type of explosive contained in the warfare material.

When initiated, a shock wave develops inside the explosive material that drives the reaction further by compressing and heating the material. Next, the shock wave propagates into the surrounding medium (i.e. water) where – in very simplified terms – the following main effects occur in the near field: A typical pressure signature of an underwater detonation is characterized by a tremendously steep wave front of very high pressure (overpressure) followed by a reaction gas expansion on a slower timescale. While the primary shock pulse decays exponentially, the subsequent reaction gas bubble expands and behaves dependant on surrounding conditions like sediment type and water depth. If water depth is sufficiently large the first shock wave can be followed by a series of so-called bubble pulses. These are caused by oscillations of a gas globe which are a result of the explosion. This produces a series of secondary much weaker pressure pulses. All resulting far field effects depend strongly on the surrounding conditions and have therefore to be assessed and estimated for each specific case.

Underwater detonations are the loudest anthropogenic point sources of noise in the oceans and have the potential to cause serious injury in marine vertebrates and invertebrates (Richardson et al. 1995; Lewis 1996; Schmidtke 2010). Both the steep wave front and the high peak pressure caused by underwater detonations lead to severe injuries to marine vertebrates (Landsberg 2000) such as fish, water birds and marine mammals (chapter 3.4). A large fraction of the total chemical energy in an explosive material is radiated upon detonation as acoustic energy (e.g., 40% for a 1 lb charge (Urick 1967)). Marine invertebrates can also be directly impacted by the shock wave. However, such effects have been studied to a lesser extent and are not yet well understood.

The effects of underwater detonations are in fact a combination of shock, produced by a very high detonation velocity, and blast, appearing as a gas bubble. The nature of the environment causes the two mechanisms to operate over different timescales. (Urbański 1984)

The extent of an explosion is not only determined by the detonation velocity of the explosive but also by the integrity of the shell. By a defined weakening of the shell and a deliberately low energy input the much weaker deflagration can be triggered.

3.1.2 Warfare Materials Housings Corrosion

The chemicals in warfare materials are enclosed by metal housings, therefore the corrosion of metal is a critical process through which contaminants can be released into the marine environment (Wang et al. 2013). However, munitions corrosion is exceptionally difficult to predict, in part because housing materials are highly diverse and may have changed over the course of the war due to availability of raw materials (Silva and Chock 2016; Jurczak and Fabisiak 2017). Furthermore, the quality and thickness of metal differs among munitions types, and has also likely varied during the wartime period. Warfare materials are often made of combinations of metals, which can lead to galvanic corrosion. Others have protective coatings such as paints, which can protect the metal from exposure to sea water, thereby delaying or slowing corrosion. Local environmental factors also influence corrosion rate. For example, corrosion varies with time of exposure, depth of burial in the sediment, exposure to anoxic vs. oxic conditions, concentrations of chemicals such as sulphides and methane, salinity, temperature and microbial activity (Rossland et al. 2010; MacLeod 2016; Silva and Chock 2016; Cybulska et al. 2020). Corrosion rates also increase with current speed and water mixing (MacLeod 2016; Overfield and Symons 2009), so munitions in dynamic shallow coastal waters are especially likely to show deterioration and damage.

Some estimates have predicted that corrosion in the Baltic Sea will lead to maximum chemical release rates from submerged munitions in the early twenty-first century (Granbom 1994; Malyshev 1996; Glasby 1997). Other and more recent reports generally confirm these predictions of munitions deterioration and show that chemical munitions dumped in the Baltic and Adriatic Seas exhibit severe to complete corrosion (Sanderson and Fauser 2015; Amato et al. 2006; Lisichkin 1996; Surikov 1996). Shipwrecks in the Skagerrak were investigated with Remotely Operated Vehicles (ROVs) and many chemical weapons were found with thin walls frequently breached by corrosion (Tornes et al. 2002). Virtually all of these reports describe the extent and frequency of corrosion only in a qualitative sense, and there is only limited data available that quantifies the disintegration of underwater munitions housings. For example, the OSPAR Commission compiles reports of munitions encounters in the North Sea from beachgoers, divers, fisherpersons and militaries (Nixon 2009), and includes both munitions type and corrosion state (when available). This database shows that most munitions throughout northwest European waters are “extensively” or “completely” corroded, and munitions in the Baltic Sea are likely to show a similar state of degradation. This is consistent with recent results from the DAIMON project showing that the average corrosion rate of barrels equals 0.0434 mm/year, bombs 0.0365 mm/year, and artillery shells 0.0313 mm/year. In experimental setups, the original steel samples from museum collections were placed for two years at different the Baltic Sea munitions dumpsites, both in the near-bottom water and in surface sediments. The results suggest complete breach of barrels and bombs between 2020 and 2030, while the artillery shells will completely corrode roughly by the year 2100. As a result, many underwater munitions are likely to be breach within the next decade, while their fillings will get exposed to seawater. (Bełdowski 2020)

3.1.3 Dissolution and Release of Compounds

Once the protective metal housings are breached, the release of the solids inside depends upon the dissolution of munitions compounds. The solubility of TNT in water is only approximately 130 mg/L, and even lower in seawater (Beck et al. 2018). In general CWAs are low water-soluble, with some compounds such as Clark I, Tabun, and phosgene that have relatively higher solubilities, on the order of grams per litre (Szarejko and Namiesnik 2009). The solubility of thioxane, a degradation product of Sulfur mustard, is also substantially lower in seawater than in fresh water (Zhang et al. 2009). The most frequently found compounds of Sulfur mustard degradation are water extractable salts of so-called mustard heel and the polymerization products 1,4 Dithiane and 1,4-Oxathiane (Vanninen et al. 2020).

Dissolution rates of munitions compounds from solid explosives depend on formulation, where less-soluble components such as RDX reduce dissolution rates of more soluble components such as TNT (Lynch et al. 2001; Monteil-Rivera et al. 2010; Dontsova et al. 2006). This means that the rates of chemical release and spread in the environment depend in part on the type of explosive fill. With some exceptions (Tørnes et al. 2020), there is, however, still very limited information available on the dissolution rates of CWAs from underwater munitions.

Submerged warfare materials are a greater source of munitions compounds to the water column where munitions are unburied (not buried) and breached, for example, by corrosion. Release rates increase with exposed surface area of the solid explosive material and with increasing current speeds and water mixing (Wang et al. 2011). Like corrosion rates, dissolution is higher in high-energy environments and therefore the Baltic Sea may be particularly susceptible to both exposure and dissolution of explosive compounds. Furthermore, sedimentation rate in the Baltic Sea is comparatively low (1-2 mm/year (Leipe et al. 2013)), meaning that warfare materials are more likely to be unburied than e.g. in the North Sea.

3.1.4 Contamination

3.1.4.1 Sea Water

It is certain that chemicals are leaking from breached underwater munitions, as shown for the chemical munitions dumped in the Bornholm and Gotland Basins (Barsiene et al. 2014; Vanninen et al. 2020). CWAs, particularly arsenic-based compounds, have been detected throughout the Bornholm dumpsite, as well as the surrounding area (Missiaen et al. 2006; Missiaen et al. 2010; Bełdowski et al. 2016a). Leakage of CWAs is also evident indirectly, as degradation products of Clark I and TPA have been detected in biota samples from Skagerrak and Bornholm Deep CW dumpsites (Niemikoski et al. 2017; Niemikoski et al. 2020a). In addition, explosive compounds released from conventional munitions have been detected in the water column and wild-collected organisms (Gledhill et al. 2019; Beck et al. 2022) at a conventional munitions dumpsite on the German Baltic Sea coast.

Numerical simulation of chemical release from CWA dumpsites suggests that some chemicals (i.e. Tabun) will be hydrolysed to non-toxic products within 48 h of release, but near-bottom currents and water column mixing can lead to long-range transport of the remaining toxic compounds (i.e. Sulfur mustard degradation products and arsenic-based agents) (Korotenko 2003; Jakacki et al. 2020). Indeed, CWA release modelling in Bornholm Basin indicated potential bottom water contamination of tens of kilometres from the source site (Jakacki et al. 2020; Vanninen et al. 2020).

The measured levels of dissolved munitions compounds tend to be very low in seawater, even very near munitions objects. These low concentrations make it difficult to detect CWAs and munitions compounds in the water column. A pilot study in Bornholm Basin collected 61 near-bottom water samples but did not detect any CWA compounds in the dissolved phase (Missiaen et al. 2010). Water samples near chemical munitions-laden shipwrecks in the Skagerrak also did not show any presence of CWA compounds, despite the fact that munitions showed corrosion breaching and high levels were detected in sediments (Tornes et al. 2002). Although CWA compounds have not been widely detected in the water column, they can be found at high concentrations in porewaters of contaminated sediments (Bełdowski et al. 2016; Christensen et al. 2016; Vanninen et al. 2020). These studies highlight the need for more sensitive analytical methods in studies of dissolved munitions compounds in marine waters.

Rodacy and colleagues (2001) made some of the first successful measurements of conventional munitions compounds in seawater and found sub-µg/L concentrations at distances less than 1 m from underwater munitions in the Bedford Basin (Canada). Similarly, Porter et al. (2011) found dissolved explosives at µg/L levels near munitions in Puerto Rico. These concentrations are generally considered “trace” for chemicals in seawater.

In the Baltic Sea, passive samplers have shown positive accumulation of TNT and its degradation products in the dissolved phase. One study in the Bay of Kiel detected TNT on five of ten passive samplers deployed during test detonations of munitions (Pfeiffer 2009). A set of four passive samplers deployed in Gdansk Bay next to a WWII-era ship containing munitions showed accumulation of TNT, RDX and degradation products of TNT (Warren et al. 2018). Although it is difficult to contextualize these results in terms of concentrations, they do confirm that substances are released from underwater munitions.

Gledhill et al. (2019) recently developed a highly sensitive method for detection of conventional explosives compounds in seawater. At one munitions dumpsite in the Bay of Kiel, they detected dissolved munitions compounds in seawater at concentrations of 0.01 – 10 ng/L. For context 1 ng/L is the equivalent of dissolving 2-3 mg of material in an Olympic-sized swimming pool. Subsequent samples collected by divers directly adjacent to exposed explosive material at the site showed concentrations up to nearly one million times higher (Beck et al. 2019). This latter study showed clearly that chemicals are released from the underwater munitions, but also demonstrated that they are rapidly mixed and diluted away from munitions surfaces. The combination of slow dissolution and rapid dilution leads to the low concentrations in the water column, but it also means that munitions compounds have a high potential to spread away from the source. Mussels (*Mytilus edulis*) transplanted to the same munitions dumpsite showed accumulation of TNT and its degradation products (Strehse et al. 2017; Appel et al. 2018), confirming that although concentrations may be low, chemical release from conventional munitions is bioavailable and accumulates in biota.

3.1.4.2 Sea Floor and Sediment

Munitions objects located on the seafloor and on beaches represent a sort of primary contamination. They are similar to other anthropogenic marine litter, such as plastics, scrap metal, abandoned fishing gear and shipwrecks. However, warfare materials have the potential to detonate and contains toxic chemicals, making it substantially more hazardous than other litter.

Chemical contaminants leaked from corroded warfare objects can also be found in seafloor sediments. Conventional explosive compounds (including TNT, TNB, DNB, and DNT) have been detected in sediments throughout the Baltic Sea, including the Bays of Kiel and Lübeck (Germany), Bornholm Basin (Denmark), and Gdansk Deep (Poland) (Dawidziuk et al. 2018). Observed concentrations were between 0.5 and 1.5 µg/g dry sediment.

One of the most extensive sediment CWA datasets was collected in Bornholm Basin and Gotland Deep (Missiaen et al. 2010; Vanninen et al. 2020). Intact parent compounds were detected in low amounts, usually not exceeding 1% of total CWAs (this included Sulfur mustard, tabun, Clark I, Clark II, Adamsite or α-chloroacetophenone), but degradation products of Sulfur mustard, Adamsite and components of arsine oil (PDCA, Clark I, TPA and $AsCl_3$) were found in sediments throughout both dumpsites. On a spatial scale of hundreds of metres, higher levels of CWA contamination were observed near shipwrecks and identified chemical munitions. Early studies showed that within tens of meters, sediment CWA content was poorly correlated with distance from the putative sources (Missiaen et al. 2010). In contrast, recent investigations demonstrated an exponential decrease in the concentration of Sulfur mustard degradation products up to 250 m away from the source, although in some cases, concentrations in the immediate vicinity (up to 10 m) showed irregular patterns that are related probably to near bottom currents (Vanninen et al. 2020),

Whereas intact CWA compounds are often below detectable levels, degradation products are frequently observed in sediments around chemical munitions dumpsites (Missiaen et al. 2010; Sanderson et al. 2010; Vanninen et al. 2020). This includes constant detection of previously unknown degradation products and metabolites (Niemikoski et al. 2020b). Degradation products of cyclic Sulfur mustard (1,4-Oxathiane 1,3-Dithiolane 1,4-Dithiane 1,4,5-Oxadithiephane) were detected in sediments in the Bornholm Basin at concentrations between 15 and 308 µg/kg dry weight (Magnusson et al. 2016). These concentrations are higher than the 1 - 10 µg/kg levels observed in sediments from the Skagerrak using similar methodologies (Roen et al. 2010). Several CWA compounds, including Sulfur mustard, Clark, and other arsenic-containing compounds were detected in sediments around shipwrecks containing chemical munitions in the Skagerrak (Tornes et al. 2002). Most samples had CWA levels < 1 µg/kg, but many samples were 10- to 100-fold higher. Sediments collected in the immediate vicinity of munitions in the Bornholm primary dumpsite contained Sulfur mustard degradation products as high as 2,900 µg/kg d.w. and degradation products of arsenic-based agents up to 18,700 µg/kg (Vanninen et al. 2020).

Modelling studies have shown that CWA migration in sediments is likely to be limited (< 1 m) due to the relative time scales of diffusion and CWA hydrolysis (Francken and Hafez 2009). This study however, postulated diffusion as the only mechanism. The presence of Sulfur mustard degradation products in the sediments of Gdańsk Deep, where objects were detected 0.5-1.5 m below the sediment-water interface, suggests that sediment mixing, porewater flows associated with advection of dense near bottom water and compaction may enhance the migration process (Bełdowski et al. 2016; Vanninen et al. 2020).

Persistence of intact compounds and degradation products, especially arsenic and its associated compounds, can lead to long-term toxic contamination of the sediments (Francken and Hafez 2009, Nawała et al. 2021). Moreover, the possibility of arsenic reemission from the uppermost sediments in Baltic Sea dumpsite areas has been suggested, due to reduction of As V to As III under anoxic conditions (Szubska 2020). Conventional explosives may not pose such a long-term risk considering that they lack a toxic inorganic component and the organic material is, in principle, possible to completely remineralise.

3.1.5 Potential Effects of Climate Change

Climate change coincides with changes in temperature, precipitation, the frequencies of extreme weather events and ocean acidification (Doney et al. 2012 Ipcc 2014, Masson-Delmotte et al. 2018). Although there can be no doubt that climate change will alter the marine munitions problem (Scharsack et al. 2021, Reckermann et al. 2022), empirical data enabling authorities to address potential issues specifically are currently not available. However, based on the current knowledge, factors of climate change which are likely to interfere with marine munitions issues can be identified and their possible effects on marine warfare materials and their interaction with marine environments can be estimated.

A fundamental question is how corrosion of marine munitions will be altered by climate change. Some factors that influence the corrosion speed of submersed military materials are susceptible to climate change, including exposure to anoxic vs. oxic conditions, temperature, microbial activity and water mixing (MacLeod 2016, Silva and Chock 2016). Shifts in oxic and anoxic conditions accelerate corrosion (Videla 2000), but in the Baltic Sea more stable stratification is predicted as a result of rising temperatures (Hordoir and Meier 2012, Meier et al. 2017). This will coincide with sedimentation and decomposing of organic matter which causes hypoxia in deeper water layers (Meier et al. 2017). In deeper zones of the Baltic Sea, in which most munitions were dumped, in future, more stable stratification and more stable (prolonged) hypoxic/anoxic conditions have to be expected which might slow down corrosion.

On the other hand, temperatures will rise and warmer conditions increase corrosion rates (North and Macleod 1987, MacLeod 2016). In addition, a higher water temperature increases the solubility of compounds leaking from marine munitions (Lynch et al. 2001) and sorption of organic explosives to sediments and passive samplers decreased with temperature rise (Ariyarathna et al. 2016, Warren et al. 2018). Accordingly, rising concentrations of munitions compounds in the water column must be expected. However, an in-situ study in the Baltic Sea did not find substantial differences in the solubility of organic explosives across seasons with changing water temperatures (Beck et al. 2019).

Changing temperature will alter physiological activity of most marine organism (including microbes). On the one hand biodegradation of organic munitions compounds is positively correlated with temperature rise (Chappell et al. 2011). On the other hand, toxicity of explosives rises with temperature (Bickmeyer et al. 2020).

Climate change will influence a number of factors that determine the fate of munitions compounds in marine environments. Direct effects concern mechanical impact through water turbulences which is likely to increase the leakage of toxic compounds from dumped munitions. Corrosion is a ticking time bomb, which will lead to increased leakage from dumped munitions. Organism confronted with munitions compounds seem to be able to metabolise them to some extent, but toxic effects of munitions compounds might outweigh the benefits of metabolization and degradation, in particular when organisms are exposed to environmental stress due to climate change.

The marine munitions issue is extremely complex; multiple factors have to be considered and their interactions may depend on local conditions. Although general information about locations of munitions dumps is often available, detailed data on types of munitions and their state are often missing. Furthermore, it is often unknown if munitions compounds are leaking out and what the effects on the environment are. More detailed investigations at multiple contaminated sites are urgently needed. In particular, long-term monitoring data and comparisons of data from dumpsites across different seasons and climate zones would be desirable to address the question how climate change impacts marine munitions.

3.2 Potential Risks to Humans

From a human risk perspective, the problem of sea-dumped munitions has been growing simultaneously with the maritime economy. Given the increase in marine traffic and the expansion of offshore activities, the presence of scattered explosives and dangerous chemicals poses a potential risk for overall safety at sea. Offshore operations may result in accidental detonation, relocation, retrieval, release of hazardous compounds and environmental contamination or potential resurfacing on beaches.

By design, the CWAs are extremely toxic to humans. CWAs like Sulfur mustard, phosphorous- and arsenic-based compounds were designed to trigger severe biological effects even at very small doses. Munitions containing CWAs might detonate and release their content. Effects can also result from direct or indirect contact with CWAs that were released due to corrosion (e.g. via vapours). Koch (2009) compiled more than 580 CWA related incidents in the Baltic Sea. These particularly involve fishing vessels and offshore personnel, but there are also many documented incidents on beaches.

These and other aspects that determine the risk of warfare materials in the Baltic Sea to humans are discussed in the following sections. These aspects can be grouped according to the groups of people at risk who work or spend time at sea or on beaches.

3.2.1 Fishermen

Fishermen and -women can potentially be exposed to warfare materials in the Baltic Sea. According to numerous reports, Baltic Sea fishermen have been the main group coming into involuntary contact with all types of munitions. Risk levels are site-specific and depend on the type of fishing gear that is used. Bottom trawling is connected to the highest likelihood of both explosives and CWA containers accidently getting caught in fishing nets. The risk is highest when trawling is performed inside or near dumpsites. In this context, the reported practice of en route dumping is of special interest since these scattered warfare materials pose a risk that is very difficult to assess due to the unknown locations outside the assigned dumpsites. While the likelihood of trawling one of these objects outside their designated dumpsite areas is low, any incident might have severe consequences. When salvaged, the explosives may detonate and CWAs may be released, each potentially deadly to the crew. In addition, it renders the catch nonmarketable. For this reason, several areas in the Baltic Sea are marked on the official sea charts discouraging or overall prohibiting fishing activities, anchoring and extracting seabed materials.

HELCOM has tracked the frequency of reported contacts with chemical munitions and CWAs, and it has determined that Sulfur mustard type compounds account for 88% of all reported incidents involving fishermen. The frequency of encounters is likely related to Sulfur mustard's low solubility and the fact that its lumps form hard outer shells of intermediate breakdown products in cold sea water (Greenberg et al. 2016). Most instances of accidental retrieval of CWAs took place in the Bornholm Basin and approximately 200 fishermen have sustained injuries requiring medical attention between 1947 and 1992 (Sanderson et al. 2010). Reported incidents involving CWAs were most frequent throughout the 1980s and peaked in 1990, 1991, and 1992, when 19, 103, and 58 incidents were reported, respectively. With the exception of 2003, when 25 incidents were reported to HELCOM, there has been a notable decline in reported incidents since the early 1990s. The decrease is attributed to the decline of fishing activities in the area off Bornholm and the overall decrease of Baltic Sea fish stocks. The latter led to smaller quotas, fewer fishing hours and to the application of more efficient fishing technologies. Table 4 provides an overview of the number of reported bycatch incidents by fishermen around the island of Bornholm from 2010 until 2021. It is unknown how many cases remain unreported. Additional information on this matter can be found in the HELCOM MUNI report (2013).

Table 4. Number of CWA bycatch incidents by fishermen around Bornholm in the years 2010-2021 (Information received from Royal Danish Navy.)

Year	Incidences of bycatch
2010	• 1x bouncing mine, weight 15 kg • 1x part of KC 250 gas bomb, weight 40 kg • 1x part of KC 250 gas bomb, weight 10 kg (brought to Vestermarie depository)
2011	• 1x part of KC 250 gas bomb, weight 70 – 80 kg • 1x part of KC 250 gas bomb, weight 3 kg (brought to Vestermarie depository)
2012	• 1x part of KC 250 gas bomb, weight 45 kg (front part of bomb)
2013	• 1x part of KC 250 gas bomb, weight 50 kg
2014	No incidents
2015	• 1x part of KC 250 gas bomb, weight 90 kg • 1x part of KC 250 gas bomb, weight 80-100 kg • 1x part of KC 250 gas bomb, weight 85 kg • 1x part of KC 250 gas bomb, weight 100 kg
2016	• 1x part of KC 250 gas bomb, weight 90 kg

	• 1x part of KC 250 gas bomb, weight 40 kg
2017-2021	No cases

3.2.2 Offshore Construction Workers and Nautical Personnel

With the growth in offshore activities an increase in incidents with warfare materials can be expected. Many permanent structures, such as offshore wind farms, subsea cables and pipelines, and a wide variety of temporary facilities are deployed during various offshore operations every year. All operations that involve disturbance of the seafloor may lead to an encounter with warfare materials and to damaging them. Intense disturbances such as pile driving or cable ploughing are commonly considered higher risk activities for causing an accidental detonation than jack-up or anchoring.

In general, activities capable of moving large objects like bombs or lumps of Sulfur mustard will also be sufficient to achieve the spreading of contaminants in solution, as particles or bound-to-sediment particles. When dredging contaminated sediments, these may be re-suspended and the contamination spread. Chemical munitions casings may be disturbed, contributing to greater leakage of agents.

The experiences documented during the construction of the Nord Stream underwater pipeline (which connects Russia and Germany) demonstrated that underwater munitions represent serious obstacles to infrastructure expansion and the energy sector. Furthermore, it has substantiated the claim that chemical munitions are a potential risk to developments in areas outside the limits of dumpsites marked on navigational charts. Overall, the construction of the pipeline required the clearance of over 100 items in Russian, Finnish, Swedish, and German waters (Nord Stream 2011).

Members of crews of commercial enterprises and navies operating underwater face a higher probability of coming into contact with warfare materials. This is specifically true in the vicinity of dumpsites. Poor underwater visibility, the large variety in shapes of warfare materials and the degree of their corrosion and colonization by biota pose a challenge to recognizing the potential danger. Some warfare agents will penetrate through the material of gloves and diving suits and some substances (e.g. thickened Sulfur mustard mixtures), may stick firmly to the surface of objects they come into contact with. In addition, personnel on board are at risk of being exposed to CWAs that could have contaminated underwater robots, tools, diving suites and related gear.

3.2.3 Harbour Staff and Workers

Discoveries of warfare materials were reported in many Baltic Sea harbours. The need for relocation or detonation can severely affect any commercial activity. All harbours that were under attack and extensively used during wartime, and where dumping operations originated (such as in Flensburg or Wolgast), must be considered as potentially contaminated by warfare materials. Discovery of chemical and conventional warfare materials can be expected during any future harbour development projects.

Accidents involving CWAs took place at numerous harbours used in the process of post-war warfare materials dumping. In 1945, two accidents took place on 18 September and 1 October in the port of Flensburg. There is also a report of an accident in Denmark that took place during the unloading of rail cars filled with chemical munitions. It can be assumed that some of the sediments in the harbour are therefore still contaminated.

Historically there have been cases where warfare materials are accidentally transported into harbours by fishing vessels. In April 2011, fishermen unknowingly caught a Sulfur mustard bomb off the coast of Blekinge (Sweden) and transported it back to the harbour at Nogersund. Here it was placed on one of the jetties for emergency personnel to handle it. In December 2005, a trawler retrieved a naval mine and transported it back to Gothenburg. As a consequence, parts of the port had to be shut down.

3.2.4 Recreational Divers

Recreational diving becomes a more and more popular hobby. Increasing availability of cheaper but sophisticated equipment makes this sport safer and more accessible for the population.

Most chemical munitions that were dumped in the Baltic Sea are located well away from the coastline and at depths exceeding 80 m, so they are not easily accessible to recreational divers. However, conventional munitions are randomly scattered along all coastlines and may therefore be encountered accidentally. In soft Baltic Sea sediments, all submerged objects, including warfare materials and wrecks can serve as the constitute hard grounds that are populated by benthic flora and fauna, often causing a locally increased biodiversity (Bałazy et al. 2019). This attracts pelagic and demersal fish, which may in turn attract divers to such areas.

Wrecks in general, including those from WWII, are of special interest to recreational divers. Being an interesting type of submerged objects themselves and combined with higher occurrence of marine fauna, Baltic Sea wrecks are regularly visited by recreational divers and tour operators. Due to multiple risks, ship-wreck exploration is considered to be one of the most extreme forms of recreational diving, in many cases requiring official permits. If the ship was sunk due to military operations during WWII, it is likely that it contains various types of munitions.

3.2.5 Beach Visitors

Since most of the chemical warfare materials dumped in the Baltic Sea were dumped into water depth of at least 80 m, they are relatively inaccessible to beachcombers. However, CWAs that were dumped en route are located closer to shore and at shallower depths. Objects were reported to float and drift before sinking, which further dispersed munitions outside of designated dumpsites. Dumping of conventional warfare materials did not take place as far away from shore and dispersed munitions that originate from combat may be present at any given location along the coast.

Therefore, the most likely scenario of human exposure to warfare materials during leisure or tourist activities involves finding them along shorelines. Young children are the most at risk for accidental exposure, mainly because they are naive to the dangers and likely to pick up something curious or shiny at the beach. Chemical munitions have been washed ashore in numerous sites, including fragmented chemical munitions that have been spotted on beaches in Poland (e.g., Fabisiak et al. 2018). There are also numerous reports of conventional munitions and compounds (both explosive and incendiary) being washed ashore (e.g. Böttcher 2011). Regardless of their type, warfare materials containing an active fuse and explosive material can easily detonate and cause severe damage to health and infrastructure.

Most frequently reported cases of contact and exposure to warfare materials along the Baltic Sea coastlines involve white phosphorous, a pyrophoric substance used in incendiary weapons (see 2.1.1.4). White phosphorus can be mistaken for amber and upon drying it can self-ignite and burns at up to 1,300° C. In the Baltic Sea, cases of people being severely burned occur on a yearly basis, particularly on the German island of Usedom. The high concentration of white phosphorus in this area is related to bombing campaigns against the German rocket testing facility at Peenemünde that took place in 1943 (see 2.4.2). According to HELCOM there are approximately 1.2 to 2.5 tonnes of white phosphorus in the Usedom area. Another troubling area is Liepaja beach in Latvia, as the Soviet Union used a dumpsite roughly 70 km away. Furthermore, cases have been reported, e.g., in Germany and Denmark in which location-markers containing small quantities of phosphorus have washed ashore (HELCOM MUNI 2013).

3.2.6 Seafood Consumers

The highest likelihood of getting into direct contact with chemical and conventional warfare materials in the Baltic Sea is through commercial fishing. Consequently, there is also a risk for any fish netted with the warfare materials to be contaminated with e.g. small lumps of potentially sticky Sulfur mustard. When this occurs, the authorities must be alerted, the fishing gear decontaminated and the whole catch destroyed to minimize the risks for seafood consumers. Various kinds of fish, mussels and crustaceans are consumed worldwide, but little is known whether conventional explosives or CWAs occur in seafood. Likewise, data on body burdens of those compounds occurring in marine biota in laboratory studies are rare. Nevertheless, measurable readings of explosive residues were detected in biota from the vicinity of dumped munitions like naval mines and others that may indicate their entry into the marine food chain. There are no existing quality regulations for TNT and CWA-contaminated food. Thus, safe rates of fish consumption by humans are unknown as of yet, which puts the whole Baltic Sea area fisheries and aquaculture industries at a potential risk.

For example, besides playing a role as the CW dumpsite, the Bornholm Deep offers fishing grounds, as it is also the main spawning area for migrating Eastern stock of Baltic Sea cod, an economically and ecologically important fish population which has previously been heavily harvested (Eero et al. 2015). On the other hand, large numbers of blue mussels, one of the most common seafood species worldwide, are found in shallow-water dumpsite for explosives in the Bay of Kiel. Because of their sessile behaviour, even small amounts of explosive materials near to their habitat could lead to measurable body burdens of those substances. Shell fishermen could harvest contaminated mussels, and both the increasing consumption of harvested wild mussels or aqua cultures established near munitions dumpsites could affect the human seafood consumer worldwide. The situation is similar with fish. The possibility of Sulfur mustard poisoning occurring via seafood consumption is supported by newspaper reports stemming from the late 1940s (June 1948, April 1949). It was reported that some Danish and German seafood consumers had become ill after eating fish caught in the area of the Bornholm dumpsite – cod roe later assessed by medical staff was found to contain Sulfur mustard (HELCOM MUNI 2013). However, the exposure occurred due to mechanical mixture of warfare compounds with fish roe that was consumed. Bottom-dwelling fish chronically exposed to CWAs due to their on-habitat association in vivo in a dumpsite in the Mediterranean Sea off Bari, Italy, have been shown to carry obvious signs of biomarker responses; however, no CWAs were found in the fish flesh and thus any skin diseases, parasite infestation and general low health could be connected to overall environmental stress factors (Della Torre et al. 2013).

Due to the limited number of studies on seafood products contaminated with explosives or CWAs, the current state of knowledge reveals that effects and risks for human seafood consumers cannot be clearly denied or defined at the present time. It is proven that munitions compounds like TNT and its derivatives are known for their mutagenicity and carcinogenicity. The role of TNT in the occurrences of cancer of the urinary tract in exposed humans has been confirmed by experimental evidence and supporting observations (Bolt et al. 2006). However, most of the studies have been carried out with highly exposed persons from munitions factories or military waste disposal units. The assessment of the impact on seafood looks even worse with CWAs because of the limited data.

Based on model results, Sanderson et al. (2009) assessed the maximum recommended monthly amount of fish servings stemming from the primary dumpsites/no-fishing zones in the Bornholm dumpsite to be zero to one. This assessment was based on extreme worst-case assumptions, considering the load of arsenic-containing CWAs dumped in the area, but not specifically addressing all potential transformation or break-down products. Their study concluded that there was a need for further empirical research, especially regarding the speciation of arsenicals in fish and their carcinogenesis as well as the effects of human exposure to CWAs via seafood.

Niemikoski et al. (2017) published the first methodological study that also reported the occurrence of oxidation products of Clark I and/or Clark II found in lobsters (*Nephrops norvegicus*) and a flatfish species collected at Måseskär dumpsite. However, only trace concentrations below the limit of quantification were detected. Already in 2020, Niemikoski et al. (2020a) application of this method has confirmed their ongoing biological uptake in the Baltic Sea ecosystem, as trace concentrations of degradation products of both Clark I and TPA have been detected in cod samples from the Bornholm Basin. Furthermore, Höher et al. (2019) reports that blue mussels (*Mytilus trossulus*) bioaccumulate the oxidized forms of CWAs Clark I and Adamsite.

In two case studies carried out in Kolberger Heide, a known dumpsite for different types of munitions in the Bay of Kiel in the Baltic Sea, blue mussels (*Mytilus spp.*) were deployed selectively at moored mines or loose hexanite lying on the seafloor. Blue mussels are one of the most common seafood species worldwide and because of their sessile behaviour, even small amounts of explosive materials near to their habitat could lead to measurable body burdens of those substances. After approximately three months, in the mussels deployed at the moored mines body burdens of 4-amino-2,6-dinitrotoluene (4-ADNT), a degradation product of TNT, was found up to 10 ng/g mussel-tissue (wet weight) (Appel et al. 2018). In mussels directly deployed at lumps of loose hexanite, 4-ADNT and 2-ADNT plus TNT itself were found in total concentrations summing up to 260 ng/g mussel-tissue (wet weight) (Strehse et al. 2017). The question if seafood from marine sites of dumped World War relics can be eaten was addressed in a review by Maser and Strehse (2021). Mariussen et al. (2018) investigated the uptake of TNT in juvenile Atlantic salmon (*Salmo salar*) and found small quantities of TNT 2-ADNT and 4-ADNT (< 0.05 mg/kg) in the muscle tissues. The applied water concentrations of TNT in this in situ experiment were 1 and 10 µg/l, respectively. Of note, similar concentrations of TNT were measured in free water at the former dumpsite for explosives Kolberger Heide (Beck et al. 2019). Fish specimens are not as sessile as mussels, but the increasing number of fish farms has to be considered. In aquaculture the fish are kept in a relatively small area and might therefore be more affected by dumped munitions in the vicinity compared to wild living fish.

3.3 Potential Risks to Marine Life

Dumped munitions contain various cytotoxic, genotoxic, and carcinogenic chemicals associated with conventional explosives, CWAs, and other compounds, such as heavy metals (Tornero and Hanke 2016; Sanderson et al. 2017, Bełdowski et al. 2019). Release of explosive and chemical compounds in the environment was documented for many sites throughout the world, resulting in the contamination of surface and ground waters, soils, and sediments (Talmage et al. 1999; Bełdowski et al. 2016b; Edwards et al. 2016; Silva and Chock 2016; Jurczak and Fabisiak 2017, Missiaen et al. 2010, Chmielińska et al. 2019; Vanninen et al. 2020). Due to the narrow connection to the North Sea through the Danish Straits and the subsequently limited water exchange, the Baltic Sea acts as a sink for xenobiotics of all kinds, including CWAs and explosives.

The toxic effects of TNT were first noticed after the First World War (Lima et al. 2011; Lotufo 2012). In humans it is mainly absorbed through the skin and reduced in the liver (Johnson et al. 1994; Lima et al. 2011). Depending on the dose, human exposure of TNT can cause serious irritation of the skin and mucous membranes, impaired liver function, red blood cell disorders, aplastic anaemia, skin and hair peeling (Lima et al. 2011), hemotoxic symptoms (Esteve-Nuñez et al. 2001) as well as causing carcinogenic and mutagenic effects (Ahlborg et al. 1988).

The uptake of dissolved TNT by aquatic organisms is likely by diffusion processes from the surrounding water e.g. via gills (Mariussen et al. 2018). Swallowing contaminated food items is another possible pathway, and also swallowing contaminated water in those species which drink.

In the marine environment TNT interacts with sediments and soils, where it was detected in harmful concentrations (Böttcher et al. 2011). Trinitrotoluene and dinitrobenzene were the most abundant munitions compounds, occurring in water at concentrations between 0.1 and 11.8 ng l^{-1} in a dumpsite in the Baltic Sea. In benthic organisms sampled from the same site ten munitions compounds were detected at concentrations up to 24 µg g^{-1} dry weight (Gledhill et al. 2019). TNT and its major metabolites have demonstrated toxic effects on fish and benthic invertebrates (Schuster et al. 2021; Koske et al. 2019; Nipper et al. 2009; Lotufo et al. 2009). Therefore, the presence of those compounds in aquatic systems may pose ecological risks and could represent a significant remediation challenge (Robidoux et al. 2003).

In contrast to explosives, CWAs were invented (and produced) to harm humans in other ways than detonation and there is accordingly no doubt about their toxicity to humans. As for now all tested CWAs are also labelled as very toxic or toxic to the freshwater model organism *Daphnia magna*. Acute toxicity thresholds had been assessed using OECD Test No. 202: *Daphnia sp*. According to those immobilization studies Soman, Tabun, VX (Kalinowski et al. 2013), Lewisite, Adamsite, phenyldichloroarsine (PDCA) and Clark I are very toxic and Sulfur mustard (HD) and TPA are toxic to this model aquatic organism (Czub et al. 2020, Czub et al. 2021). Moreover, two of the Sulfur mustard degradation products: 1,2,5-trithiepane and 1,4,5-oxadithiepane are more toxic than the parent compound (Czub et al. 2020). In more detailed studies, exposure to Clark I (Brzeziński et al. 2020) and 1,4,5-oxadithiepane (Chmielińska et al. 2019) induced multiple negative sublethal effects on *Daphnia magna*. Reported toxicity thresholds of investigated CWAs and their degradation products are lower than some concentrations detected in sediments from the CW dumpsite areas, thus may potentially affect inhabiting benthic or demersal organisms (Czub et al. 2018). However, the general knowledge about toxicity to organisms from marine and brackish water environments such as the Baltic Sea is scarce both for compounds of explosives and CWAs. Multiple biomarker studies indicate that those compounds may impact fish health (Lastumäki et al. 2020; Niemikoski et al. 2021) as well as their gastrointestinal microbiota (Wilczynski et al. 2022).

RDX (Hexogen) exhibits toxicity to biological receptors. It was manufactured in large quantities during WWII. It is carcinogenic, genotoxic and toxic for reproduction. Biological uptake of HMX (Octogen) has been observed, but no toxicity was evident at any of the levels tested (Rosen and Lotufo 2010). Effects of exposure to RDX and HMX in the marine environment are largely unknown. Metallo-organic compounds (e.g. fulminates, azides, and styphnates of mercury, lead, and silver) which were used as initiators for detonation of secondary explosives due to their sensitivity are also found in the marine environment (Beck et al. 2018). Their marine environmental behaviour and fate is very poorly known.

Another serious threat of explosives to the environment is their very high detonation velocity, which produces a shock wave when initiated. The conventional removal by blasting presents a great hazard to the marine environment. Marine mammal and fish species are especially vulnerable to underwater noise (HELCOM 2019). Underwater detonations are the loudest anthropogenic point sources of noise in the Baltic Sea and have the potential to cause serious injuries in marine vertebrates at ranges of several kilometres (Koschinski 2011, von Benda-Beckmann et al. 2015a) and also on invertebrates. By conversion of solid energetic compounds into a much larger volume of gaseous reaction products, any explosion results in a shock wave characterised by a tremendously steep wave front and a very high-pressure maximum called "overpressure" (chapter 3.1.1).

Animals can be seriously injured by the overpressure of the shock wave which is transmitted directly through water-saturated body tissues. Both the extremely short signal rise time and the high peak pressure in the pressure signature of a detonation are related to the extent of injury to marine vertebrates. The shock wave can result in primary blast injury originating from the compression of tissues or organs by the incoming wave front. High-amplitude pressure pulses may cause differential tissue displacement disrupting cells and tissues of different density such as muscle and fat. Especially at the interface with gas-filled cavities capable of compression, molecules are displaced resulting in damage to these tissues. Tissues at these interfaces are torn or shredded by instantaneous compression of the gas. Hence, massive damage can occur in lungs, intestines, sinuses, and ear cavities of vertebrate species (Landsberg 2000). Based on experimental data from terrestrial mammals held under water it is assumed that smaller animals are more vulnerable to shock waves than larger ones (Yelverton et al. 1973; Young 1991).

In addition to the trauma generated by the blasting operations, detonations also increase the concentrations of explosives in the environment. This leads to increases of concentrations of TNT and its metabolites in organisms living close to the now uncontained chunks of explosives (Maser and Strehse 2020).

3.3.1 Marine Mammals

The most obvious threat to marine mammals derives from munitions clearance by detonation. Besides the rupture of tissues in the lungs and ear cavities mentioned above, further types of blast injuries have been described for marine mammals. Most frequently occurring are the fracture or dislocation of ossicles (ear bones) and massive bleeding in acoustic fats of the melon and lower jaw which have an important function in echolocation of toothed whales (Siebert et al. 2022). The compression of the thorax by the shock wave causes rapid increase in blood pressure resulting in the rupture of blood vessels and haemorrhages (e. g. in the brain or ears) (Ketten 1995). The rupture of lung alveoli leads to air embolism inhibiting oxygen supply (Landsberg 2000). Cavitation by the negative pressure occurring shortly after the shock wave may cause gas embolisms through nitrogen bubble formation in the blood and tissues of diving animals such as seals and cetaceans (Lewis 1996).

Information on fatalities of marine mammals are mostly anecdotal because these are considered “accidents” and post-detonation surveys are rare. However, a few documented examples exist. In 2011 a time-delayed underwater detonation resulted in the death of several long-beaked common dolphins as their group entered the impact zone prior to the detonation (Danil & St. Leger 2011). Further, in August 2019, after the detonation of 42 ground mines (with charge weights ranging from 275 to 425 kg) by the Standing NATO Mine Countermeasure Group 1 (SNMCMG1) in the German marine protected area (MPA) “Fehmarn Belt”, a number of dead harbour porpoises washed ashore along the coasts in the area. Ten of the 24 dead porpoises which were investigated had characteristic injuries related to blast trauma. Noise modelling from sound recorders revealed that for the three consecutive days of the operation noise levels in at least 67% of the MPA were high enough to injure harbour porpoises. Acoustic click detector data demonstrated that in fact harbour porpoises were in the area and signals used to deter them obviously did not have the desired effect (DW-Shipconsult 2020, Gallus 2020, Siebert et al. 2020).

Besides direct and immediate mortality by the shock wave, sublethal effects such as hearing impairment (acoustic trauma) can also contribute to overall effects. Depending on the severity of the blast and the distance of the animal from the detonation site, acoustic trauma can either be temporary or permanent. Depending on the charge weight and location of the detonation, harbour porpoises can suffer acoustic trauma at distances much farther than 10 km from the blast (von Benda-Beckmann et al. 2015a). Such sublethal auditory effects can impact the fitness of affected animals as hearing is vital for their ecology and behaviour. This is especially important for small cetaceans such as the harbour porpoise, which rely on this sense for their orientation and prey acquisition. Increased mortality of detonations can be overlooked as e. g. by-catch in set nets or collisions with vessels, due to the animals' inability to echolocate (Siebert et al. 2022).

As top predators, marine mammals may consume also prey contaminated with explosives and their degradation products and metabolites. They are potentially exposed to biomagnification of parent compounds or toxic intermediates. A bioaccumulation of these compounds in top predators cannot be excluded, because the knowledge about the metabolic pathways for common explosives and their metabolites in the bodies of mammals, their retention time in tissues and body fluids, and their way of excretion remains fragmentary. Further, it is well-known that CWAs are toxic and TNT has toxic, mutagenic and carcinogenic effects on humans. Based on the close relation between marine mammals and humans similar sub-lethal effects are most likely.

Any sublethal impact leading to reduced survival, growth, or reproduction can negatively impact populations (National Research Council 2005). Such negative population impact was already predicted using a modelling approach based on harbour porpoise density data from the Netherlands and available information on number, location and charge sizes of all explosive ordnance disposal operations conducted by the Dutch Navy over a one-year period (von Benda-Beckmann et al. 2015a).

3.3.2 Water Birds

Marine ducks such as common eider (*Somateria mollissima*), common scoter, velvet scoter, greater scaup or long-tailed duck (*Clangula hyemalis*) predominantly feed on mussels. It is not known how much TNT and its derivatives from contaminated blue mussels (chapter 3.4.4.) are taken up or further accumulated in water birds. In a feeding study with common pigeons, it was shown that the metabolic intermediates 2-ADNT and 4-ADNT were accumulated in their bodies. Exposed pigeons showed a number of responses including weight loss, neuromuscular effects, and changes in haematological parameters, liver, kidney and ovary weight. It was concluded that subchronic exposure to TNT metabolites can adversely affect the central nervous system and haematological parameters in birds (Johnson et al. 2005). Since marine ducks are long-lived and slow-reproducing species, this may be another pressure to be considered in the context of conservation of these birds.

There is anecdotal information on fatalities of birds caused by underwater explosions. For example, in 2006, 70 western grebes (*Aechmophorus occidentalis*) were killed by six demolition charges of 4.5 to 13.2 kg at 15 m water depth. Necropsied birds showed clear signs of blast injuries. The birds may have been attracted to fish killed or debilitated by explosions and suffered from subsequent detonations (Danil and St. Leger 2011). Since shock waves radiate through water-saturated tissues, even a swimming bird may get seriously harmed by a detonation. Diving birds may be at even greater risk.

3.3.3 Fish

Fishes are an ecologically and economically important component of marine ecosystems and some species represent the top of the marine food chain. Thus, they are particularly vulnerable to the uptake, accumulation and adverse biological effects of leachable toxic chemical constituents of warfare materials, either due to direct exposure or due to biomagnification throughout the food chain. Recently, fish were sampled close to a munitions dumpsite in the Bay of Kiel. The target fish species was the common dab (*Limanda limanda*), a flatfish species that is abundant in the western Baltic Sea, comparably territorial and has been regularly used as a bioindicator in environmental research and monitoring concerning biological effects of anthropogenic contaminants (Lang 2002). Fish collected in the periphery of the Kolberger Heide dumpsite (fishing in the munitions dumpsite is strictly prohibited) by gill net fishing were examined for various diseases. Findings revealed that they were afflicted by neoplastic liver lesions (benign and malignant liver tumours as well as the precursor stages) at a prevalence that exceeded the prevalence detected in fish from reference sites at a level of statistical significance. In chemical analysis, TNT metabolites in the ng/ml range were detected in the same fish specimens sampled close to the dumpsite. In fish from reference sites, metabolites could only be detected at low concentration in a few specimens (Koske et al. 2020). It was furthermore demonstrated that TNT as well as its two main metabolites 2-ADNT and 4-ADNT are genotoxic (Koske et al. 2019). Therefore, a potential risk of TNT for fish health can be assumed. Even if TNT itself has been metabolized, the toxic metabolites are still present in the environment and in the fish. In addition to the main metabolites 2-ADNT and 4-ADNT, more metabolites can be assumed to occur in fish which have so far not been tested for toxicity. Thus, a link between exposure to explosives, uptake of the compounds and development of liver cancer is plausible.

Furthermore, fish and shrimps from dumpsites for CWAs located in the Skagerrak and east of Bornholm were analysed for metabolites of arsenic-containing CWAs such as triphenylarsine and Clark I/II (Niemikoski et al. 2017; Niemikoski et al. 2019, Niemikoski et al. 2020). The detected concentrations were in the lower ng/g range. The toxicity of the mentioned CWA was tested with the standardized OECD *Daphnia magna* immobilisation test, and recorded concentrations did not exceed observed toxicity thresholds (Czub et al. 2020). On the other hand, DPA, a degradation product of Clark I and Clark II, labelled as non-toxic to *Daphnia magna*, was recently reported to induce cytotoxic effects to a rainbow trout liver cell line RTL-W1 (Niemikoski et al. 2021).

In other investigations, cod (*Gadus morhua*) acquired in dumpsites of chemical munitions and CWAs in the Baltic Sea was studied and did not show clear signals of a worse health status when compared to munitions-free reference sites (Lang et al. 2017) – however, no chemical analysis was included in this study. A more recent study included chemical analysis, showing that 14% of the cod collected close to the main CWA dumpsites in the Baltic Sea, the Bornholm Basin, contained CWA-related compounds in their muscle tissues. For these individuals with detected CWA-related compounds the biomarker response was higher than in those with no detections. Atlantic hagfish (*Myxine glutinosa*) showed effects from dumped CWAs in the Skagerrak (Ahvo et al., 2020; Straumer et al., 2020). This suggests that there can be a direct linkage of uptake and exposure to these compounds and biological effects. Importantly, this stresses the fact that the individual fish are not exposed evenly to the CWAs, since the CWAs are widely dispersed, scattered around the sea bottom (Niemikoski et al. 2020).

These investigations are snapshots of the situation and have covered only few fish species and few dumpsites. There is so far no larger-scale systematic chemical investigation of spatial distribution of TNT, other explosives or CWAs and related metabolites in Baltic Sea fish covering further dumpsites and species. However, it cannot be excluded that TNT metabolite concentration in seafood may in some cases reach concentration levels of concern.

Remediation of munitions by detonation also raises serious concerns about shock wave effects on fish and their larvae (Koschinski 2011; Stein 2010), which would directly threaten protected fish species, raise animal welfare concerns and also have economic consequences with respect to commercial species. At close ranges, underwater explosions are lethal to all fish species regardless of size or internal anatomy. At greater distances, species with gas-filled swim bladders suffer higher mortality than those without swim bladders (Yelverton et al. 1975; Young 1991; Lewis 1996). However, due to their bottom contact, flatfish (without swim bladder) might specifically be affected by boundary layer effects from seismic waves preceding the shock wave. Accordingly, fish are hit by two consecutive pressure waves from below and from above leading to differential tissue displacement and injuries associated with overpressure (see above). Retrieving dead fish at a detonation site is a well-known result of shock waves. “Dynamite fishing”, a widely banned fishing technique, has effects that are akin to those of munitions detonation. It is known to effectively kill fish in the vicinity and to create damage to fish habitat such as reefs. In a documented case, only 3% of killed fish floated to the surface (Gitschlag et al. 2000). Besides direct mortality by the shock wave, sublethal effects such as hearing impairment (acoustic trauma) or increased mortality by predation can also occur.

3.3.4 Blue Mussels

Bivalves are filter-feeding organisms filtering many litres of water every day and as a result accumulating chemical substances either as particles or dissolved in water, in their tissues. In contrast, their ability to metabolize organic contaminants is relatively low when compared to other marine organisms. Further, mussels are robust and survive under moderate levels of different pollutions. Moreover, repeated sampling of naturally occurring specimens is possible; they can be used for laboratory exposure experiments and they are suitable to be transplanted to test areas for controlled biomonitoring. Beyond that, many bivalves are an important diet for other marine species such as fish and diving ducks and can be used as indicators for the entry of toxic substances into the food chain (Farrington et al. 1983). Furthermore, blue mussels are grown in aquaculture or targeted by commercial fisheries for human consumption and as livestock feed.

During recent field and lab projects mussels were exposed to arsenic containing warfare agents, such as Clark and Adamsite. The results clearly show that blue mussels from the Baltic Sea take up CWAs in accordance with the provided treatment concentrations (Höher et al. 2019). The exposed mussels showed measurable genotoxic, cytotoxic and immunotoxic effects even at low exposure concentrations (Höher et al. 2019).

In addition, mussels were exposed to TNT and its derivatives 2- and 4-ADNT, both in the field and under lab conditions. All experiments showed that mussels are able to take up TNT and derivatives in accordance to the exposure concentrations (Schuster et al. 2021; Strehse et al. 2017). Mussels exposed to higher concentration of dissolved TNT in the lab immediately close their shells to protect themselves from the toxic environment. Overall, lab exposure experiments revealed that “no-effect” concentrations seem to be rather low, since the lowest exposure concentrations used in the experiments resulted in negative biomarker responses

(Schuster et al. 2021). Further, in field exposure studies tissue concentrations in mussels reached alarmingly high values when mussels were placed in close vicinity of openly exposed TNT lumps, excluding them e.g. from human consumption (Strehse et al. 2017). Moreover, the mussels themselves showed symptoms of oxidative stress upon establishing the gene coding for carbonyl reductase as a new and promising molecular biomarker for TNT exposure (Strehse et al. 2020).

3.3.5 Other Marine Life

Measurable readings of explosive residues were detected in biota from the vicinity of the dumped warfare materials that may indicate their entry into the marine food chain. For example, Gledhill et al. (2019) found several kinds of explosives in marine biota like algae and starfish which were collected at Kolberger Heide. They found body burdens in starfish of HMX, RDX, TNT and ten other explosives with highest measured concentrations up to nearly 25 mg/g.

In addition, explosives like TNT, 1,3,5-trinitrobenzene and 4-nitrotoluene were detected in feather duster worms, corals and long-spined sea urchins in the area of Isla de Vieques, Puerto Rico (Barton et al. 2004). Ballentine et al. (2015) showed in a laboratory exposure study that different marine species, such as the algae bladderwrack and sea lettuce, Asian shore crab and common periwinkle (a marine snail), are able to uptake, transform and accumulate TNT and RDX in their tissues.

Despite this research, only little is known about the effects of chemicals released from munitions on marine biota. Rosen and Lotufo (2010) investigated lethal and sublethal toxicity effects as well as bioaccumulation of TNT and RDX in e.g. two amphipod species (*Eohaustorius estuaries* and *Leptocheirus plumulosus*), and in the polychaete *Neanthes arenaceodentata*. In another lab study, algae, polychaetes and sea urchins were exposed to different types of explosives like RDX, Tetryl and TNT. For the mentioned species LOEC (Lowest Observed Effect Concentration) were calculated. LOEC is the concentration at which the first effects on a species become visible or measurable like changes in behaviour, spawning activity or food intake. For instance, with regard to Tetryl and TNT, LOECs for all tested species were determined between 0.13 - 1 mg/L and 0.18 - 103 mg/L, respectively (Nipper et al. 2001).

Remediation by detonation poses a threat also to marine invertebrates. Shock waves can be deleterious for marine invertebrates even if they do not have gas-filled cavities in their bodies. Even small explosives have the potential to kill all kinds of invertebrates (e.g., Metillo et al. 2016). However, knowledge about the mechanisms involved and the size of effect zones for invertebrates is scarce. Some information can be extrapolated from known effects on different life stages of marine invertebrates by other high-intensity acoustic pulses (e.g., seismic impulses which usually contain less energy and have a less pronounced signal rise time compared to underwater explosions of warfare materials).

Due to the lack of systematic studies other studies must be used as proxies to explain possible mechanisms of injuries caused by shock waves. Circumstantial evidence suggests that high-intensity acoustic pulses such as the ones produced during seismic surveys represent a threat to squid species (Guerra et al. 2011). Shock wave injury in squid resulting from underwater explosions is thus also likely. Increased mortality and ultrastructural damage in hair cells, both associated with impulsive noise from seismic surveys, was observed in cephalopods off the

Spanish coast. Controlled sound exposure experiments in the laboratory revealed that exposure to low-frequency sounds can result in permanent and substantial alterations of the sensory hair cells of the statocysts, which are the structures responsible for the animals' sense of balance and position. Such massive acoustic trauma is life threatening (André et al. 2011; Solé et al. 2013a, b).

Malformations and delay in development of marine invertebrate larvae have been observed as effect of high-intensity impulsive noise – such as in scallop larvae exposed to playbacks of seismic impulses (Aguilar de Soto et al. 2013). Since explosions also produce high intensity acoustic pulses, occurrence of such types of injuries after the detonation of warfare materials can be inferred from this information. In sensitive areas such as recruitment sites these effects may have serious implications for the viability of a population. In the case of commercial species this would furthermore have economic implications.

4. Warfare Materials – Methods for Detection and Management

4.1 Historic Reconstruction

All military decisions and circumstances were documented in different forms. Archives, especially military archives, store these documents. It is highly important to research and check relevant documents, and information generated during historical reconstruction is relevant for the determination of subsequent measures. Due to the large amount of preserved orders, reports, diaries, logs and other documents, military archives are extremely valuable. The challenge, however, is to be able to find and identify the relevant documents for the research scope.

<u>Sources</u>

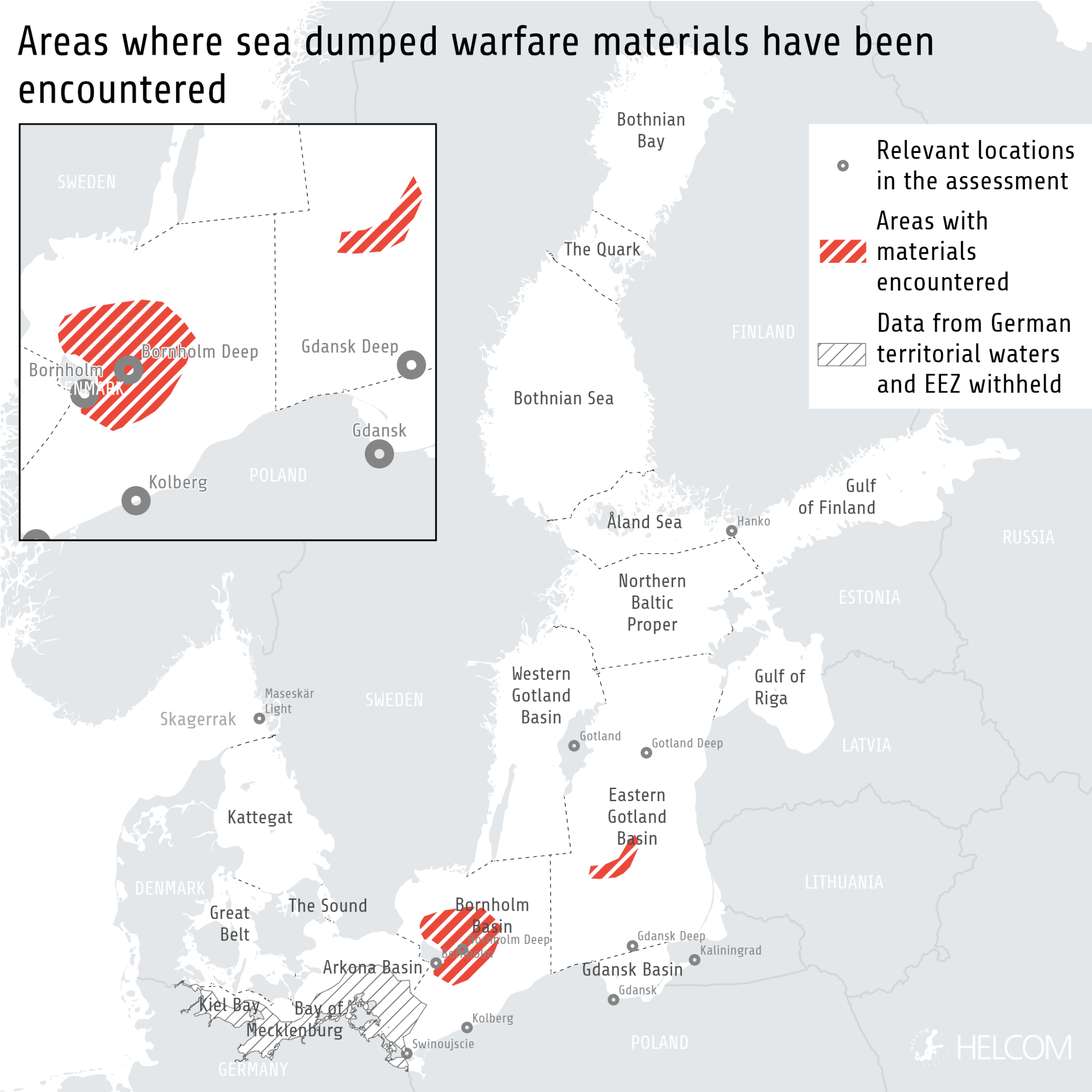
The military archives of Germany and the UK both contain a massive stock of documents. German military documents were captured during the final weeks of World War II or after the war and were brought to the UK and USA for evaluation. Most were later given back to Germany and they are now stored in the military archive in Freiburg. Around 51 km of files are currently stored, and the archive is a source of paramount importance for historic reconstruction. The database is however not complete: some gaps in the special operations section indicate that some files were lost.

The UK National Archive in Kew holds a significantly larger volume of documents than the German archive. The quality of the files is similar to that in Germany and is complemented with files of the naval historical branch and the UK Royal Air Force (RAF). It is therefore possible to generate an excellent historical reconstruction.

<u>Methodologies</u>

The first step of historical reconstruction is scoping and the definition of research boundaries regarding a specific operation, a geographic area or a timeframe. Furthermore, the affected components are determined. The archival research is initiated with basic data and information. In the research process war logs of the involved units, diaries of members of staff and of higher commanders are investigated. All influencing factors, such as weather conditions, enemy threat, navigation and morale of the crew and commanding officers constitute important inputs. Collecting complementary information from the opposing warring faction leads from a one-sided representation to the development of a complete picture.

A very good example are the minelaying activities conducted by the RAF in February 1944. The account was completed by examining the war log of the air defence area Kiel, the war logs of the minesweepers in the Bay of Kiel, the mine laying operations maps produced by the RAF and the summery report of the Royal Navy.



4.2 Quality Management in Offshore EOD

If activities surrounding the detection and clearance of warfare materials are executed erroneously, managed poorly or even overall omitted, warfare materials threaten the lives of construction workers (see 3.2.2), the construction schedule, marine fauna (see 3.4.1) and the public image of the involved parties. However, it is challenging to maintain consistently high-quality EOD operations in the offshore environment for a number of reasons:

- Private businesses perform EOD or parts thereof in some countries. Entry barriers into the attractive market are low, leading to cost pressure.
- Geographic legal areas are manifold and oftentimes not rigorously regulated.
- No guideline for the validation for the appropriateness of applied technologies or for the qualification of appointed personnel exists.

The successive increase in knowledge about the potential impacts of the warfare materials legacy has led to an urge to address the problem on a strategic level. The Quality Guideline for Explosive Ordnance Disposal was developed to tackle the above challenges. This quality guideline is posed to serve as a normative reference framework for all stakeholders involved in warfare materials operations (Frey 2020).

Some aspects of offshore warfare materials removal are covered in normative or other guiding documents. The most extensive document is an account on assessing and managing warfare materials risk published by British construction industry and research association CIRIA. This document focuses on the assessment of probabilities and consequences of warfare materials encounter and proposes management options (Cooper & Cooke 2015). A technical work aid (Baufachliche Richtlinien Kampfmittelräumung) available in German details the procedure of warfare materials treatment onshore. Notwithstanding its limited transferability to the offshore domain, it has been utilized during offshore warfare materials campaigns in the past (AK AH KMR 2018). Other aspects relevant to offshore warfare materials clearance, such as diving, hydroacoustic measurements and piloting of ROVs, have been addressed in other documents published by certification organizations and international governmental organisations (e.g. Hagenah & Klaproth 2016; IHO 2005; IMCA 2016).

4.3 Modes of Detection

To perform mitigative actions it is first necessary to detect warfare materials. For this task, numerous technologies are available. These comprise geophysical, hydroacoustic, optical and chemical analysis methods as well as the use of biomarkers and bioindicators. However, only geophysical and hydroacoustic technologies are considered best available technologies for commercial use (Winkelmann 2014; Frey et al. 2019).

The detection of warfare materials mainly concerns the thorough investigation of the seabed and the demersal zone, which is the water column near to the seabed. The available methods are utilized accordingly. Warfare materials can either be present on the seabed or buried in the sediment. The bedrock is the lower limit for the presence of warfare materials as they do not penetrate into solid rock. Some warfare materials such as moored mines were designed to float in the water column when active. However, the moored mines that are present now, are a legacy of past wars. They are therefore not floating, but have either sunk to the seabed or were cleared in post-war efforts.

The detection of warfare materials in the sea is challenging for a number of reasons. The challenges differ, depending on the scale of the area that is subject to the investigation. The sheer size of 377,000 km² makes it economically infeasible to conduct a holistic detection campaign of the entire Baltic Sea (SERDP and ESTCP 2007). This is a consequence of the technological limits of the available technologies, which are laid out in further detail in the following subchapters. Similarly, endeavours to perform full area detection of warfare materials of a single nation's territorial waters or EEZ are not considered reasonable. At this point, no full area detection campaign that would fulfil the requirements of warfare materials detection has been conducted. Consequently, no planning of large-scale preventive action on a strategic level has been possible. Even if such campaigns would be conducted, the potential mobility of warfare materials would contribute to gradually rendering the acquired data outdated before further measures could be conducted on a larger area. Due to the comparatively low sedimentation in the Baltic Sea, this challenge may be secondary, especially for smaller countries. Nonetheless, it is recommended to limit the magnitude of every investigated area to a manageable size and to ensure maintaining a small time-gap between detection campaigns and subsequent management options.

As a result of the infeasibility of a global detection campaign, efforts for the location of warfare materials are most commonly conducted as part of offshore economic development endeavours or scientific projects. Depending on the aim of the detection campaign, either one or two steps are performed. If a general overview of an areas is required, conducting a full technical survey of this area is sufficient. Previously gathered historic evidence will allow for an interpretation of the data, roughly indicating which type of warfare materials were detected. The result of this step is a list of points, referred to as a target list, where warfare materials are suspected to be present. However, at this point in the process the amount of information for each object will be limited. No single technology that is currently available can doubtlessly discriminate warfare materials from false alarms originating from scrap metal or other anomalies. If the acquisition of detailed knowledge on individual items is the aim of the detection, a second step is therefore performed. Every point of the target list is individually addressed and scrutinized with the aim of confirming or refuting the target point suspicion. Subsequently, detailed information about the item is gathered and documented.

The following chapters focus on one of the available technology groups each. They describe those that are considered best available technologies and those that have successfully generated results during the execution of economic or scientific projects. Each chapter briefly introduces the mode of operation of the respective method, its area of application and its limitations.

4.3.1 Geophysical Methods

Geophysical surveying methods measure different properties of surface and subsurface materials and are capable of detecting changes in these properties. Some geophysical methods are called passive methods because they measure naturally occurring fields or properties of the earth and spatial variations in this field or property. Active methods, on the other hand, require the introduction of energy into the earth, thereby triggering a response that can be measured. The property measured by a passive method exists regardless of the conducted survey, while the property measured by an active method only exists because of the signal that was introduced. A multitude of geophysical methods exist. They include seismics, radioactivity, gravity and many other methods. The two geophysical methods that have been proven to be suitable for the detection of warfare materials in the sea are magnetic and electromagnetic methods, both of which are introduced in the following chapters. (Butler et al. 1998)

4.3.1.1 Magnetic Methods

Magnetic methods are potential field methods. This means that they exploit the existence of a pre-existing field, which in this case is the earth's magnetic field. They detect anomalies in the earth's magnetic field that are caused by the presence of magnetic objects and materials in the sensor's vicinity. Anomalies actually consist of a dipole; a negative north pole and a positive south pole (Reynolds 2011). Since magnetic sensors measure anomalies in an existing magnetic field without inducing energy to produce a local magnetic field, they belong to the group of passive sensors. The magnetic anomalies caused by warfare materials are solely attributed to its magnetic components and not to any other material such as the explosives it contains. The total field amplitude of the magnetic anomaly depends on numerous variables such as the ferrous mass of an object, a parameter that is different for every type of warfare material. Other parameters influencing the amplitude are an object's degree of corrosion, its orientation in relation to the earth's magnetic field (Butler et al. 1998) and even the type of steel that was used for its construction.

The quality of the performance of a magnetometer depends on its ability to detect the magnetic field anomaly and measure the strength of the total field amplitude. In addition to the above factors, which are out of the control of the surveyor, this ability is determined by the controllable distance between the sensor and the object that causes the anomaly (Winkelmann 2014). Due to the complex dependencies of the multiple parameters laid out above, it is important to note that a precise universal value indication for the measuring range of a particular sensor for a specific object is not possible (Winkelmann and Fischer 2009). Consequently, magnetometers need to be deployed close to the seabed. They are mostly applied on systems that are towed by a survey vessel at a height of no more than 3 m above the seabed. Towing the sensor also allows for the necessary establishment of a large enough distance to the ship, which contains large amounts of magnetic material and is therefore a source of magnetic noise (Dimitru et al. 2017). Using an array of multiple sensors allows for the coverage of a larger area with each crossing (Chabert w.Y.). Finally, towing the sensor with a survey vessel allows for higher surveying speed when compared to the use of an ROV. Still, magnetometers may also be deployed with ROVs or autonomous underwater vehicles (AUVs). Magnetometers' ability to detect anomalies in water and sediment alike makes their use feasible for the detection of buried objects (Böttcher et al. 2011). If applied correctly, magnetic sensors therefore provide a surveyor with the ability to detect the largest part of warfare materials that may be present on top or buried in the seabed and that poses a threat to offshore construction projects. Their larger measuring range is their biggest advantage over electromagnetic systems (Ruffel et al. 2017). In contrast to hydroacoustic systems, they allow for the detection of objects buried in the sediment over large areas. Consequently, magnetometers are considered a best available technology for the full technical survey of an area, which should however be supported by an SSS survey. Furthermore, they may be used during relocation of objects during target point investigation. (Frey et al. 2019)

For smaller magnetic objects there is, however, a lower detection range. These cause a magnetic field anomaly that is too small to be detectable due to the inevitable distance between the object and the sensor. The main development gap here lies in the availability of platforms that can be deployed closer to the seabed. While ROVs may allow for the required application closer to the seabed, towed systems do not, especially in areas of high bathymetric variability. An exception are AUV-towed magnetometers, which can be lowered closer to the seabed and follow it more closely. However, existing AUV-towed magnetometer sensors are small, and usually limited to single detector. A further developmental need lies in the reduction of noise (SERDP and ESTCP 2007). Another limitation of magnetic methods is the physical nature of magnetic anomalies. Not only warfare materials create anomalies in the earth's magnetic field, but also other magnetic objects of anthropogenic and even those of natural origin. The signatures of these different types objects are often not distinguishable. Accordingly, targets detected by a magnetic sensor may be any of these object types. Data from additional sensors is required to enable further discrimination (Chabert, w.Y.). The uncertainty connected to the source of the magnetic anomaly remains high unless a detailed assessment of these target points is performed (Fauser et al. 2018). The susceptibility to the magnetic signature regardless of the cause leads to an additional challenge: if areas of the seabed are covered with or contain a high amount of ferrous material, it is not possible to identify single anomalies that may lie beneath, above or enclosed in this material. The same is true for the detection of warfare materials beneath structures like cables and pipelines or in the close vicinity of other buildings like wind farms or any structures comprising of reinforced concrete. (BFR KMR 2018) In summary, the feasibility of magnetometers depends on the degree of natural geologic magnetization or magnetization caused by anthropogenic objects such as scrap or infrastructure. Finally, magnetometers do not enable the detection of warfare materials that do not contain any or very low levels of ferrous metals, such as LMB mines (Lauritzen 2013) or lumps of explosive material or other compounds that are not encased due to a release from their container (Frey et al. 2019).

4.3.1.2 Electromagnetic Methods

Electromagnetic (EM) methods induce an electromagnetic field which is produced by a coil. If this induced electromagnetic field meets an object that is made of a conductive material electric currents are in turn induced. These currents cause the development of a secondary field which is measured by the electromagnetic sensor. Due to the induction of energy for the purpose of detecting objects, EM sensors belong to the group of active methods (AK AH KMR 2018). The secondary field is a consequence of the presence of conductive material, usually metal, which is a common component of warfare materials. Accordingly, there is an overlap between the types of materials that magnetic and EM systems can detect. The strength of the secondary field depends on the amount of conductive material contained in the object (AK AH KMR 2018).

Performance of EM systems depends on their ability to detect the secondary field. It is a main influencing parameter for the measuring range which is smaller than that of magnetic sensors. In consequence, EM sensors have to be applied very closely above the seabed. The electromagnetic field is produced only under the coil, which has the advantage that conductive materials that are situated to the side of the coil, such as buildings, do not constitute an impediment (AK AH KMR 2018). However, it does also mean that the measured area is limited to the size of the coil (Hollyer et al. 2008). Due to the limited range both vertically and horizontally, EM systems are commonly used for the investigation of smaller areas such as suspected points on a target list. Towing EM systems up to 3 m above the seabed would not lead to any meaningful results. They may therefore be deployed with ROVs. While their ability to detect buried objects is lower than that of magnetometers, it still constitutes an advantage over hydroacoustic systems. A large advantage over magnetic sensors is the EM systems' ability to detect non-ferrous metals such as LMB mines (Chabert w.Y.). An additional field of application are areas with high geologic magnetization originating from non-ferrous materials. As electro-magnetometers are not susceptible to these magnetic anomalies, they may be applied for the detection of unburied or near-surface warfare materials (Frey et al. 2019). EM systems can therefore also be used to discriminate geogenic magnetic non-metallic anomalies that were detected with a magnetic sensor in a previous survey.

While natural magnetic anomalies are not detected by EM systems, anthropogenic scrap metal will be detected nonetheless. The data obtained from detecting scrap or warfare materials may be very similar, which is especially true for scrap that resembles warfare materials in shape and size. As a consequence, the discrimination between these objects is very challenging (SERDP and ESTCP 2007). Another limitation similar to magnetic systems is that they cannot detect loose lumps of explosives due to the absence of metal (Frey et al. 2019). The conductivity of salt water leads to an overall increase in the noise level during measurements. However, it has been shown that the conductivity's effect on target classification is limited (Bell et al. 2018).

4.3.2 Hydroacoustic Methods

Hydroacoustic methods are the most commonly used technology for the investigation of the seabed and objects on the seafloor. They transmit acoustic signals and measure the time and/or amplitude of the signal on its return. Properties of the reflecting surface, such as its material and structure or inclusion of air or any gas have an effect on the signal backscatter (Böttcher et al. 2011; IHO 2005; Lurton et al. 2015). Different types of hydroacoustic methods may be used during the detection of warfare material. These include side-scan sonars (SSS), synthetic aperture sonars (SAS), multibeam echosounders (MBES) and sub-bottom profilers (SBP), all of which are sonar technologies.

Understanding differences in acoustic response between warfare materials and the surrounding environment is an important quality driver for the successful application of all types of sonars (SERDP & ESTCP 2007). Another very important quality parameter of hydroacoustic datasets is their spatial resolution (IHO 2008), which in turn depends, among other parameters, on the height of the sensor above the seabed, the acoustic frequency, the band width available for signal processing and the beam width of the transmitted signal. It determines whether an object is actually visible on a sonar image. Simplified, the higher the acoustic frequency and the shorter the pulse length, the higher the spatial resolution, but the lower the range of the signal (Frey et al. 2019).

4.3.2.1 Side-Scan Sonar

A Side Scan Sonar consists of a line antenna (a number of acoustic transducers) mounted on either side of a tow fish or an AUV. The longer the antennae, the narrower is the cone shaped beam that is formed. This determines the system's along-track resolution. In very sophisticated multi-beam systems this results in an along-track resolution of about a few decimetres. The range in this case will be less than 100 m (roughly 200 m total swath width, i.e. the combined range on both sides), with the range resolution about 10 mm. The resulting spatial resolution is sufficient to detect a large percentage of warfare material.

The altitude of the tow fish above the seabed has significant influence on the range of the SSS. This quite often causes problems with limited range in very shallow waters like in the German Baltic coastal waters. It is furthermore possible to derive the precision of positioning of detected objects, which depends on the accuracy of the GPS and USBL navigation used, as well as the position of the tow fish, which is determined by speed, cable length and the fish's hydrodynamics. A weakness of SSS is the nadir gap, since the antennae cannot transmit sound underneath the tow fish or AUV. Depending on the altitude a gap of up to a few meters may result. This gap can be covered by a neighbouring line when appropriate smaller line spacing is selected, but this will result in a smaller search area per time unit. Some products integrate an additional nadir gap filler sonar, a downward pointing scanning sonar.

For the detection of warfare materials that are located on the seabed, the use of SSS has numerous advantages over magnetometers and EM-systems. One of them is their longer range (seafloor coverage), which is limited by requirements for spatial resolution, however. The resolution should be at least half of the shortest dimension of the warfare materials that are expected to be detected. SSS offers another advantage in that their measurements are not impaired by the presence of geologic magnetic anomalies and their detection capabilities are independent of the warfare material's ability to cause magnetic anomalies or to induce a secondary magnetic field. Therefore, both LMB mines and loose lumps of explosive material or other warfare agents are generally detectable. However, due to their indistinct shape, chunks of compounds remain difficult to spot. Furthermore, SSS allows for the detection of objects that are located in close vicinity or above buried infrastructure (Frey et al. 2019). SSS are typically used as towed systems in relatively close vicinity to the seabed, as this allows for the use of high frequencies which have low range but high resolution (Bjørnø 2013). This provides the ability to detect the majority of objects that differ in structure from the surrounding sediment material that may be present at the seabed and that may pose a threat to offshore construction projects. As an auxiliary means to support the full area magnetic survey, SSS is therefore considered best available technology. Its data also allows for the discrimination of objects that are false positives in the magnetometer data (Winkelmann 2014), albeit this is only possible in areas where no or very little burial of warfare materials takes place. AUV-mounted SSS has been utilized for the identification of chemical warfare materials hotspots in both the Bornholm and the Gotland Deep, by analysing its spatial distribution. The acquired data was deemed of high quality, highlighting its high resolution, enhancing the ability to classify objects as chemical warfare materials (Majcher et al. 2017).

The most apparent limitation of SSS is their inability to detect objects that are fully buried in the sediment. Accordingly, SSS are mainly useful in areas of low sediment thickness. In addition, the presence of other types of coverage such as coral or plants makes detection efforts very challenging (Schwartz and Brandenburg 2009). In addition, even for unburied and half-buried objects, shortcomings exist. Even though all these objects are visible in the sonar image, it is very challenging to distinguish between warfare materials and other objects, both natural and anthropogenic (Böttcher et al. 2011). This becomes especially evident in areas with a high density of rubble and debris, which may have a shape similar to larger warfare materials such as ground mines (Frey et al. 2019). The same is true for the detection of small warfare materials of a few cm in size when present on gravel (Marine Estate and Mineral Products Association 2010).

4.3.2.2 Synthetic Aperture Sonar

As shown above, in an SSS the antenna length determines the beam width and thereby the along-track resolution, which is at least more than an order of magnitude lower than the range resolution. A tow fish antenna cannot be sufficiently long to increase the along-track resolution to a satisfactory level.

A solution for this challenge was to apply the principle of airborne Synthetic Aperture Radar (SAS) (Skolnik 1980) to sonar technology. Successful SAS imaging requires several challenges to be overcome. The sonar position accuracy must be higher than a fraction of a wavelength along the entire synthetic aperture. At e.g.100 kHz this is an accuracy required of around 1 mm along tens of metres of travelled distance. SAS uses algorithms to interpret measured data of consecutive transmissions and returns as if they would have been generated by a transducer that is multiple times larger than the physical one.

Since the aperture (i.e. beam width) is linear to the antenna length, the result is a spatial resolution of around 30 x 30 mm. Because of the precision requirement mentioned above, the position needs to be determined within millimetre-range. The development of SAS is therefore closely linked to the development of precisely positioned AUVs. This requirement cannot be fulfilled when using a tow fish because of the mechanical influence onto the tow cable and the tow fish. A positive side effect of the SAS signal (post-)processing is that along-track resolution is constant over range whereas with SSS it decreases with range.

There are numerous challenges, however. When operating an SAS (or any sonar) environmental influence (season, weather, etc.) can lead to quite diverse results, even for repeated surveys within the same area. Furthermore, using SAS also leads to a nadir gap. An MBES may be used as a nadir gap filler, which will, however, produce lower spatial resolution data than the SAS.

4.3.2.3 Multibeam Echosounders

A Multibeam Echosounder (MBES) uses a transducer to transmit a number of beams which insonifies a wide angle of seabed across-track with a single ping (typically 10° to 150° swath, the resulting footprint depends on water depth) and a very narrow sector along-track (between 0.2° to 5°, depending mainly on frequency and antenna length). The receiving phased array (a receiver which electronically steers its receiving direction) disaggregates the returned signal into multiple beams (typically either 256, 512 or 1024 of them), giving the technology its name.

Due to beam steering the beam footprint increases for the outer beams. To avoid this issue an equidistant mode can be chosen for acquisition: beam angles vary across the swath, but beam distances on the seafloor are the same; compared to equiangular mode beam angles are the same across the swath; footprints differ from nadir to outer swath. In equidistant mode, beam resolution can be lower than nadir resolution in equiangular mode. Choosing the best suitable method depends on survey parameters, such as minimum object size, profile spacing, survey time, etc.

MBES can be either installed on a vessel (hull mounted, in a moonpool or on a pole) or mounted on an AUV. In either case, the position and orientation of the antennae with reference to the motion reference unit (measuring roll, pitch and heave) and the position unit must be determined with utmost precision. It is impossible to use a MBES without those external reference systems.

Advantages are similar to that of SSS as this method allows for detection of objects present on the seafloor surface, independent from the object's and its surroundings' magnetic and electromagnetic properties (Frey et al. 2019; Kampmeier et al. 2020). If mounted on the ship's hull, MBES does not suffer from the positioning challenges of towed systems or other platforms and provides overall improved positing data of target locations. It may therefore be applied in monitoring programs of known dumping grounds (Kunde et al. 2018; Kampmeier et al. 2020). Its dependency on the distance between the ship's hull – and therefore the sensor – and the seabed results in limitations for the spatial resolution. In waters deeper than 25 m, it is therefore regarded as a support system for general information. Suspicious areas can then be repeatedly mapped with higher resolution and additional sensors (Frey et al. 2019). In parallel to the bathymetry, MBES can record backscatter snippets and water column data. Backscatter snippets give additional SSS-like information about seafloor properties and water column data and might enhance imaging munitions on the seafloor. Multibeam data includes bathymetry, acoustic backscatter and water column data.

4.3.2.4 Sub-bottom Profiler

Sub-bottom profilers (SBP) are used to acoustically image the seafloor and subseafloor. Their relatively low frequencies (roughly between 2 and 40 kHz) allow them to penetrate the sediment. The main types of sub-bottom profilers include conventional echosounder (pinger), chirp and parametric echosounder (PES). They can be installed on the ship's hull, towed behind the ship or attached to the side of the ship. Pingers emit a very short, single high frequency pulse, whereas chirps emit a pulse which varies its amplitude and frequency over time (a so-called frequency-modulated sweep) which allows optimal extraction of information from the bottom sediment. The PES, however, emits two very high frequency wavelets (around 100 kHz), whose interaction generates by nonlinear interference a new secondary signal with the resulting difference frequency (roughly between 6 and 12 kHz). This secondary signal is ideal for the detection of (small) objects buried below the seabed.

The PES can be operated from very small vessels. The transducer is normally attached to the side of the ship, and only a signal recording unit and a precise positioning system is needed on board. The generated secondary signal has a short signal length (0.07 – 1 m/s), with a small beam width (±1.5 and ±2.5° depending on the transducer arrangement) and virtually no side lobes during transmission. Penetration depth will highly depend on the bottom sediments (for soft, muddy sediments penetration can be up to 50 m). The system has a high vertical resolution of 10-15 cm, and a horizontal resolution of 5-25 cm (depending on the mode and speed). Thanks to the short pulse length it is suitable for very shallow water environments. Additionally, the narrow footprint of parametric systems also decreases the occurrence of diffraction hyperbolae from small objects (Schneider von Deimling et al. 2016). Contrary to pingers, the full waveform is recorded which allows to detect phase inversions.

The resolution of the parametric echosounder allows the detection of small objects on the seabed, partially exposed, or buried within the sediments. It provides accurate information about the depth (top) of the object, but its exact size and orientation are difficult to deduce. Moreover, due to the narrow beam width any objects that lie outside the survey path will often remain undetected (Missiaen and Feller 2008). Therefore, recently a novel approach was developed using a multi-transducer parametric echosounder system (SES-2000 Quattro). This system consists of four individual transducers in a line array which allows 3D imaging of the sub-bottom with very high data density. The simple acquisition makes this system particularly fit for rapid, cost-efficient site surveys (Missiaen et al. 2017). The small transducer spacing (25 cm) provides ultra-high resolutions (bin size 20x20x1cm or smaller), but limits the maximum water depth to 12-15 m (due to beam overlap) and requires precise ship navigation. An additional advantage is the flexible configuration of the individual transducers, which also allows for a 2D single beam set-up (e.g. 4 transducers configured into a quadrangle and acting as a single transducer), resulting in higher energy and deeper penetration, or a pseudo-3D dual beam set-up (2 transducers combined as a single transducer), which will also increase the energy level and has an intermediate data density (max. water depth ~20 m).

Whereas (electro)magnetic methods allow to detect buried ferrous objects, they do not allow for a specific object signature since most of the dimensional results are empiric and model-based (e.g. iron mass and depth). The multi-transducer PES is able to pinpoint the exact burial depth of the object and allows a better dimension estimation (Figure 21B). Moreover, it can discriminate an object individually, ruling out the most common ambiguities (e.g. a big object with a high (magnetic) signature or a group of objects that together have a high (magnetic) signature). Since it is possible to generate 3D imaging from dense coverage 2D profiles, this will facilitate the interpretation of the object dimensions.

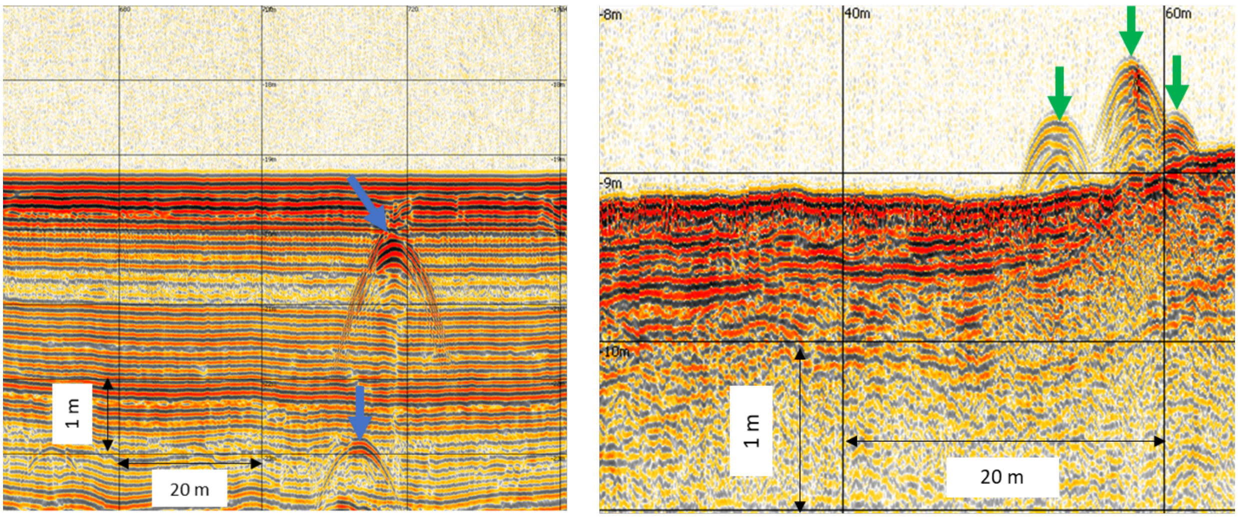


Figure 21A. Left. 2D PES profile showing two objects buried 1 m and 2 m below the seabed (blue arrows). **Right.** 2D PES profile showing objects exposed on the seabed (green arrows). (© VLIZ)

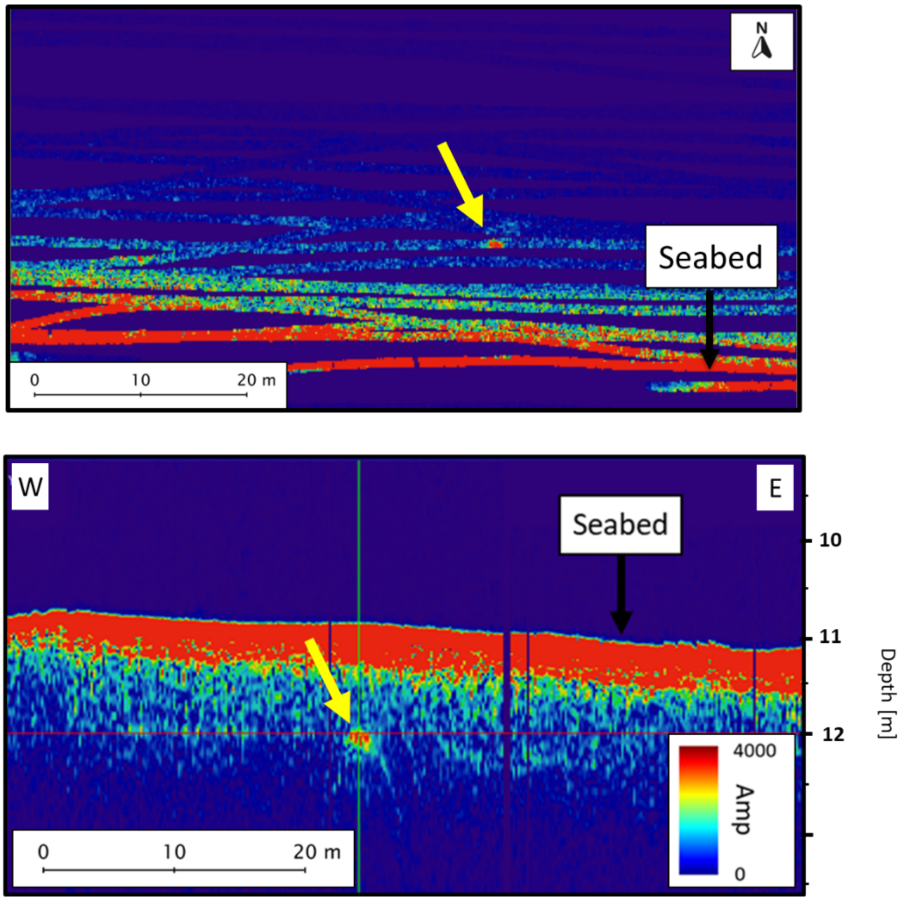


Figure 21B. Top. horizontal cross-section through a 3D PES data volume. Bottom: vertical cross-section through the same volume. The yellow arrow indicates the same buried munitions object. (© VLIZ)

The PES can also provide valuable information on the sedimentary background of the site and may help to distinguish between different materials of the buried objects. However, its small beam width makes searching for objects rather time-consuming (especially during the interpretation), and penetration in gas-rich or hard sandy layers is not optimal. Moreover, the applicability of the multi-transducer PES system is limited by the required ultra-high positioning accuracy (which will highly depend on weather conditions (waves) and vessel and wind speed), the limited area of coverage (on average 250 x 250 m) and the limited water depth.

4.3.3 Optical Methods

Optical underwater sensing methods are usually based on visible light, i.e. electromagnetic radiation with wavelengths in the range of about 400nm to 700nm. In clear and shallow water passive visual sensing can be applied by using cameras mounted to AUVs, ROVs, towed platforms or by divers. In deeper waters (certainly for more than a few tens of meters), or in case the composition of the water limits the sunlight illumination of the seafloor, the capture systems must be equipped also with active illumination. The seafloor is then photographed from a certain distance and characteristics can be observed, including objects on the seafloor, those sticking out of the seafloor, and seafloor deformations. Either single photos are captured for later analysis, or as recently done, systematic mapping campaigns are accomplished for larger areas. In such visual mapping campaigns, subsequent photos (or videos) of the seafloor are arranged in a way that they show significant overlap (e.g. 80%), such that each photo can be registered with the previous/next image. The footprint of a single photo covers only a few square meters, meaning that a single tow or transect will only map a narrow seafloor corridor. Larger areas are therefore typically scanned in a “lawnmower fashion” going back and forth while making sure that the footprint of neighbouring tracks overlaps (e.g. by 50%), this way mapping many parallel lines. These photos, often thousands of them, can then be registered using computer vision technology (Jordt 2015) to generate virtual orthophotos of an entire area, jointly with a 3D digital elevation model of the seafloor. Depending on distance and resolution of the camera, lighting conditions and water quality, these methods reach centimetre to sub-millimetre resolution. At the same time, the image registration process can also provide the micro-navigation of the camera platform (visual odometry) to facilitate also the registration of other sensors (e.g. magnetic, acoustic) that do not provide localization by themselves and have to rely on external sensors.

Optical data can be used in different ways. Single images can be inspected by skilled experts or can be analysed with machine learning. Machine learning tools need to be trained with a huge number of positive and negative examples. Both for skilled experts, as well as for computers, the often-varying capture conditions pose a challenge: depending on the distance, the water composition and the lighting regime, the appearance of objects can significantly vary between different seasons or capture campaigns. One solution to this issue is to compensate the water and lighting effects (“image restoration”), which can be accomplished using heuristics or using physical models of underwater light propagation. Trained experts can also inspect raw photos.

Rather than inspecting single images with a limited field of view, thousands of photos can also be registered to obtain digital elevation models and virtual orthophotos. While compensating all lighting effects in murky water is still subject of research, in general such colour-enhanced large-scale machine vision mapping methods provide a larger overview of an area, and the 3D shape information of objects can support detection, classification and interpretation when being viewed by an expert in a 3D viewer, or can be used also for applying AI techniques. Since the cameras have to be protected from the surrounding water, they have to be enclosed in a water-proof housing and view the environment through a glass window. Depending on the shape of the window (e.g. flat port or dome port) light rays into the camera will undergo refraction when passing the water-glass-air boundaries. Since the camera is used as a sensor (and not only for watching) it has to be calibrated properly to allow later for bias-free mapping of an area.

The key advantage of visual methods as compared to other methods is due to their simple and cheap application (using cameras). For humans, visual information plays a key role when we understand the world. Therefore, visual data is naturally understood well by humans and can not only be used by experts, but also to involve other stakeholders or to inform the general public. For systematic mapping campaigns visual data can also be used to infer the micro-navigation of the platform from the images which enables usage of extra sensors (e.g. magnetics). In any case, a systematic visual map will also help plan further operations, e.g. using divers or robots, and can be used for monitoring campaigns.

Due to the physical properties of water shorter and longer wavelengths than those of visible light undergo strong attenuation when traveling through the medium and lead to very low signal-to-noise ratios. Underwater optical measurements outside the visible spectrum, e.g. ultra-violet or infrared, are only feasible at very small distances (centimetres to decimetres), and are thus unpractical for mapping because of the small area inspected. Depending on the composition of the water (algae, particles, stirred-up sediment) the range of optical methods in the visible spectrum is usually limited to about 1 m to 3 m (e.g. Baltic Sea) and rarely higher than 5 m to 10 m (crystal clear water). Also, visual methods can only “see” objects that are not entirely buried.

4.3.4 Chemical Analysis Methods

Chemical Warfare Agent Compounds and Degradation Products

A comprehensive description of methods for CWA analysis is available from the Finnish Institute for Verification of the Chemical Weapons Convention (VEREFIN) (Vanninen 2017). Sediment samples have been analysed for CWAs by gas chromatography–mass spectrometry (GC–MS) for intact volatile chemicals or derivatized chemicals, and liquid chromatography–tandem mass spectrometry (LC–MS/MS) for intact water-soluble chemicals or oxidized derivatives (Missiaen et al. 2010). CWAs in fish tissues were extracted with acetonitrile and hydrogen peroxide, and measured by LC–MS/MS (Niemikoski et al. 2017).

Conventional explosives

A variety of analytical methods have been used to detect munitions compounds in environmental samples (Barshick and Griest 1998; Bromage et al. 2007; Badjagbo and Sauvé 2012a; Xu et al. 2014; Rapp-Wright et al. 2017) but vary in their specificity, simplicity, and detection limits. A widely used method of dissolved munitions compounds analysis uses solvent extraction, separation by liquid chromatography and Ultraviolet–visible spectroscopy (UV-VIS) detection, with detection limits in the µg/L range (US EPA Method 8330) (EPA, US 2007). It does however have numerous shortcomings. First of all, UV-VIS detection is not possible for munitions compounds that absorb light poorly, such as nitro-glycerine or PETN. In addition, differences in sample solution composition can affect the chromatographic separation of different compounds, making the identification of specific compounds difficult. Moreover, abundant coloured organic matter in seawater can interfere with detection by UV-VIS spectrometry. More recently, mass spectrometric techniques (Badjagbo and Sauvé 2012b; Rapp-Wright et al. 2017) provide enhanced sensitivities and specificity. Nanomaterial-based electrochemical detection of explosives (O'Mahony and Wang 2013) has shown promise.

A recently developed method uses solid-phase extraction (SPE) to eliminate the seawater matrix and preconcentrate trace levels of dissolved explosives (Gledhill et al. 2019). This approach allows confident detection of explosive compounds at the ultra-trace levels required for environmental samples, but limited availability of the analytical instrumentation may limit a wider application. Nonetheless, SPE preparation can help improve analytical capabilities of other detection technologies for both conventional explosives (Jönsson et al. 2007; Sun et al. 2011; Rosen et al. 2018) and CWA compounds (Kanaujia et al. 2007).

Novel detection methods employing Molecularly Imprinted Polymer (MIP) and electrochemical sensor systems have been tested for explosive detection in seawater (Atlas Elektronik 2015; Baudoin et al. 2017). Limited information is currently available on the sensitivity and specificity of these methods.

Passive samplers have also been successful at accumulating explosive compounds from seawater (Rosen et al. 2018; Lotufo et al. 2018; Warren et al. 2018). These samplers comprise a sorbent which may be held within filter membranes. They accumulate dissolved compounds over time, providing a time-integrated sample which helps eliminate temporal variability in compound levels associated with heterogeneous plumes in the water column (Rodacy et al. 2001; Camilli et al. 2009). However, it is not possible to calculate ambient seawater explosive concentrations from the passive samplers as the diffusion rates to the sorbent are very difficult to ascertain. These samplers' applicability is therefore limited to detect the presence of explosive compounds without allowing for an assessment of the degree to which they are present.

Conventional munitions compounds in biotic tissues from the Baltic Sea have been extracted with acetonitrile and measured by GC-MS (Strehse et al. 2017; Appel et al. 2018) or LC-MS (Gledhill et al. 2019) (see 3.4.3). A further improvement of the limit of detection (LoD) and limit of quantification (LoQ) by GC-MS has been developed by Bünning et al. (2021).

4.3.5 Bioindicators and Biomarkers

By definition, a bioindicator is a species or an ecological community that is monitored over time for changes in abundance or health, giving evidence on the status or quality of a particular environment (Ewing & Mattison 1987). The organism used as a bioindicator should be sensitive to the stressor present in its environment. If chemical contaminants are present, the organism may, as a response, exhibit changes in its physiology, morphology or, behaviour, or it may even die (Davies & Vethaak 2012). However, mostly robust organisms such as blue mussels, that are able to survive an expected level of pollution, are used in common environmental monitoring programmes. The selected bioindicators should preferably be abundant, widespread, and easy to sample and handle (Goldberg 1986). It is also beneficial if they can be conveniently used in laboratory experiments to investigate how the substances are bioaccumulated and/or metabolised and what are their sublethal biological effects and modes of toxic action.

In contrast to pure physical or chemical assessments, bioindicators display biological reactions to the observed environmental changes and enable correlations of contaminant concentrations to possible health effects. Biomarkers are commonly accepted tools to measure health effects of contaminants in organisms. They are roughly defined as biological responses to environmental chemicals at an individual level or below (Lagadic et al. 1997). Biomarkers provide means of translating environmental levels of contaminants to biological terms. They are used to assess the effects of pollution at different levels of the target organism, ranging from changes in gene expression and protein synthesis, e.g., of key enzymes, over enhanced cell death events to the bioaccumulation of metabolic end products and damage on tissues and organs up to the pathological developments and diseases.

Responses of the organisms at lower organisational level such as gene expression and protein synthesis are usually correlated with lower exposure concentrations of contaminants and short exposure times. In contrast, changes on tissue, organ or individual level are more likely resulting from higher concentrations and require a longer exposure time. Severity of the measured effects is also connected to the organisational level, with effects on organ or individual level are more severe and often irreversible compared to the effects recorded at lower organisational levels, such as increasing bioaccumulation of certain metabolic products or a differing expression of genes or proteins.

Organisms naturally have different sensitivities to different chemicals, both at the individual level and between different species; however, the modes of protection against the impacts of certain groups of chemicals are often comparable in species that are not closely related. As a result, specific biomarker responses to individual chemicals are relatively rare, and a single biomarker approach is usually not feasible; it is therefore recommended to use a battery of biomarkers measured at different levels of biological organisation, representing different biological functions to adequately assess biological effects of a contaminant. This approach is especially useful when investigating the utmost realistic situation in the field where the organisms are usually exposed to a mixture of numerous different compounds. Using multiple biomarkers in the assessment reveals the amount and type of total cumulative stress experienced by the target organisms at the site of collection.

There are numerous potential bioindicator species available, depending on the part of the marine ecosystem intended to be investigated. Regarding the assessment of potential negative health effects of marine munitions lying on or buried in the sediments on organisms, bottom dwelling organisms would be the best choice. These species get most likely in contact with solid explosives still trapped in corroded munitions shells or get exposed to the dissolved fraction of explosives in the vicinity of the open munitions materials. Sessile species such as blue mussels (*Mytilus spp.*) are very suitable bioindicators because they directly display the pollution level within a certain site. As filter-feeders, blue mussels are able to filter extensive amounts of seawater, thus being highly exposed to chemical contaminants, and, due to a low biotransformation capacity, have a notable tendency to bioaccumulate these substances from the surrounding water. Also, some stationary crab species and non-migrating flatfish species such as dab and flounder are used in biomarker monitoring.

As mentioned above, organisms used as bioindicators should preferably be abundant and geographically widespread. However, the strong salinity gradient in the Baltic Sea restricts the distribution of many marine species. For example, the common marine blue mussel *Mytilus edulis* is found only in the Skagerrak and Kattegat until the Little Belt area. In contrast, the closely related *Mytilus trossulus* inhabits the less saline areas in the eastern and northern parts of the Baltic Sea. Many areas are also inhabited by hybrids of the two species. Also, flatfish such as the common dab are limited to the more saline areas found in the western Baltic Sea. Specimen caught from the edges of their natural habitat are usually smaller with a lower condition factor, and thus being in different physiological status compared to their counterparts in the more saline areas. Caution is needed when comparing the biomarker results.

Another factor limiting the application of bioindicators in the Baltic Sea is the dramatic level of eutrophication resulting in large oxygen depletion zones, especially in the deep areas of the

Baltic Proper, the Gulf of Finland, and also in many coastal areas. In these areas there is no macrozoobenthos and fish avoid the anoxic bottom waters. By accident, also the largest dumping grounds of CWAs, the Bornholm Basin and the Gotland Deep, are situated in these areas, and thus an assessment using benthic bioindicator species as done in many other dumping grounds is impossible, and either pelagic organisms or infauna have been used instead (Kotwicki et al. 2016; Lang et al. 2018). However, fish are probably avoiding the oxygen-depleted near-bottom layers and are thus not fully exposed to the dumped materials, while infauna communities are limited to the most resilient organisms.

The use of bioindicators and biomarkers is an essential measure to detect, track and assess the effects of contaminants deriving from dumped munitions. Without this information a holistic risk assessment is not adequate. However, the special hydrological characteristics of the Baltic Sea are challenging when applying common bioindicator species; in practice this signifies that the area has to be divided into subregions where the local species adapted to the respective environmental conditions are used. Biomarker responses are affected by many abiotic conditions, and local baseline levels have to be determined. Finally, transplantation of organisms, e.g., the mussel caging approach, may be considered in regions devoid of suitable local bioindicator organisms.

Within the recent pilot projects several bioindicator species were successfully used to assess the effects of dumped munitions. Blue mussels were transplanted in the field to dumping grounds and exposed in the lab to dissolved TNT. In this way the uptake of TNT was proven, biological effects at several levels and protective behavioural were documented and toxicity thresholds were established (Schuster et al. 2021; Lastumäki et al. 2020; Strehse et al. 2017). A new biomarker for TNT was established by Strehse et al. (2020), who found a concentration-dependent upregulation of the gene coding for carbonyl reductase by TNT in lab and in field studies (Strehse et al., 2020). Additional field approaches revealed that pelagic fish are also getting in contact with warfare compounds proven by traces of compounds in the muscle tissue (Niemikoski et al. 2020) and that flatfish species living within a dumping ground have traceable amounts of dissolved TNT and its metabolites in their bile (Koske et al., 2020) and were severely impacted resulting in higher tumour rates than fish from unburdened reference sites. Further, in the lab also flat worms and fish embryos were exposed completing the picture of harmful effects of dissolved TNT on every investigated organism (Bickmeyer et al. 2020; Koske et al. 2019).

4.4 Modes of Clearance

This report does not provide information on the clearance of chemical warfare materials. Their clearance is more complex and less experience exists than for conventional materials. For more information, the reader is referred to Sutolovic & Cekovic 2004; Nawala 2019 and Kim et al. 2011.

For combustion of conventional warfare materials two types can be distinguished, deflagration and detonation. If the propagation is associated with a velocity greater than the speed of sound and a strong shock, the term “detonation” is used. If the rate of combustion is subsonic (i.e.

lower than the speed of sound) and associated with heat conduction to sustain the wave, it is called deflagration. A deflagration can turn into a detonation under special conditions (confinement, shock sensitivity, burning velocity) if the pressurization rate inside the unburnt material increases over a critical threshold (deflagration to detonation transition) (Bourne et al. 2020).

4.4.1 High Order Detonation

High order detonation occurs when detonation velocity reaches its maximum for an energetic material. The energetic output is therefore maximised which is the design function of all munitions (Fickett and Davis 1979; Mader 2007). Clearance of warfare materials can require intentional execution of a high order detonation. It usually follows the placement of a donor charge or firing of a projectile. With high order detonation, the aim is the complete consumption of the explosive. Note that for propellants detonation is not a desired outcome. High-order detonation is characterized by high detonation velocity (5,000 to 10,000 m/s) resulting in an extremely short rise time of the pulse and consequent shock waves that can proliferate for many kilometres (von Benda-Beckmann et al. 2015a).

In order to obtain a stable detonation, a sufficient amount of material has to be present so equilibrium (i.e. maximum detonation velocity) can be achieved. Therefore, a critical mass is needed below which the detonation cannot be sustained. The geometry should be such that the critical diameter – this is the diameter below which there will be no steady state detonation – is exceeded. High order detonation is also affected by the confinement of the explosive, since this can act as a focusing effect for the detonation reaction with the shock wave being directed inwards and thus enhanced and driven, while accelerating it towards the maximum velocity.

As a consequence of an efficient reaction most, though not all, of the explosive will be consumed and residues will remain as the end products of the reaction chain. These contain significant quantities of gas but also solids such as aluminium compounds. Resulting end products depend on the composition of the detonating explosive material.

A variant of the high order detonation is the intended sympathetic detonation. A consolidated denotation is executed when numerous warfare materials objects are detonated at the same time and at the same location (Schwartz and Brandenburg 2009). Several reasons from cost-reduction to local seafloor condition (detonation only possible in one place) or safety reasons (risk of unintended sympathetic detonations) might lead to the decision to conduct one consolidated explosion rather than several individual ones. The overall impact of the detonation is higher when numerous objects are detonated simultaneously.

4.4.2 Low Order Detonation

Low order detonation is characterized by a much lower detonation velocity (>1,000 and <5,000 m/s) (Kiciński & Szturomski 2020). It occurs when the detonation reaction does not reach steady state and hence the maximum detonation velocity is not reached. It is still a detonation with a supersonic reaction rate, which produces a shock wave and is therefore not a deflagration. It is possible for a deflagration to burn to detonation, which is termed Deflagration to Detonation Transition (Bourne et al. 2020). Such reactions can produce high order responses that depend on the critical properties (mass, diameter and geometry) of the explosive and on its confinement. Low order detonation may occur when non-planned stimuli occur which may take place during disposal operations. Low order is also a risk with high performance propellants.

When dealing with warfare materials in the sea, which may have been damaged, the risks of both low order and high order detonation should always be considered. Attempts to disrupt or move such warfare materials can lead to an initiation stimulus and a violent reaction, which would be sufficient to do damage and risk lives despite not being the full operational effect. While water can act as a damper to the reaction, it may also act as a form of confinement and so the effect may be greater than in air, especially if a bubble is generated. In addition, such a low order detonation may itself act as a stimulus to other warfare material, if it is located in close proximity to the initial detonation, leading to sympathetic reaction and to a full high order event.

A low-order detonation requires an energetic impulse, e.g. through a booster charge. It is possible to place such a charge in a way that the warfare materials object opens and detonates in low-order. However, the risk of an unintended high-order detonation of the object taking place can never be fully excluded. Nonetheless, a low-order treatment under water can be executed more effectively than on land.

During low order detonation the explosive material does not operate in its designed mode. It therefore leads to the release of unreacted, partially reacted or completely reacted materials into the environment. Unreacted or partially reacted materials may pose a further risk in disposal (Fickett and Davis 1979).

4.4.3 Deflagration

Reactions within energetic materials – explosives, propellant etc. – can take several forms. These forms are generally governed by the speed of reaction and range from high order detonation to simple combustion. Deflagration is normally defined as a very rapid form of combustion, but one in which the chemical reaction velocity does not exceed the speed of sound in the material and thus no shock wave is produced. Kiciński & Szturomski (2020) indicate a propagation speed in a deflagration of less than 1,000 m/s.

In some cases, a deflagration can lead to detonation where the reaction accelerates to a supersonic rate (Bourne et al. 2020). This acceleration can be produced by several factors such as an increase in the quantity of material available for reaction, geometry, or the confinement of the energetic material, where the pressure is increased locally inside the reacted and unreacted material.

Damage to the material can allow the reaction rate to accelerate. Such damage produces compression hotspots or sufficient porosity to increase the reaction rate. Such increases can give rise to what is called Deflagration to Detonation Transitions and these can be unpredictable and hence risky.

Rapid combustion or deflagration can be used to destroy dumped materials. A shaped charge of modest size can be used to weaken the shell and initiate deflagration rather than a high order detonation. The acoustic output of a deflagration is much smaller compared to a detonation and there is no shock wave (Robinson et al. 2020). Thus, deflagration could provide disposal options where a high order detonation is considered a high risk for material or environment. However, deflagration is associated with other specific risks such as contamination of the marine environment (Koschinski 2011). Another drawback of using deflagration as a disposal method is the increased risk of Deflagration to Detonation Transitions under certain conditions of the confinement, including the combination of casing and water.

The rate of deflagration combustion is therefore unpredictable and depends both on the local environment and the confinement. It should therefore not be used regularly for planned destruction of warfare materials. If it is considered as an option, then it is essential that the risks described above be thoroughly considered in the planning phase.

4.4.4 Impact Mitigation

In the light of the increasing need to perform clearance of warfare materials in the Baltic and the negative consequences of detonation practices for the marine environment (see 3.3), this chapter describes ways to mitigate the impact of existing clearance techniques. If a detonation cannot be avoided, the presence of surrounding marine organisms should be considered and a combination of technical and organisational mitigation measures be implemented that are appropriate to protect the environment (Table 5).

In certain situations, such as imminent danger to humans, detonations cannot be completely avoided. In these cases, the application of mitigation measures can minimise adverse effects on the marine environment. In light of the critical situation of the harbour porpoise population of the Baltic Proper with less than 500 animals remaining (ASCOBANS 2016a), the HELCOM Expert Group on Marine Mammals expressed deep concerns about potential effects of unmitigated detonations on individuals and underlined that for the critically endangered harbour porpoise population; all use of explosives having an effect on the individual level are very likely to have effects also on the population level (HELCOM 2019b).

Resolution no. 8 (2016) by the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) "Addressing the Threats from Underwater Munitions" (ASCOBANS 2016b) encourages Contracting Parties to support research investigating the risk to marine animals and habitats from underwater warfare materials, and recommends that international guidelines should be developed, including those advising on safe recovery methods and mitigation measures, when no alternatives to detonations are feasible.

Table 5. Summary of available mitigation methods for reducing the impact of underwater detonations on marine animals

Planning stage
Perform an impact assessment and develop mitigation strategy for unavoidable detonations • Involve nature conservation and fishing agencies. • Determine the radiation of sound and shock waves with a suitable model. • Analyse the vulnerability of species and habitats in the affected area.

• Determine impact and safety zones for wildlife. • Consider possible effects of seismic waves and shock waves to nearby sensitive habitats, • Consider the share of the explosive material that does not undergo chemical conversion and therefore remains in the environment. • Analyse options for relocating warfare materials or postponing detonations. • Develop a site-specific deterrent strategy. • Analyse effectiveness of acoustic deterrents. • Analyse suitability of technical mitigation measures. • Plan of pre- and post-detonation surveys. • Plan protected species observer schemes and passive acoustic monitoring (PAM). • Develop safety procedures.
Analyse options to recover warfare materials • Adapt deterrent strategy to expected injury zone.
Measures before detonation
Pre-detonation survey • Perform air based marine mammal survey in greater area. • Perform PAM covering the wider area for a representative period of time.
Use of acoustic deterrents for marine wildlife • Consider variations in scaring distance between types of devices and species. • The minimum scaring distance is relevant for safe scaring. • Take scaring distance and size of zone of injury into account when determining number and arrangement of deterrents.
Protected species observers (PSOs) • Employ PSOs to cover the safety zone and stop detonation in case of sighting.
Measures during detonation
Bubble curtain • Execute performance monitoring.
Options for other sound absorbing measures • Execute detonation of warfare materials close to the water surface. • Execute detonation of warfare materials in shallow water or on shore. • Execute detonation of warfare materials in areas shielded by islands or flats. • Execute detonation of warfare materials within a crater • Use a rigid or collapsible shockwave shaper (experimental).
Measures after detonation
Post-detonation survey • Perform air-based marine mammal survey in wider area. • Conduct beach surveys in wider area of detonation site. • Conduct autopsies of stranded marine vertebrates with a special focus on investigation of possible explosion trauma in marine mammal ears. • Recovery of undetonated energetic substances after low order detonation or deflagration.

Table 5 provides a toolbox of mitigation methods to reduce the impacts of underwater detonations on marine animals from which a set of suitable methods should be chosen based on a case-by-case assessment. Performance monitoring is required for all mitigation measures in order to document the fulfilment of legal conservation requirements such as those mentioned in 5.2.1 and to enable further improvement of mitigation methods. The following chapters explore some of these mitigation options during clearance of warfare materials.

4.4.4.1 Detonation Risk Assessment and Mitigation Strategy

In the planning stage, a proper detonation impact assessment and a mitigation strategy should be developed in co-operation with competent nature conservation and fishing authorities with the aim of protecting the marine environment and commercial fish stocks from shock waves. This strategy may cover potential impact on and mitigation for:

- Protected and sensitive species
- Marine protected areas (MPAs)
- Sensitive habitats

It includes a number of steps (Table 5). Such an assessment may not be possible in case of imminent danger posed by warfare materials to humans. Strict standards should be applied to the assessment of whether danger is imminent. This signifies that upon examination, sufficient corroborating evidence appears to exist. Especially if the presence of mines or other munitions has been known for a long time, imminent danger is generally difficult to invoke as a justification for urgency (Wissenschaftliche Dienste 2020). For cases of imminent danger, previously developed standard procedures should apply. These should be based on readily available information (e.g., from databases on animal occurrence and general knowledge on sensitivity of animals) and be developed involving various stakeholders and responsible authorities.

The first step in an impact assessment is a thorough determination of possible impact zones (e.g., for marine vertebrates with respect to injury and hearing impairment) based on a site-specific shock wave and noise propagation model and current knowledge of shock wave impact on biota. An adequate safety margin should be established as part of the safety procedures in a precautionary manner (Dos Santos et al. 2010).

The vulnerability of species and habitats in the affected area should be analysed. In the Baltic Sea, seal haul-outs, occurrence of harbour porpoises and sensitive areas for fish species (spawning grounds etc.) are of special concern (HELCOM 2019a), as these are especially vulnerable to the shock waves originating from detonations. Furthermore, seabird colonies need to be considered because swimming or diving birds can be injured by underwater detonations (Koschinski 2011). In some cases, the effect on terrestrial animals or habitats should also be analysed. For example, coastal colonies of cliff-dwelling birds might be affected by seismic shocks of explosions, such as the bank swallow whose tunnels including eggs or juveniles could be buried by ground shaking. Not only sensitive animals should be taken into account but also MPAs in general (Frey et al. 2019), even if the detonation occurs outside the MPA but the radiating sound or shock waves are predicted to affect the MPA. Also, nearby sensitive habitats, such as reefs and other habitats with fragile benthic species, might be affected by an underwater detonation or subsequent sedimentation of fine material, which would require including them in the impact assessment.

As part of the mitigation strategy, possible alternatives to blasting should be considered and best available techniques be identified. To date, a variety of munitions objects can already be salvaged without risk to humans. Other items that are not assumed to be safe to transport are usually detonated. Methods where robots take care of the handling to enable delaboration may at some point be available and allow salvaging of unsafe to handle items (see RoBEMM project in 5.7.4.5). Currently, only about 20-30% of the Baltic Sea area affected by munitions can be cleared due to the prevailing danger and current costs associated with munitions disposal. Within the next ten years, the improvement of clearance technologies and an increase of available resources could significantly grow the percentage of munitions that can be recovered safely, largely without danger for humans and the marine environment (Abbondanzieri et al. 2018).

If a detonation cannot be avoided, spatio-temporal mitigation is a very effective protective measure by avoiding most vulnerable areas or time periods and postponing or relocating warfare materials before executing detonations. In order to safeguard protected marine species when executing detonations underwater, the time and place of detonations which have the least impact on the environment should be determined (Dolman et al. 2009). Detonation in shallow water or on shore can be considered. In such cases munitions which are safe to handle underwater can be relocated using e.g., a lifting balloon. A safe tow connection and suitable weather conditions are a prerequisite (BfN 2022).

Before detonation, the suitability of technical mitigation measures should be analysed. Appropriate measures should be based on best available techniques (BAT) and best environmental practice (BEP) (HELCOM 1992). If a detonation in sensitive areas or during sensitive times cannot be avoided, this is of utmost importance to protect the environment. A technical mitigation measure (see 4.4.4.2) in combination with suitable deterring methods (see 4.4.4.3) may be very effective.

Pre-detonation surveys (air-based and passive acoustic monitoring (PAM)) of the wider area well in advance of the detonation for a representative period aid the analysis on which species and how many individual animals might be affected by detonations and whether it is possible to keep them at safe distance using acoustic deterrent devices (see 4.4.4.3) (Yelverton et al. 1973; Yelverton et al. 1975; Goertner 1982; Thiele and Stepputat 1998; von Benda-Beckmann et al. 2015b). HELCOM (2019a) provides a list of Baltic Sea species that are specifically vulnerable to underwater noise (see 3.3).

The implementation of a protected-species observer scheme in order to maintain a safe exclusion zone around the blast is one of several components of a comprehensive mitigation strategy. Procedures for a safe abortion of the detonation in the case of a sighting within the impact zone should be developed. This mitigation measure relies on the thorough determination of possible impact zones, a skilled observer team, and suitable visibility conditions (calm sea, good light). The probability of sightings decreases with sea state. For this reason, the procedure must be ceased if the sea state is greater than 2 on Beaufort scale, when harbour porpoises cannot be reliably sighted even by trained observers. For small cetaceans such as harbour porpoises, visual monitoring is usually complemented with PAM in order to increase the likelihood of an animal being detected in the impact zone, which may have a radius of several kilometres depending on factors such as charge weight, depth and orientation of the animal (von Benda-Beckmann et al. 2015b). The advantage of PAM is that it is performed continuously underwater whereas a visual detection is only possible in a short time window during surfacing. However, the acoustic detection distance for harbour porpoises is shorter than the visual detection distance, which is only up to a few hundred metres (Kyhn 2010). PAM is of no use if animals do not vocalise or are orientated away from the hydrophone. Seals cannot be reliably monitored acoustically because they mainly vocalise during the short mating period (Van Parijs et al. 1999). Aerial platforms and unmanned devices, such as drones with live video feeds, may also be considered for observations.

Post-detonation air and beach surveys in the wider area around the detonation site should be performed. This enables the evaluation and documentation of the mitigation strategy and supports the recovery of dead specimen and veterinary care in the case of injured animals.

4.4.4.2 Technical Mitigation Measures

A very effective mitigation measure is the bubble curtain. It is generated by pressurised air forming a ring of bubbles freely rising from a weighted nozzle pipe on the sea floor to the surface at a distance of over 70 m from the detonation site. Its design should ensure that the bubble curtain is fully closed around the detonation site to avoid noise leakage. This can be achieved by a uniform pressure distribution within the bubble curtain (Bellmann et al. 2020). Bubble curtains are among the technical mitigation measures considered a best available technique (BAT) (German Bundestag 2018).They have a very high potential to reduce impacts of sound and shock waves on marine wildlife by significantly reducing the affected danger area. This has been proven in various experiments and applications. It has been shown repeatedly that air bubbles in the water effectively reduce the sound pressure and the shock wave from detonations (Keevin and Hempen 1997; Keevin et al. 1997; Keevin 1998; Notarbartolo Di Sciara 2002; Rude and Lee 2007; Nützel 2008; Schmidtke et al. 2009; Schmidtke 2010; 2012; Grimsbø and Kvadsheim 2018). The bubble curtain radius should be much larger than the gas bubble that is created by the explosion. Otherwise it can be affected by the water mass pushed away by the developing gas globe. The radius of a bubble curtain must be increased with the charge weight (Schmidtke et al. 2009).

In one case, a bubble curtain with a radius of 22 m was used to mitigate the detonation of a 300 kg mine containing the main charge explosive Schießwolle 39 (see 2.1.1.1.2). This setup was ineffective as it did not reduce the peak pressure at all (Schmidtke et al. 2009). On the other hand, a bubble curtain with a radius of 70 m reduced the peak pressure of the shock wave by 16 dB to 19 dB re 1µPa (Schmidtke 2010). Given the sound propagation properties in water, the bubble curtain in this setup reduces the area of the impact zone for harbour porpoises, fish or birds by approximately 99%. The length of the nozzle pipe in the successful setup was 440 m. During offshore construction, it is state of the art to deploy a nozzle pipe ring of even up to 1,600 m in length in an effort to reduce piling noise. Such a long nozzle pipe allows for the deployment of a double bubble curtain, which furthers reduces the peak pressure of the shock wave.

The principle mechanisms responsible for the pressure reduction by the bubble curtain result from the compression and relaxation of the bubbles by the shock wave (Grandjean et al. 2011). The adiabatic compression of the bubbles results in a temperature rise and thus sound energy is absorbed by conversion to thermal energy. Some of the thermal energy is then transferred to the surrounding water by cooling. Oscillation of bubbles rereleases some of the absorbed sound energy to the water with a loss of energy and a time delay due to the higher viscosity of water compared to air. The relaxation of bubbles creates rarefaction waves, which decrease pressure. Overall, these effects reduce the pressure peak and distribute the energy over a longer period of time. Furthermore, part of the sound energy is reflected inwards back to the detonation site. The efficiency of bubble curtains depends on their diameter, width and shape, air volume stream, bubble size and on the water depth. Its performance can be monitored by using pressure sensors located inside and outside the bubble ring. The bubble curtain is an effective and practical method and can be cost-efficient if adequately planned.

Today's bubble curtain systems are robust and the entire handling of the bubble curtain can safely be done from only one vessel and without divers. The pipe-laying vessel is fitted with a driven winch, which is used to install a circular or elliptical nozzle pipe ring on the sea floor. By means of a pressure pipe that is long enough for the vessel to stay out of the danger zone the pipe ring is supplied with air. Compressors located on the vessel are used to supply air into the nozzle pipe. The air-supplying vessel is held in position by a dynamic positioning (DP) system to avoid anchoring on top of dangerous warfare materials.

In current bubble curtain systems, the operational depth is limited to about 40 or 50 m by the hydrostatic pressure and by currents. The required minimum pressure difference between pressure inside the hose and hydrostatic pressure is 2 to 3 bar and the air needs to be filled into the nozzle pipe from both ends to ensure a uniform and optimal air release (Bellmann et al. 2020). Scaling effects concerning the total amount of air needs to be considered in order to provide sufficient air: at greater depth an increased air volume stream is needed due to the compressibility of air bubbles. (This is called free air delivery (FAD), which is measured at the input side under atmospheric conditions.) Furthermore, the length of the nozzle pipe needs to be increased depending on the weight of the explosive charge. Both factors have a major effect on the required number of compressors.

In tests at a water depth of 12 m, a bubble curtain showed high damping values of about the same order of magnitude with a FAD of 1 m^3/min/m and 0.5 m^3/min/m (Schmidtke 2010). Whether a further reduction in air flow would still show similar damping is unknown. The minimum required air volume at the exit point of the nozzle pipe under hydrostatic pressure translates to approximately 0.23 m^3/m/min. Therefore, a minimum required air volume needs to be calculated from this factor as a function of water depth.

In the German EEZ, the use of bubble curtains is mandatory for the execution of detonations when offshore construction sites are secured by EOD companies against warfare materials hazards. Bubble curtains are also recommended by numerous nature conservation agencies in the United States for the protection of rare or commercially relevant fish species (Keevin and Hempen 1997; Keevin et al. 1997; Keevin 1998) and have recently been used in Norway to protect salmon in a commercial fish farm (Grimsbø and Kvadsheim 2018). Bubble curtains were also used for clearance of warfare materials during installation of the Nord Stream 2 gas pipeline in the Finnish EEZ whenever the net explosive weight of warfare materials to be cleared exceeded 22 kg (Sitowise OY 2018).

However, even a damped shock wave can harm marine life with the remaining pressure. Furthermore, it needs to be mentioned that any detonation, especially of old warfare material, releases toxic warfare materials constituents into the water due to incomplete combustion. This cannot be prevented using a bubble curtain (Pfeiffer 2009). When bubble curtains are used, it is advised to use oil free compressors to avoid introduction of oil into the sea by the air stream.

In shallow waters, other dampening strategies could be applied. A part of the energy could be redirected to the surface by positioning the warfare materials in a crater from previous explosions at the same site (Schmidtke 2012). However, this practise is much less effective than the use of a bubble curtain. Another approach may be lifting warfare materials and detonating them close to the surface (von Benda-Beckmann et al. 2015a). Furthermore, the placement of a rigid ring, such as a cofferdam, around the warfare materials (rigid shockwave shaper) or an air cushion on the top (collapsible shockwave shaper) (Wallace 1982) have been discussed as options. However, these approaches require further development and examination of their shockwave reduction potential.

4.4.4.3 Scaring Devices

Acoustic deterrents produce unpleasant noise with the aim of establishing an exclusion zone for noise-sensitive species around a site before the detonation is executed. The application of such means requires careful consideration because of species-specific behaviour and different properties of devices. For example, electronic acoustic scaring devices are not suitable for deterring birds (Melvin et al. 1999) or fish. The frequency spectrum of these do not cover the hearing spectrum of most fish species (Au and Hastings 2008).

The range of customary gillnet pingers, designed for reducing bycatch in fishing nets, is only a few hundred metres, and it only deters certain species such as the harbour porpoise (Culik et al. 2001). Dolphin deterrent device (DDD) pingers are louder and thus the deterrence distance for harbour porpoises can be assumed to be greater (Morizur et al. 2009; Kingston and Northridge 2011). DDD signals have to be adjusted to the species which is to be deterred from a detonation site. Systematic studies of the deterrent effect and range with respect to harbour porpoises are lacking.

Seal scarers are effective for harbour porpoises, but much less effective with respect to seals. Thus, it is not recommended to rely on the deterrent effect on seals. Mikkelsen et al. (2017) experimentally found that harbour porpoises exhibited avoidance reactions at ranges of up to 525 m from seal scarer signals at a reduced acoustic output. Contrary to this, seal observations even increased during sound exposure within 100 m of the speaker. Different studies have given contradictory results in regards to the effectiveness of seal scarers on seals (Jacobs and Terhune 2002; Fjälling et al. 2006; Graham et al. 2009). The strong repellent effect on harbour porpoises has, however, been confirmed in multiple studies (Johnston 2002; Olesiuk et al. 2002; Kastelein et al. 2010; Brandt et al. 2013a; Brandt et al. 2013b). For marine mammals, the motivation to exploit a food source, habituation and learning all seem to influence the scale of avoidance of seal scarers (Götz and Janik 2010). In conclusion, electronic acoustic scaring devices are not suitable for deterring other species than harbour porpoises.

The effect of explosive scaring charges is not proven. So-called “fish scaring charges” of 20 g explosives were used during munitions clearance for the Nord Stream pipeline in the Baltic Sea (Nord Stream 2011). However, no flight response has been reported in numerous experiments conducted so far (Lewis 1996; Keevin and Hempen 1997). It is also questionable whether marine mammals can be safely scared away from a detonation site by scare charges as their effects on marine mammals are inconclusive and not well understood (Jefferson and Curry 1994; Continental Shelf Associates 2004; Moore et al. 2006). There is clear evidence in mammals that a startle response is elicited by sudden intense acoustic stimuli (Yeomans et al. 2002). However, the startle response is mediated by a synaptic reflex and not the result of a behavioural decision such as avoidance or fear conditioning which would be needed for a deterrent device to be effective (Götz and Janik 2011).

It should further be considered that, similar to the effect on human divers, even a charge of less than 20 g can be harmful to marine life at ranges of up to a few hundred metres (Young 1991). Depending on the size of the charge, the species and distance between charge and the animal, scaring charges may thus contribute to injury or mortality. Moreover, in areas where detonations occur on a regular basis marine mammals or birds could be even attracted by scaring charges. They might learn that following such detonations, leads them to killed or debilitated fish, which are an easy to exploit food source. They could therefore be subsequently exposed to and killed by further explosions (Continental Shelf Associates 2004; Danil and St. Leger 2011).

In explosions of warfare materials with charges of a few hundred kilograms of explosives, the effective deterring range of neither of the scaring methods mentioned above cover the full impact zone of injury and hearing loss. The conclusion of these findings is that, due to the discrepancy between deterrent radius of devices and impact radius of detonations, scaring devices are only suitable as an additional measure for mitigation, e.g. in combination with a bubble curtain (see 4.4.4.2).

4.4.5 Salvaging

In cases where it is both safe and possible the best option for avoiding negative impact to the marine environment in general and marine vertebrates in particular is to recover the warfare materials instead of blasting them in place (Koschinski & Kock 2009). With current technologies it is not always possible to use recovery methods, as certain warfare materials items are not safe to handle. Detonations may be necessary when the safety of personnel dealing with the munitions cannot be adequately assured. The monetary expenses of utilising safe recovery methods rather than detonation should not be the only determining factor because true costs (e.g., for environmental damage or damage/contamination of commercial stocks) may far outweigh the immediate expenses.

Warfare materials that are not safe to handle (e.g. with an armed fuse or a sensitive main charge such as picric acid) shall not be recovered aboard a manned vessel unless an appropriate containment system is used to mitigate the risk to personnel (UNMAS 2014). A general problem of the surfacing of munitions from deeper water levels is the sudden change of ambient pressure, which may for some explosives lead to spontaneous detonation, or for heavily corroded shells to mechanical failure and leakage (Pfeiffer 2012). Another risk posed by the surfacing and transportation on ship and land is the drying of warfare materials. Pfeiffer (2012) describes that the complex and often unclear chemical constitution of old munitions can potentially react when dried, therefore arguing for deliberate wet arrangements (Pfeiffer 2012).

In specific cases these can be used for relocating warfare materials to a wet storage site for later recovery and treatment and salvage (BfN 2022).

Munitions that are not safe to transport but safe to handle under water may be moved under water in order to remove munitions from the vicinity of infrastructure or to perform a consolidated detonation of several munitions objects. If it is not safe to handle warfare materials under water, currently the only options are high and low order detonation as well as deflagration. Salvaging may be executed by ROVs, cranes, or divers.

4.4.5.1 Extraction by Dredging

Extraction by dredging is the underwater surface abrasion of sediments and smaller warfare materials. It constitutes a full volume clearance, during which a previously defined area is completely swept up to a certain depth. The dug-out material (dredge spoil) is analysed for warfare materials, which are removed before the sediments are dumped again. As the BMUB catalogue (2014) explains, larger warfare materials have to be identified and extracted before extraction by dredging takes place (e.g. manually by divers). For the dredging process, safety standards are to be chosen in a way that loss of equipment and injury of workers can be excluded. Therefore, the largest potential explosion (unintended, due to the mechanical stress during dredging) has to be anticipated (BMUB and BMVg 22018).

Dredging operations can be performed with clamshells (dredge spoil is loaded on barge) or suction (dredge spoil flushed through pipes) (Schwartz and Brandenburg 2009). The separation of explosive items can be done either by using a strainer with a mesh size appropriate to filter out the smallest relevant warfare materials (to be defined beforehand based on survey and warfare materials identification) or by a combination of geophysical measures (magnetometer) and eyesight (BMUB and BMVg 22018). Disadvantages of dredging include high costs, heavy disturbance (destruction) of local marine environment, and increased efforts for workers' safety given that spontaneous detonation cannot be disregarded as a possible risk (BMUB and BMVg 2018).

4.4.5.2 Extraction by Electromagnets

The procedure of utilizing underwater electromagnetic extraction of warfare materials, another full-surface recovery, is described by BMUB and BMVg (2018) as follows. Electromagnets with built-in flushing nozzles are fastened to a swimming platform (ship or pontoon) and lowered to the seafloor, where waterjets from the flushing nozzles drive the magnets into the ground. The maximum penetration depth depends on the seafloor sediment characteristics and usually does not exceed a few decimetres. Magnetic material is pulled towards the electromagnet and is thereby separated from the soil. New technologies allow monitoring and preventing possible losses during the extraction movements, where friction- and weight-induced resistances have to be overcome by the electromagnetic force. The extracted material is then brought up on the platform and warfare materials are separated from scrap material. Protection against spontaneous detonation has to be ensured. Several limitations have been detected by BMUB and BMVg (2018): the use of electromagnets is only suitable for near-surface extraction in relatively loose sediments. Uncontrolled movements of explosives can lead to detonations and (with older equipment) to loss of items. Due to a magnetization of the area, a follow-up magnetometer scan is not possible.

4.5 Other Tools

4.5.6 Monitoring

Since 1979 monitoring has been established as part of the Helsinki Convention and has also been addressed by the Baltic Sea Action Plan (BSAP) (HELCOM 2007 and HELCOM 2021). To fulfil the Marine Strategy Framework Directivity (MSFD) European states need to monitor their national waters and determine the Good Environmental Status (GES) of local habitats (Zampoukas et al. 2014). As munitions dumpsites inevitably became part of the marine environment and TNT is part of the list of chemical contaminants in the marine environment (Tornero and Hanke 2016 2017) which require monitoring, all kind of processes related to them needs to be analysed and understood (Zampoukas et al. 2014). Generally defined as a permanent observation of a system or processes, monitoring allows long-term changes and developments to be detected which are not possible via single measurements. Sea-dumped munitions monitoring should ideally provide information on migration and spreading of munitions shells, release and spreading of toxic compounds into the environment and uptake of toxic compounds into the food web, including seafood consumers. It is not in place yet, however.

Data from a successful monitoring may not only serve for observation purposes, but provide data for prediction models, risk assessment and risk-management analyses as it is incorporated inside the Decision Support Tool developed within the DAIMON project.

All three topics have been processed by the German UDEMM project (BMBF funded) for a shallow water dumpsite containing conventional munitions in the Baltic Sea. In parallel, continuous research of CWA dumpsites is performed by CHEMSEA, MODUM and DAIMON projects. Baseline studies prior to monitoring help to characterize dumpsite areas regarding seafloor properties, munitions occurrences, hydrodynamic forces, habitats and physical-chemical properties. They have been performed by Czub et al. 2018 and Kampmeier et al. 2020. Based on such studies suitable methods and sensitive areas were identified for long- and short-term ad-hoc monitoring on various scales ranging from feature scale (<100 m; munitions objects and cluster), local scale (100 – 3,000 m; munitions dumpsites) to regional to coastal scale (>3,000 m; bays and entire coastlines). Ideally, all three spatial levels should be considered in a full monitoring set-up. The set of best practices in monitoring of chemical munitions dumpsites was published as a result of the MODUM project (Bełdowski et al. 2018).

To evaluate the state of migration and displacement of munitions shells, high resolution mapping with high positional precision is essential. The required data resolution depends on object sizes and must ensure repeatable detection of single objects. Only object displacements greater than the achieved position precision can be reliably measured. Hydroacoustic and optical mapping methods are suitable for warfare materials laying on top of seafloor sediments. This includes multibeam sonar, synthetic aperture sonar, side scan sonar and AUV-/ROV-based optic surveys (Czub et al. 2018; Kampmeier et al. 2020; Kunde et al. 2018). In addition to this, the presence of open explosives and corroding munitions shells can be efficiently monitored via repeated optical surveys (ROVs, AUVs, towed cameras and inspection by divers). Buried munitions detection requires ground penetrating methods such as sub-bottom profiler and magnetometer (Missiaen and Feller 2008; (Missiaen and Noppe 2009). For the actual contamination detection and confirmation of release of explosive and CWA-related compounds into the environment, multiple water, pore-water and sediment samples need to be collected in the vicinity to the munitions using safe and standardized methods. Additionally, a passive sampler can be installed within monitoring areas for defined time periods. This can be done via ultra-high-performance liquid chromatography-electrospray ionization mass spectrometry (uHPLC-ESI-MS) described in Beck et al. 2018 2019 and Gledhill et al. 2019 and gas chromatography mass spectrometry (GC-MS) (Strehse et al. 2017; Appel et al. 2018). Due to the hazardous nature of CWAs in potentially contaminated samples, chemical analyses should be performed by well-equipped and in CWA-detection case OPCW-accredited laboratories. To quantify the real uptake into the food web, the explosive compounds concentrations have to be measured inside flora and fauna using appropriate biomarkers. For all listed purposes the DAIMON2 project provides multiple Standard Operational Procedures (SOPs). As metabolic effect can alter concentrations, biota of different food web levels should be examined. Biomonitoring makes it possible to analyse in-situ TNT accumulation within organisms (e.g. blue mussels) (Strehse et al. 2017; Appel et al. 2018) and fish (Koske et al. 2020). Detailed methods and measuring intervals are published within the *Practical Guide for environmental monitoring of conventional munitions in the sea* (Greinert 2019).

4.5.7 Biomonitoring

The term biomonitoring is used inter alia in ecology to describe the periodic measuring of the stock and state of health of organisms as well as their communities with the aim of determining the quality of environmental conditions. Modern analytical methods enable detection of many pollutants in very low, ecologically relevant concentrations. In ecological studies biomonitoring records biodiversity and abundance of organisms over time and across locations. At contaminated sites changes in the composition of species and their frequencies are to be expected. More robust (stress resistant) species might survive, while others die out, such as mortality from acute toxicity. Long-term exposure to toxins might have chronic effects which may also result in mortality.

Water and sediment samples can be analysed and the measured concentrations of a pollutant (such as munitions compounds, CWAs or (heavy) metals) can be used to evaluate the severity of contamination in a specific area with dumped munitions. Nevertheless, simply the presence of contamination does not determine its impact on the environment and does not answer the question if these compounds enter marine biota and/or accumulate in the marine and human food web.

Biomonitoring is differentiated in active and passive biomonitoring. For passive biomonitoring, marine animals are collected in suspected burdened areas and analysed for the presence of particular compounds. For this approach, fish, bivalves, and most vertebrates as well as invertebrates are suitable. For example, Niemikoski et al. (2017) have published the occurrence of CWA residues of Clark I and/or Clark II found in lobster (*Nephrops norvegicus*), shrimp

(*Pandalus borealis*) and a flatfish species collected at Måseskär on the West coast of Sweden. Gledhill et al. (2019) found several kinds of explosives in marine biota like algae, asteroidea and tunicata which had been collected at Kolberger Heide, a known dumping ground for different types of munitions in the Bay of Kiel in the Baltic Sea. They found body burdens of HMX, RDX, TNT and ten other explosives with measured concentrations of nearly 25 mg/g in starfish.

For active biomonitoring the species of interest are collected from an unburdened area prior to being selectively deployed in the suspected dumping ground to be tested. Advantages of the latter are: 1) time periods of exposure are known exactly, which offers the opportunity of variation in exposure time to register long- and short-term trends of effects; 2) the ability to vary the distances to a suspected source of contaminants, so that chemical and physical gradients can be detected; 3) a sufficiently large number of test organisms can be exposed and a repetitive test design is possible, both ensuring the statistical power of the study; 4) a better estimation of the health impact on the species used is enabled by analysing biomarkers and comparing the results with species from a reference site.

The difficulty of performing an active biomonitoring is the clever choice of a suitable species. The test organism should, on the one hand, be able to accumulate the contaminants coming into question and should, on the other hand, be robust enough to survive in the test area throughout the study.

For a number of reasons mussels (bivalves) are particularly suitable for the detection and monitoring of chemicals that leach from corroding munitions in the marine environment. Mussels are widespread representatives of the marine fauna; they are benthic and sedentary organisms and they constitute a main source of food for fish, birds, crustaceans and starfish. In addition, their filter feeding lifestyle and their slower metabolic rate favour the absorption and bioaccumulation of explosives. Further, they are a resistant species which can thrive even in unfavourable conditions. Finally, bivalves are important sea food species and can be used as indicators for the entry of toxic substances into the marine food chain even at low concentrations. Biomonitoring with mussels offers the opportunity for long-term studies to predict potential risks for the ecosphere and for human seafood consumers (Farrington et al. 2016; Salazar and Salazar 1995). Mussels have been used in national and international mussel watch programs for more than 40 years to monitor a wide spectrum of contaminants (Farrington et al. 2016), e.g. heavy metals, pesticides, persistent organic pollutants (POPs) and pharmaceuticals (Regoli et al. 2014; Álvarez-Muñoz et al. 2015; Zuykov et al. 2013). Recently it was determined that mussels are very suitable bioindicator species for the monitoring of explosives and CWAs (Strehse and Maser 2020).

Within the frame of the CHEMSEA Project blue mussels (Mytilus edulis) were deployed in the dumping ground of Bornholm and analysed for CWAs, CWA metabolites and a selection of biomarkers (Bełdowski et al. 2014).

The first biomonitoring with blue mussels (*Mytilus* spp.) for munitions compounds was established in the German dumping ground of Kolberger Heide. The area served as a test site to develop new methods and workflows for detection, monitoring and assessment during the German project UDEMM. Divers placed moorings with mussel bags at varying positions near a pile of about 100 moored mines distributed over an area of approximately 70×30 square metres. After recovery, the bioconcentration levels of TNT and its main metabolites 2-amino-4,6-

dinitrotoluene (2-ADNT) and 4-amino-2,6-dinitrotoluene (4-ADNT) were measured successfully in mussel tissues by using a GC/MS-MS analytical method (Maser and Strehse 2020; Appel et al. 2018; Strehse et al. 2017). This method is described in detail within the *Practical Guide for environmental monitoring of conventional munitions in the sea* (Greinert 2019) and could serves as an orientation guide for future monitoring projects.

Bottom dwelling flatfish, common dab (*Limanda limanda*), collected in proximity to the Kolberger Heide munitions dumpsite (fishing within the dumpsite is not possible) were used for passive biomonitoring. Similar to other vertebrates, the livers of fish are major organs for detoxification and products of these processes are excreted via the bile fluid. Indeed, bile fluid from dab collected at the Kolberger Heide dumpsite had higher concentrations of the TNT degradation products 2-ADNT and 4-ADNT compared to dab from uncontaminated sites (Koske et al. 2020).

5. National and International Efforts and Activities

The national and international efforts and activities are grouped according to the relevant International Governmental Organizations (IGOs) and HELCOM Contracting Parties. Each of the IGOs and HELCOM Contracting Parties is covered in a separate chapter, each of which follows the same structure. First, relevant authorities are introduced and the legal situation is outlined. Next, ongoing management activities (as covered in chapter 4 of this assessment) are described. The third section addresses other ongoing activities, such as expert groups, political initiatives and long-term research. The fourth section deals with current scientific and technological development projects that are publicly funded. Finally, past activities and noteworthy research projects are highlighted.

5.1 NATO

This chapter was last updated July 15, 2022.

5.1.1 Ongoing Activities

Ongoing activities are related to NATO units, especially the Standing NATO COUNTERMEASURE GROUPS that are conducting historic ordnance disposal operations (HOD) as one of their regular tasks. In addition, there are regularly scheduled manoeuvres with naval forces of the member states to reduce risks posed by munitions and explosives of concern in European water bodies.

Besides that, NATO's Science for Peace and Security (SPS) Programme has funded the project MODUM. The Science & Technology Organisation (STO) has recently appointed a research task group "Impact of munitions and explosives of concern (MEC) on maritime safety, security and sustainable remediation" (AVT-330), which released a report in 2023.

5.1.2 Past Projects and Activities

<u>MODUM</u>

In 2013, the NATO Science for Peace and Security Program approved the MODUM (Towards the Monitoring of Dumped Munition Threat) research project, aimed at creating the foundations for the monitoring of dumpsites. The project aimed at establishing a cost-effective monitoring network to observe munitions dumpsites in the Baltic Sea, using AUVs and ROVs, and utilizing research vessels of partner institutions as launching platforms. As part of this program, an AUV was used to investigate the Bornholm Deep and Gotland Deep in great detail. The project included nine institutions from Poland, Russia, Denmark, Finland, Germany, Canada, Sweden, Lithuania and Estonia. The results of the project were published in the book from the NATO Science Series by the Springer publishing house (Bełdowski, Been et al. 2017).

Information: http://www.iopan.gda.pl/MODUM/

5.2 European Union

This chapter was last updated July 15, 2022.

5.2.1 Authorities and Legal Situation

In the European Union aspects related to "munitions in the sea" fall under different authorities. So far, no clear leadership can be recognized within the European Parliament or the European Commission.

However, some European Directives clearly address related aspects and thus both the European Commission and the Governments of the Member States are concerned.

<u>European Commission</u>

In the course of parliamentary referral, the European Commission has published the *Study on underwater unexploded munition* related to the European Union Maritime Security Strategy and the Communication on the Sustainable Blue Economy. As the security of seas and oceans appears vital for "economic development, free trade, transport, energy security, tourism and good status of the marine environment" the EC expressed its concern regarding the amount, distribution and status of discarded military munitions in all waterbodies around the European continent.

<u>Maritime spatial planning</u>

Maritime spatial planning (MSP) works across borders and sectors to ensure human activities at sea take place in an efficient, safe and sustainable way. That is why the European Parliament and the Council have adopted legislation to create a common framework for maritime spatial planning in Europe.

<u>Integrated Coastal Zone Management</u>

Coastal zones are among the most productive areas in the world, offering a wide variety of valuable habitats and ecosystems services that have always attracted humans and human activities. The beauty and richness of coastal zones have made them popular settlement areas and tourist destinations, important business zones and transit points. Currently, more than 200 million European citizens live near coastlines, stretching from the North-East Atlantic and the Baltic to the Mediterranean and Black Sea.

<u>Marine Strategy Framework Directive</u>

The aim of the European Union's ambitious Marine Strategy Framework Directive (MSFD) is to protect more effectively the marine environment across Europe. The Marine Strategy Framework Directive was adopted on 17 June 2008.

The Directive shall not apply to activities the sole purpose of which is defence or national security. Member States shall, however, endeavour to ensure that such activities are conducted in a manner that is compatible, so far as reasonable and practicable, with the objectives of this Directive.

Since then, numerous activities to increase the quality status of marine habitats were undertaken. Some Member States have included munitions-related aspects in their national implementation programmes.

In Invitation of the EEAS and DG ENV a colloquium "The Challenges of Unexplodes Munitions" (Brussels 20 February 2019) has addressed concerns in line with DG HOME, MOVE, MARE, DEVCO and many regional and national entities active in marine nature conservation.

<u>EU Maritime Security Strategy Action Plan</u>

In action number B 4.2 (Baltic Sea) of the recent EU Maritime Security Strategy Action Plan a close cooperation between HELCOM and the EU is stated to tackle the challenges caused by UXO and sea-dumped chemical munitions. One of the goals of this action item is to "promote exercises and training programmes, […], to optimise the disposal and, where possible, the elimination of sea-dumped chemical munitions and unexploded ordnances".

Information: https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/2018-06-26-eumss-revised-action-plan_en.pdf

<u>Species protection</u>

In EU Member States the Habitats Directive regulates the protection of specially protected habitats and species. It requires a system of strict protection for the species listed in Annex IV which includes inter alia all species of cetaceans. Among other aspects, this covers the prohibition of all forms of deliberate capture or killing of specimens of these species in the wild. The Birds Directive likewise prohibits deliberate killing or capture of wild birds by any method including deliberate destruction of, or damage to, their nests and eggs or removal of their nests. The EU Marine Strategy Framework Directive (MSFD) covers inter alia the introduction of energy into marine waters, including underwater noise and has a special relevance for underwater explosions, which are the loudest anthropogenic underwater point source of impulsive noise (Koschinski 2011). The aim of the MSFD is that by 2020 noise levels "do not adversely affect the marine environment" within the EU.

5.2.2 Ongoing Activities

<u>JPI Oceans</u>

On a European level, Joint Programming Initiatives (JPI) are the result of a structured and strategic process of voluntary agreement on common visions in order to address major societal challenges by EU member states, associated countries and international partners. JPI Oceans focuses on achieving a state of healthy and productive seas and oceans.

As a result of discussions between the most relevant stakeholders, it has been decided that JPI Oceans will conduct activities along three lines:

Science Support – By combining different scientific disciplines, JPI Oceans intends to support the development of a service to forecast changes in the sea state in relation to munitions. Investigations will study the impact of removal, dispersion and detonation on human health, the environment and economic activities.

Technology Transfer – JPI Oceans will analyse different technologies and procedures for intervention to support decisions by operators and policy makers. The development demonstration of technologies and procedures can be used to increase safety, improve the efficacy and reduce the environmental impacts of interventions. JPI Oceans will provide support to exchange findings between different disciplines, projects and initiatives.

Exchange of Knowledge – Panels of experts will support the transfer of knowledge and experiences of dealing with munitions in the sea.

Information: https://www.jpi-oceans.eu/munitions-sea

5.2.3 Current Projects

MARTERA AMMOTRACE (2021-2024)

Project AMMOTRACe (AMMunitiOn exploration by surface- and underwater-based laser mass spectrometric TRACing tEchnology), funded under the MARTERA programme, draws together European companies and research organisations that develop analytical techniques and instruments for environmental contaminant measurements, design and build hardware for underwater operations in marine systems, assess the presence of historic munitions in marine waters and sediments, and conduct underwater munitions clearance operations. AMMOTRACe aims to develop new shipboard and in situ measurement approaches to detect conventional and chemical warfare munitions compounds in coastal systems in real-time. It will demonstrate the application of chemical sensing alongside traditional geophysical measurements at munitions dumpsites and other regions with the presence of munitions. The project will develop new approaches based on laser photoionisation mass spectrometry (PIMS) and ion mobility spectrometry (IMS) by combining the latest laser, ion detector, platform and communication technologies to be used for marine munitions detection and clearance. AMMOTRACe is a transdisciplinary project, involving science, engineering and companies across a range of disciplines to develop new solutions beyond disciplinary perspectives. The project has been co-designed with companies marketing environmental monitoring instrumentation and conducting marine EOD operations, and AMMOTRACe aims to co-produce its technologies and thereby facilitate a smooth technology transfer to companies and society.

Information: https://www.geomar.de/en/ammotrace

Contact: Dr. Aaron Beck (ajbeck@geomar.de)

MARTERA PROBANNT (2021-2024)

The tools that are developed during ProBaNNt (Professional intelligent munitions assessment using 3D reconstructions and Bayesian Neural Networks) address the most critical point in the value chain of munitions clearance: after the detection of munitions and before the clearance operation itself. The ProBaNNt project aims to improve the decision-making capabilities on various levels, thereby generating a comprehensive tool to support offshore explosive ordnance disposal (EOD) campaigns. It integrates sustainable convergence, use and analysis of existing EOD data with new data acquisition techniques, such as 3D photogrammetry and ad-hoc assessment of sediment properties. All of this information will be integrated into a decision-making software (an EOD support tool) that uses Bayesian Neural Networks to propose the most viable clearance option for a given munitions object at a given location. Data will be gathered both by reviewing past EOD campaigns, by accompanying EOD campaigns and through specific data acquisition campaigns that take place in known munitions dumpsites. The viability of all developments will be validated though dialogue with EOD experts to determine whether and how these tools improve decision-making capabilities and to be able to make adaptations the research according to industry needs.

Information: https://www.probannt-munition.eu

Contact: Torsten Frey (tfrey@geomar.de)

<u>MARTERA EROVMUS (2022-2025)</u>

Enhanced Remote Operated Vehicle interface for munition studies Project (EROVMUS) aims to create an improved interface for ROV pilots to enable easier and more cost effective ROV deployments in missions related to dumped underwater munitions. This will include both the creation of multisensory platforms and improved software solutions. Proposed activities are related to navigation improvement, introduction of autonomous identification routines, as well as image enhancement technologies. Information from multiple sensors will be overlaid to produce an equivalent of a Heads Up Display (HUD) for the pilot, reducing the number of displays needed for effective operation. In addition, Virtual Reality (VR) solutions will be investigated to enable the use of virtual displays and combine image from multiple cameras to create large virtual displays to improve munitions identification. The project will develop, test and optimize a range of tools, as well as approach their interoperability with multiple models and makes of existing ROVs. This will potentially create a range of products that could be deployed by ROV manufacturers. The results of this project could potentially improve state-of-the-art technology, as well as creating new jobs and improve the competitiveness of the European underwater tech sector.

5.2.4 Past Projects and Activities

<u>INTERREG -CHEMSEA</u>

CHEMSEA investigated official and unofficial dumping grounds using hydro-acoustic detection and magnetic surveys to find links between objects on the seabed and magnetic field disturbances, to examine currents and to sample sediment so as to characterise the natural conditions of the sites. Mapping involved categorising objects, selecting those needing further investigation and feeding coordinates of munitions and contaminated sediment into maps. Toxicity studies aimed to investigate biological uptake of CWAs under varying conditions. Cages were deployed where the concentration of munitions was highest before accumulation and biological effects of chemical substances in fauna were measured. CHEMSEA reviewed national CWA legislation and formulated guidelines for munitions handling as well as hazardous waste and contaminated sediment disposal. A regional contingency plan was drawn up comprising of codes of conduct in the event of an accidental catch of chemical munitions at sea or their being washed ashore. Models were developed for both scenarios, leading to the standardization of national response procedures and plans. Awareness levels of groups at risk of contact with CWAs were evaluated, including fishermen and offshore workers. Training was aimed to spread knowledge of chemical munitions dumped at sea along with best practices for minimizing threats.

<u>INTERREG-DAIMON</u>

In 2016, the European Union financed the DAIMON (Decision Aid for Marine Munitions) project under the INTERREG Baltic Sea Region program. It was composed of institutions from Poland, Finland, Sweden, Norway, Germany and Lithuania. The question which DAIMON took up is how to proceed with the identified and mapped warfare objects. Remediation or no action are subject to heated disputes among the decision-making bodies. Since there cannot be a general answer to this question, DAIMON has analysed identified and localized objects with artificial intelligence incorporating large amounts of spatial and non-spatial datasets based on latest scientific research. The DAIMON project developed a tool to assess the risk of individual bombs and other warfare materials, chemical and conventional. For each detected munitions object, the software formulates a risk assessment, incorporating information about the location and overall state of the warfare materials, the surrounding environment and state of biological pollution or damage. Furthermore, it recommends possible actions, such as recovery and destruction, accumulation, encapsulation, capping, blasting or non-action. DAIMON followed an integrative approach and incorporates the results of former projects (e.g. CHEMSEA) for an efficient use of data and a consecutive development of knowledge. This tool is used to support decisions on possible remediation methods. The project also produced a set of risk assessment methods for chemical and conventional munitions, known as the ECOTOX Toolbox. In the DAIMON project first results showing bioaccumulation of CWAs in fish tissue were published.

In 2019, the INTERREG BSR program approved the Decision Aid for Marine Munitions, Practical Applications (DAIMON2) project. The project brought together nine institutions from Poland, Lithuania, Germany, Finland, Norway and Sweden. The project was aimed at implementing the tools developed in the DAIMON project, conducting trainings, and demonstrating the operation of the decision support system. It ended in July 2021.

Information: https://www.daimonproject.com/

Contact: Prof. Jacek Bełdowski (hyron@iopan.pl)

5.3 Russian Federation

The Russian Federation did not provide any information on past, present or future activities.

5.4 Denmark

This chapter was last updated before January 1, 2022.

5.4.4.1 Authorities and Legal Situation

<u>*The Royal Danish Navy*</u>

Email: fko@mil.dk

Phone: +45 7284 0000

Further information: www.forsvaret.dk/en/organisation/navy/

<u>*Danish Defence's Joint Operations Centre*</u>

Email: fko-joc@mil.dk

Phone: +45 7281 2300

Further information: www.forsvaret.dk/en/organisation/joint-services/joint-operations-centre-joc/

<u>Danish Emergency Management Agency</u>

In case of bycatch of chemical munitions, the responsibilities of the Danish Emergency Management Agency (DEMA) are:

- The regional DEMA Rescue Centre performs the cleaning of the vessel.
- The Duty HazMat Officer from DEMA Chemical Operation gives advice on chemical warfare agents.
- The DEMA Chemical Operation can perform chemical analysis of bycaught chemical warfare agents.

Contact: Email: brs@brs.dk, Phone: +45 4590 6000

Further information: www.brs.dk/en/

<u>The Danish Fisheries Agency</u>

In case of bycatch of chemical munition, the responsibilities of the Danish Fishery Agency are:

- Estimate the value of the fish catch in case an economic compensation is required.
- Provide the Royal Danish Navy with information on location of bycatch.
- Ensure contaminated fish are not released for sale.
- Assess in collaboration with the Danish Emergency Management Agency if the cleaning procedures have been sufficient for the vessel to be released to continue its fishing activities.
- Ensure rightful depreciation of the fish quotas.

Contact for the areas Baltic Sea, Southern Kattegat, Sounds and Belts: Email: inspektoratoest@fiskeristyrelsen.dk, Phone: +45 7218 5600

Contact for the areas North Sea and Western coast of Jutland: Email: inspektoratvest@fiskeristyrelsen.dk, Phone: +45 7218 5600

Further information: https://fiskeristyrelsen.dk/english/

Danish Maritime Authority

Email: sfs@dma.dk, mrj@dma.dk

Phone: +45 7219 6000

Further information: https://www.dma.dk/Sider/default.aspx

The Danish Veterinary and Food Administration

Phone: +45 7227 6900

Further information: https://www.foedevarestyrelsen.dk/english/Pages/default.aspx

The Danish Environmental Protection Agency

Email: *mst@mst.dk*

Phone: +45 7254 4000

Further information: https://eng.mst.dk/

Laws and regulations

The following ministerial orders apply to warfare materials in the sea:

- Ministerial order concerning landing of fish from areas with chemical munitions (https://www.retsinformation.dk/eli/lta/2009/775) (The Danish Veterinary and Food Administration). This order only covers the ICES subdivision 24-32 in the eastern part of the Baltic Sea.
- In case of bycatch of chemical munition, the procedures described in Ministerial order no. 775 of 10/08/2009 have to be followed. The bycatch is reported to the Danish Defence's Joint Operations Centre that informs the Danish Fisheries Agency's local unit in Rønne about the vessel ID and which harbour it will enter to be cleaned. A representative from the Danish Fishery Agency will be present onboard the vessel.
- *Ministerial order concerning sailing safety during entrepreneur work and other activities in Danish waters (*Ministerial order no. 1351 of 29/11/2013*) (Danish Maritime Authority)*
- *Ministerial order concerning ban against sailing, anchoring and fishing etc. in certain areas of Danish waters (*Ministerial order no. 135 of 04/03/2005*) (Danish Maritime Authority)*
- *Ministerial order concerning Marine Strategy Framework Directive (*Ministerial order no. 1161 of 25/11/2019, Ministerial order no. 522 of 2010*) (Danish Environmental Protection Agency)*

Note that the ministerial orders apply to different geographical judicial areas. Some apply to Danish coastal waters, some include the EEZ and some only refer to subsidiary areas of these.

In addition to the ministerial orders mentioned above, the Danish Fishermen's Occupational Health Services have provided documentations on precautions and on first aid related to the bycatch of munitions that should be followed.

5.4.4.2 Ongoing Management Activities

Ongoing activities on munitions assessment

None

Clearance methods

In general, historic ordnance or explosives are assessed to be unstable and relocation involves unacceptable risks. Thus, the typically used disposal method is by blasting by the Royal Danish Navy's Clearing Diving Team.

Historic files studied

No published studies

Number of items cleared

The number of items encountered and cleared (blasted) in the North Sea are reported annually to OSPAR according to their reporting guidelines. There is no similar reporting scheme to HELCOM. The Danish Environmental Protection Agency is responsible for the reporting.

Funding of the activities

The Danish Government

5.4.4.3 Other Ongoing Activities

Denmark continues to participate and contribute to the HELCOM and OSPAR work on the topic. The Danish Environmental Protection Agency and the Danish Centre for Environment and Energy (Aarhus University) are represented in the HELCOM Submerged working group. In general, Denmark will continue to support a common approach for management of warfare materials in the sea in the regional conventions.

The Danish Centre for Environment and Energy (Aarhus University) is involved as an expert group on the subject and act as technical support for the authorities.

5.4.4.4 Past Projects and Activities

The Danish Centre for Environment and Energy (Aarhus University) participated in NATO-funded research in the Baltic Sea with partners around the Baltic in the project "MODUM – Towards the monitoring of dumped munitions threat" and published findings on the topic.

5.5 Estonia

This chapter was last updated before January 1, 2022.

5.5.4.1 Authorities and Legal Situation

Governmental agencies operating at sea or having tasks related to the maritime domain based on national legislation are as follows:

- Defence Forces (www.mil.ee)
- Rescue Board (www.rescue.ee)
- Police and Border Guard Board (www.politsei.ee)

- Maritime Administration (veeteedeamet.ee)
- Heritage Board (www.muinsuskaitseamet.ee)
- Environmental Board (www.keskkonnaamet.ee)
- Environmental Inspectorate (www.kki.ee)
- Estonian Emergency Response Centre (www.112.ee)

Each of the above agencies have their own respective tasks, varying from state defence, maritime security, maritime safety, environmental protection to preservation of national heritage objects (including wrecks etc.).

<u>Cooperation between Estonian Navy and Rescue Board</u>

Based on national legislation, the Estonian Navy (part of Estonian Defence Forces under the Ministry of Defence) has the sole responsibility to react to situations connected to historic and modern warfare materials when such situations occur in the maritime domain. However, a very close cooperation is ongoing with the Estonian Rescue Board (operating under the Ministry of Interior).

The Rescue Board deals with explosive material, munitions and ordnance on land. When explosive material, munitions and ordnance is located in harbour areas or inland water bodies Estonian Navy and Rescue Board cooperate, assisting each other with their respective capabilities and expertise.

Emergency Response Centre

For the public a single 24/7 initial point of contact is the Estonian Emergency Response Centre (112) where citizens shall report all encounters with possible warfare materials both on land and at sea.

<u>Laws and regulations</u>

Currently there is no overarching single permanent legal act in place to cope with all possible challenges when dealing with warfare materials. There are, however, a number of interagency cooperation agreements that provide a sufficient basis.

5.5.4.2 Ongoing Management Activities

There are currently no dedicated governmental-funded long-term national projects or programmes to systematically and effectively deal with the challenges posed by remaining warfare materials in the sea.

<u>BOSP membership</u>

Activities dealing with warfare materials from previous armed conflicts left in Estonia’s maritime area are handled in conjunction with the Estonian Navy. Estonia is a member of BOSB (Baltic Ordnance Safety Board). Based on collective effort carried out within the framework of BOSB, regular, targeted historic ordnance disposal activities take place in a form of both multinational mine/ordnance clearance activities and national activities carried out by the Estonian Navy.

OPEN SPIRIT

The OPEN SPIRIT series of activities rotates between respective Baltic nations in such a manner that Estonia hosts this activity every third year. The Estonian Navy combines its national mine countermeasure training activities with international efforts to gradually, on a tailored, systematic and effects-based approach, reduce possible risks posed by warfare materials. These activities are targeted to the most risk-prone areas. However, they are time and resource consuming. Hence, given the best available knowledge regarding the likely amounts of warfare materials in the sea, these activities will most likely continue to a near future.

Construction Projects

The Estonian Navy regularly advises different governmentally owned and commercial entities, both international and domestic, who have interest in maritime infrastructure development projects within Estonian waters. Examples of such projects could be harbour construction and dredging works, laying of underwater communication and electricity cables, underwater pipelines, different types of aquaculture, offshore wind farms and other similar developments requiring work carried out on the seabed. A number of case-by-case assessments are conducted yearly to advise the above entities on the possible risk areas and risks posed to underwater construction by warfare materials in the sea.

5.5.4.3 Past Projects and Activities

Structured surveying and clearance

A number of dedicated warfare materials clearance activities have taken place within the Estonian maritime area since 1994. The very first of such events took place in 1994, when the Estonian Navy together with the Royal Swedish Navy charted a number of previously known Soviet era explosives dumping grounds within the Estonian maritime areas in the Gulf of Finland near Tallinn and Paldiski. Afterwards a series of MCOPEST (in total 5), OPEN SPIRIT (in total so far 8), FINEST (in total 3) activities and a vast number of different national, bilateral and international historic ordnance disposal activities were carried out in Estonia under the lead of the Estonian Navy. The result of these activities is that about 1,200 warfare material items of different types were located and identified, but due to different reasons only about one-third of them were cleared. Most of the located and identified warfare materials left in place are either in water depths great enough not to pose a risk to surface shipping or have been located in close proximity to different existing underwater installations (namely underwater cables).

Construction projects

In recent years a number of different calibre warfare materials (ranging from naval mines and costal artillery shells to small calibre munitions) have been located during harbour construction and corresponding dredging works. These types of situations have significantly improved the cooperation between different national authorities, namely the Estonian Navy and Estonian Rescue Board.

Societal Awareness

There are currently no dedicated governmentally funded long-term projects or activities ongoing in order to raise societal awareness regarding possible munitions and ordnance.

The Estonian Ministry of Interior together with the Rescue Board carries out seasonal public media campaigns with the aim of instructing the public how to act when possible warfare materials are found (call 112 or a specific phone number found on the Rescue Board website). These activities generally target people on land as there is a significant amount of land-based warfare materials found yearly.

The Estonian Navy carries out information days with the aim of raising awareness within specific target audiences. Main target group for these information days so far were primarily civilian leisure and hobby divers who may come into contact with historic munitions at sea.

As a joint agreed venture between the Estonian Navy and the Maritime Administration all navigation material (including navigation charts) published by the Maritime Administration has a notice on them stating that all maritime areas currently under Estonian jurisdiction should be considered as Former Mined Areas.

OPEN SPIRIT 2018

In 2018, OPEN SPIRIT took placed in Estonian waters. From 11-25 May 17 units with a crew of 800 sailors found and disposed 90 mines, bombs, torpedoes, depth charges and artillery shells. The three oldest objects were two German airdropped TeKa-mines and one UC 200 mines; all three were laid in August 1917. The TeKa mine was developed for laying by submarine, but the transport system in the submarine torpedo tube did not work correctly. A first try to lay the mine via airplane was successful and the decision for the first airdrop minelaying was given to the Fliegerstation Windau. Airplanes from type Gotha laid in July and August 1917 in the north part of Irben Strait 72 TeKa mines.

Figure 2. Open Spirit 2018 LMB Mine

Similar as BALTIC SWEEP and OPEN SPIRIT operations were the Swedish- Estonian-Latvian and Lithuanian Mine Countermeasure Operations. From 1995 till 2009 the Royal Swedish Navy and the Navies from the three Baltic States reduced the risk of warfare materials with joint operations. Later they were joined by NATO Forces. During 18 operations 670 warfare materials were found, marked, documented and disposed of. The operations areas were the three Baltic states' territorial waters.

5.6 Finland

This chapter was last updated June 22, 2022.

5.6.4.1 Authorities and Legal Situation

Finnish Defence Forces

The clearance of wartime materials (including chemical weapons) is the responsibility of Defence Forces by law (Explosives Decree 28.5.1993/473, 84 §):

"The Defence Forces should take possession of explosive material, which has or on the basis of its quality warrants reason to believe that it has belonged to either Finland or to the armed forces of a foreign country. Defence Forces shall ensure its proper and safe transport, storage and disposal." (Unofficial translation from the original text in Finnish)

The clearance is under the responsibility of Finnish Navy and Army engineers in cooperation with the Army's CBRN Defence Special Unit, which is complemented with a deployable CBRNE laboratory. The detachment required for the task will be formed according to the situation assessment. The current official instructions of Defence Forces that are applied to old chemical weapons clearing consists of regulations, guides and manuals related to the clearance and protection missions in general. However, these documents cover only marginally the clearance of chemical weapons in particular. The applied procedures will be chosen based on the national and international operations models on the clearance of chemical weapons.

Finnish Navy Operation centre

Email: tilannekeskus.merive@mil.fi

Further information: www.merivoimat.fi/en

Laws and regulations

When warfare materials are found the chain of action will proceed as follows in accordance with the following legislation (Act on Defence Forces 11.5.2007/551, Act on Defence Forces assistance to the police 5.12.1980/781):

- The finder notifies the Coast Guard, police, or Rescue Department.

- The notified authority sends request for assistance to the Defence Forces (for example, to the Southern Finland Military Province).
- The order will be issued to Finnish Defence Force detachments for the clearance and protection mission.

5.6.4.2 Current Projects

<u>WARTOX</u>

CWAs in the Baltic Sea: Biotransformation products and their toxicity – WARTOX is a cooperation project with the Finnish Environment Institute SYKE and Finnish Institute for Verification of the Chemical Weapons Convention VERIFIN. It is funded by the Academy of Finland for 2021-2023 and aims to:

- Investigate the biotransformation of phenylarsenic CWA and Sulfur mustard in Baltic Sea sediments and identify the main microbial groups responsible.
- Develop targeted chemical analysis methods for the identified biotransformation products.
- Study the metabolism of Sulfur mustard in aquatic biota using in vitro models.
- Assess toxicity and sublethal effects of the main biotransformation products of phenylarsenic CWAs in model species.

5.6.4.3 Past Projects and Activities

In addition to the above-mentioned ongoing WARTOX project, SYKE and VERIFIN have participated in numerous EU-projects related to chemical and conventional munitions in the Baltic Sea region.

<u>CHEMSEA</u>

During the CHEMSEA project it was proven for the first time that leaking CWAs cause biological effects in marine biota using in situ experiments. As a part of the project, a guideline concerning old munitions on the seafloor was produced for Finnish fishermen. The Finnish fishermen's guide was originally prepared during the years 1995-1996 by the Ministry of Environment together with the Ministry of Agriculture and Forestry, the Ministry of Social Affairs and Health, the provincial government of Åland, the Finnish Defence Forces and its Technical Research Centre, the Poison Information Center (Helsinki University Hospital), Institute of Occupational Health, University of Helsinki, Federation of Fisheries, and Federation of Finnish Fishermen's Association. The guide was distributed by the Federation of Fisheries starting in January 1997. During CHEMSEA-project, the guide was updated and distributed to relevant stakeholders.

<u>DAIMON and DAIMON 2</u>

During the DAIMON project, VERIFIN developed novel chemical analysis methods for studying uptake of arsenic-based CWAs, such as Clark I/II, Adamsite and triphenylarsine (component of arsine oil) by marine biota. During the project it was demonstrated for the first time that degradation products of CWAs are accumulating in different marine biota species. Atlantic cod samples that were collected from the Bornholm CWA dumpsite were analysed and results showed that 13% of the 100 analysed cod muscle samples contained CWA-related phenylarsenic chemicals. VERIFIN also identified novel phenylarsenic chemicals that originate from Clark I, Adamsite, phenyldichloroarsine and triphenylarsine in sediment samples collected from different CWA dumpsites in the Baltic Sea area. These chemicals are most likely produced by microbial activities in marine sediment. In addition, new biomarker methods were validated and a large set of marine animals from different dumpsites were analysed in SYKE.

During 2019-2021 SYKE and VERIFIN participated in the DAIMON 2 extension project. It continued development and training for the use of a Decision Support System (DSS) for marine management which was produced during the DAIMON project. In 2021 SYKE and VERIFIN gave trainings on the DSS and EcoTox Toolbox to Finnish authorities, decision makers and other stakeholders dealing with marine munitions.

5.7 Germany

This chapter was last updated before January 1, 2022.

5.7.4.1 Authorities and Legal Situation

Germany is a federal republic. Due to this political setup, the location at which warfare materials are present determines whether either the federal government or the government of one of Germany's five coastal states is responsible. In other words, responsibilities are different depending on whether the warfare materials are present in a harbour area, estuary, beach, coastal or open water. Consequently, the authority that is required to handle an issue may vary, depending on the geographic location of warfare material.

<u>State EOD Service</u>

Within German territorial waters the legal basis for the detection and clearance of warfare materials is the German Explosives Law (SprengG). The bodies listed in Table 6 are responsible for explosive ordnance disposal and may carry out clearance operations in the territorial waters of their federal state. They handle their mission with their own resources only to a certain extent. If workload is exceeded, private companies or consortia of service providers are contracted in, on a case-by-case basis. Private sector contributors serve under supervision of the responsible regulatory state authority. State EOD services may define requirements for the detection or clearance of warfare materials when conducted by other organizations. They may furthermore monitor compliance with these requirements on board the vessels used in their respective territorial waters. This is especially relevant when new technologies are used or organizations that were previously unknown are commissioned with detection and clearance services. The legal basis for these bodies are provisions made by the respective federal states. All warfare materials recovered within state territory or which have been imported to a harbour is confiscated by the locally responsible state service.

Table 6. German coastal federal states and state EOD services

Federal State	Responsible body
Bremen	Kampfmittelräumdienst
Hamburg	Kampfmittelräumdienst der Feuerwehr Hamburg
Mecklenburg–West Pomerania	Munitionsbergungsdienst
Lower Saxony	Kampfmittelbeseitigungsdienst
Schleswig-Holstein	Kampfmittelräumdienst

Outside German territorial waters no single body is responsible for explosive ordnance disposal.

Federal Maritime and Hydrographic Agency (BSH)

The BSH is a higher federal authority that is subordinated to the Federal Ministry for Digital and Transport (BMDV). It is the public institution for maritime tasks. This concerns tasks such as averting dangers at sea, issuing official nautical charts and surveying tasks in the North Sea and Baltic Sea, as well as forecasting tides, water levels and storm surges. With regard to construction projects in the North and Baltic Seas, the BSH is responsible for spatial planning and for the testing and approval of power generation systems, cables, pipelines and other systems within the scope of federal responsibility.

The following BSH activities and topics may have a relation to warfare materials:

- Hydrographic surveys and wreck search
- Geological surveys
- Offshore constructions (e.g. windfarms, sea cables, pipelines)
- National Underwater noise register (https://marinears.bsh.de/FIS_SCHALL_PORTAL/pages/index.jsf)
- OSPAR munitions encounter reporting
- Collaboration with other agencies and bodies (e.g. Federal Waterways and Shipping Directorate, German navy)

Contact: posteingang@bsh.de

Further information: https://www.bsh.de/EN

Central Command for Maritime Emergencies

In order to cope with the challenging multifaceted accountabilities and responsibilities, the German Federation and the coastal states have established the Central Command for Maritime Emergencies (CCME) in Cuxhaven, as a 24/7 central access point to multiple maritime agencies in Germany.

Contact: mlz@havariekommando.de

Further information: https://www.havariekommando.de/EN/

Waterways Police Reporting and Coordination Centre

The German Waterways Police Reporting and Coordination Centre at the Joint Emergency Reporting and Assessment Centre Sea in the Maritime Safety and Security Centre took over the responsibilities of the Reporting Centre for Munition Finds in the North- and Baltic Sea in 2012. It operates a central marine munitions reporting office where all detected warfare materials and subsequent management activities must be reported. Prior to execution, all detonations of warfare materials have to be registered with the same body. In addition, the reporting office has to be presented with verification of proper disposal of munitions and munitions components.

Contact: wsp@msz-cuxhaven.de

Further information: https://www.schleswig-holstein.de/uxo/DE/Partner/_documents/partner_Meldestelle.html

State Government Bodies responsible for Occupational Health and Safety

The bodies listed in Table 7 define requirements for adherence to the Safety at Work Act within and outside German territorial waters.

Table 7. German coastal regions and responsible bodies by state

Region	Responsible body
Lower Saxony and part of the EEZ off the coast of Lower Saxony	Gewerbeaufsichtsamt Oldenburg
Schleswig-Holstein and part of the EEZ off the coast of Schleswig-Holstein	Staatliche Arbeitsschutzbehörde bei der Unfallkasse Nord
Mecklenburg–West Pomerania and part of the EEZ off the coast of Mecklenburg–West Pomerania	Landesamt für Gesundheit und Soziales Mecklenburg-Vorpommern

Method statements for detection and clearance operations have to be handed over to the body responsible in the respective geographic area for plausibility checking and commenting. All occupational safety incidents have to be registered with these authorities.

Federal Waterways and Shipping Administration (WSV)

In general, the five coastal states in Germany are responsible for safety and security as well as law enforcement. There is one exemption: the Federal Waterways and Shipping Administration is responsible for safe and efficient vessel traffic. Nine VTS Centres are located along the German North Sea and Baltic Sea Coast and the adjacent harbour approaches. The VTS operators monitor and organise the vessel traffic and provide information as well as assistance when necessary. The VTS Centres function as primary contact points for vessel traffic regarding shipping and safety.

In this sense, the WSV supports the authorities according to Table 8 in the clearance of explosive ordnance by closing the shipping routes and by informing maritime traffic. In addition, mariners are informed by the VTS Centres if warfare materials that are dangerous to shipping is found on shipping routes. If warfare materials are found by a ship, the ship's commander is obliged to report this to the regional VTS Centres immediately. Further measures to check and, if necessary, eliminate the danger are then taken by the authorities according to Table 8.

In addition, relevant information for the shipping traffic is published in written form (in German: Bekanntmachung für Seefahrer – BfS), for example, the announcement of detection and clearance activities of warfare materials. Within German territorial waters information is published by the bodies listed according to the Electronic Waterway Information Service of the Federal Waterways and Shipping Administration.

Contact: gdws@wsv.bund.de

Information: https://www.elwis.de/DE/dynamisch/BfS/

<u>German Armed Forces</u>

The German Armed Forces (Bundeswehr) are not responsible for any activities which are relevant to warfare materials in the sea. However, they are involved in some instances.

<u>German Federal Environment Agency (UBA)</u>

The task of the German Federal Environment Agency (UBA) is to ensure that citizens are able to live in a healthy environment with clean air and water, free of pollutants to the greatest extent possible. UBAs work centres around gathering data concerning the state of the environment, assessment of the environmental status, investigating relevant interrelationships and making projections – and then, based on these findings, providing federal bodies such as the Ministry of the Environment with policy advice. UBA also provides the general public with information and answers questions on all of the various issues that it addresses. Apart from these activities, UBA together with other relevant federal and federal states institutions implements environmental law such as the Marine Strategy Framework Directive (MSFD) in Germany.

Regarding the issue of warfare materials in the marine environment, UBA has financed external research to analyse TNT and its metabolites in sediment and organisms such as mussels, fish and marine mammals in all coastal waters continuously since 1990 using samples from UBAs environmental specimen bank. Data on hazardous substances are reported to the Marine Environmental Database (MUDAB) of UBA and are assessed and reported to the EU, Regional Sea Conventions (RSC), including HELCOM, and the public. UBA itself conducts standardised eco-toxicity tests on TNT and its metabolites in its labs and derives Environmental Quality Standards (EQS) to determine if environmental concentrations of these substances are harmful to the environment. In case of occurrence of harmful concentrations above EQS, UBA would suggest measures to the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, e.g. to remove the source of pollution, such as clearance of warfare materials.

Contact: Anita Künitzer – anita.kuenitzer@uba.de

German Federal Agency for Nature Conservation

In the German EEZ the Federal Agency for Nature Conservation (BfN) is responsible for the protection of habitats and species, not only in the three marine protected areas they manage in the Baltic Sea but also outside in the EEZ. This is of special relevance when munitions clearance may compromise the conservation status of a protected species or habitat, such as blow-in-place operations. Currently, a working group chaired by BfN is elaborating a guidance on legal and practical requirements in nature conservation for the clearance and disposal of legacy munitions in the North Sea and Baltic Sea.

Contact: Jochen Krause – jochen.krause@bfn.de

Central reporting unit for munitions in the sea

The central reporting unit for munitions in the sea is integrated in the Joint Centre of the water police of the coastal federal states, which is part of the Maritime Safety and Security Centre in Cuxhaven. It was established in 2012, following a recommendation of the Cross-Administrative Working Group Munitions in the Sea in their 2011 report on warfare materials in German waters.

The unit records the occurrence of warfare material, parts thereof and suspicious objects that are found in German waters, along the German coast and in the German EEZ. It operates day and night and distributes the recorded data, photos and descriptions to other responsible bodies on federal and state level. Incoming data is based on the observations which citizens make and from the police stations that are part of the joint centre of the water police. Other reports originate from vessels of authorities and companies that are commissioned to maintain the maritime water ways. These may encounter warfare materials during surveys and dredging. A significant amount of data is furthermore provided via the discovery and clearance reports of the state EOD services of the coastal federal states and private EOD companies. The latter usually encounter warfare materials during preparatory and developmental work on the sea floor for the construction of pipelines, wind parks and cables.

Also, the central reporting unit generates yearly statistics that distinguish between the EEZ, coastal waters and internal waters in the North and Baltic Seas. Heavy fluctuations between years are a result of two factors. First, the contamination with warfare materials varies between areas that are investigated. Second, the intensity of investigations preparing the construction of wind parks and pipelines is driven by construction activity and therefore fluctuates between years. A recorded number of the central reporting may refer to a single larger object or it may refer to a cluster of small arms munitions.

Contact: wsp@msz-cuxhaven.de

Information: http://meldestelle.munition-im-meer.de

5.7.4.2 Ongoing Management Activities

This section describes all activities that are directly related to the management of warfare materials in the sea (see chapter 4). This includes assessment methods, technical investigation with the aim of detecting munitions and the clearance of warfare material.

Archival Work

The German Military Archive in Freiburg stores 51 km of relevant files of which a well-functioning team can check 5-6 m with nearly 350 individual files over the course of one week. In a total of 16 research weeks from 2010 to 2018, 1,166 files concerning warfare materials at sea were copied and scanned. Complemented by nearly 240 files from the UK National Archive in Kew and from the Royal Navy, a solid knowledge base was established. In 2018, two weeks were spent for research in the German Military Archive in Freiburg. A total of 25,917 pages of nearly 650 different documents were scanned. The focus of World War I documents lies on mine warfare in the central and eastern Baltic Sea and artillery fights in the area of the Baltic isles. World War II documents focus on mine warfare and air defence in the western Baltic Sea. They contain a large number of pages regarding minesweeping in the entire Baltic Sea, air strikes and artillery fights. Furthermore, information regarding air-defence along the German coastline against Allied bombers and the calculation of misfired artillery shells was acquired. Some documents provide information regarding the storage of warfare materials during the final months of the war and the way to the dumping grounds.

5.7.4.3 Other Ongoing Activities

This section describes other ongoing activities in Germany that are not directly related to the management of warfare materials but are related to this issue in general. These are ongoing and not project related and therefore not limited in time. Table 8 displays German ongoing activities and projects and their field of application in the issue of warfare materials in the Baltic.

Table 8. German activities and projects and their field of application in the issue of warfare materials in the Baltic

Activity or Project / Field of Application	AMUCAD	Group Munition in the Sea	BASTA	ExPloTect	MUNISEE	RoBEMM	UDEMM	Mercury Pollution	Munitect	SOAM
Mapping	X									
Environmental Impacts				X	X		X	X		
Munition's Migration							X			
Coordination		X							X	
EOD Technology						X				
Survey Technology			X	X					X	X

AMUCAD

The Ammunition Cadaster Sea (AMUCAD) is developed by north.io GmbH in close consultation with the MELUND. It deals with the acquisition, management and analysis of a wide variety of warfare materials-related datasets for the North and Baltic Seas. Therefore, a large amount of historical and modern datasets is acquired and integrated into the system and new technologies like artificial intelligence and visual analytics are used for interpreting and connecting these datasets. AMUCAD is part of several national (ERPAD) and international (DAIMON, NSW) research projects whose results will be implemented and further developed. It is designed for use in administration, research, and business, and provides a central information system for different applications such as marine spatial planning, offshore infrastructure development and environmental monitoring.

Contact: Jann Wendt – jann.wendt@north.io

Further Information: https://www.amucad.org

Cross-Administrative Working Group Munitions in the Sea

A cross-administrative working group drives the German Programme on Underwater Munitions. In 2008, today's Ministry of Energy, Agriculture, the Environment, Nature and Digitalization (MELUND) of the state of Schleswig-Holstein, initiated the collaboration and it continues to serve as leading partner. The group initially functioned as a platform for state ministries of interior and marine protection to share knowledge and discuss public relations. Federal agencies joined the group in 2009. The group's first task was the generation of the report *Munitions in German Marine Waters – Stocktaking and Recommendations*, which has since been amended on an annual basis. Furthermore, the German governing body for the implementation of the European Marine Strategy Framework Directive (MSFD) commissioned the working group with the facilitation and oversight of the implementation of recommended measures and with managing this societal challenge. The working group has established a national point of contact for munitions encounters in marine waters. It actively contributes to scientific projects in Germany and Europe and to activities within NATO, HELCOM, OSPAR and JPI Oceans. The group meets three times annually.

Members: State ministries of interior and marine protection, Federal Ministries, BSH, German Armed Forces, CCME

Contact: munition@meeresschutz.info

Further Information: www.underwatermunitions.de

Digital Ocean Lab

The development of new and efficient technologies for the detection of warfare materials requires appropriate testing facilities. Tests in real working areas are time- and cost-consuming as they depend on the weather and sea conditions. Therefore, the network is involved in the conception and construction of an "underwater munition garden" in a testing area just outside of Rostock (Germany) in the Baltic Sea. On the one hand, basic technologies for a better comparability are provided, such as power supply, underwater positioning, and communication systems. On the other hand, real conditions are necessary to show the full capacity or faults.

Water pressure, waves, currents, strong corrosive environments and biofouling have to been considered in relation to the high risks and costs due to failures of ROVs, sensors, etc. Currently there are no official standards for technologies or human safety regarding the dangerous working field of warfare materials in the sea. To avoid acting negligently, standardization and certifications are desirable. One step towards the needed reproducibility was taken at the planned munition garden in the Digital Ocean Lab (DOL) with a ground-breaking ceremony held on the 9th of August 2019 in Rostock.

NIcK e.V

An expert panel on CWAs in the sea was established. The newly registered association, Nationales Informationszentrum chemische Kampfmittel (NIcK e.V.), has various members from academia and corporations involved in unexploded ordnance, as well as semi-state organizations like GEKA Munster, the only organization in Germany that is allowed to handle CWAs with the purpose of destroying them. Two of the three executive board members are from the network Munitect and are working on these goals:

- Knowledge conservation and collection; archiving
- Determination of state-of-the-art techniques for identification and disposal of CWAs
- Consultation of official administrations
- Development of health and safety guidelines on board (with official liabilities)
- Support of sciences and new generation scientists

Further information: https://nick-ev.com/

5.7.4.4 Current Projects

The following research and technological development projects are currently being conducted or have been approved in Germany.

BASTA

Existing approaches for the detection of submerged warfare materials (see 4.3) are time consuming and costly. They suffer from limited objectivity and acknowledgement of uncertainties, which is partly due to the lack of an industry standard for data acquisition and handling. This resulted in high heterogeneity in process chains and data workflows. BASTA (Boost Applied munitions detection through Smart data inTegration and AI workflows) aims to advance munitions detection both locally and on a larger scale. The project seeks to advance data acquisition through ultra-high-resolution 3D sub-bottom profiling (SBP) and intelligent AUV-based magnetic mapping as part of an adaptive and iterative survey approach. In addition, it will foster the sustainable use of survey and historical data within the multi-sensor database of AMUCAD.org. Conducting Big Data analysis by means of artificial intelligence will lead to new approaches in detection and identification of munitions. Finally, new tools, methods and workflows will be discussed with stakeholders with the aim of formalizing recommendations for munitions detection for industry and government.

Project partners: GEOMAR Helmholtz Centre for Ocean Research (Lead), Flanders Marine Institute, north.io GmbH, G-tec SA

Funded by: European Maritime and Fisheries Fund - "Blue Economy" (2020-2023)

Contact: Prof. Dr. Jens Greinert – jgreinert@geomar.de

ExPloTect

Unexploded ordnance and relic munitions on the seafloor represent intrinsic explosion and security risks, and also contain cytotoxic, genotoxic, and carcinogenic chemicals. There is a critical need to clear undersea munitions due to these hazards. Direct chemical sensing can provide an unequivocal signature of chemical contamination from munitions and objects requiring clearance. Despite the clear need for real-time chemical detection technology, existing methods cannot detect multiple chemical compounds simultaneously, and they are all subject to interferences from non-target compounds. ExPloTect (Ex-situ, near-real-time exPlosive compound deTection in seawater) will develop a prototype system for shipboard, near-real-time detection of dissolved explosive compounds and CWAs in seawater. The underlying concept of ExPloTect is a flexible platform adaptable to explosive compounds such as TNT as well as CWAs. The technology will be based on a high-performance liquid chromatography-mass spectrometry method demonstrated extensively by GEOMAR in the Baltic Sea during the UDEMM project.

Project partners: GEOMAR Helmholtz Centre for Ocean Research (Lead), K.U.M. Umwelt- und Meerestechnik Kiel GmbH, RPS Explosives Engineering Services

Funded by: European Maritime and Fisheries Fund - "Blue Economy" (2020-2023)

Contact: Prof. Dr. Eric Achterberg – eachterberg@geomar.de; Dr. Aaron Beck – ajbeck@geomar.de

DAIMON 2 (Decision aid for marine munitions –practical application 2019-2021)

DAIMON2 used the attention on dumped munitions to share new knowledge and risk assessment methods with practitioners and decision makers from science and politics. One of the new instruments for risk assessment in practice is the DAIMON Ecotox Toolbox, developed by the international consortium of the project DAIMON1. The Ecotox Toolbox comprises over 40 single methods (tools) as well as a concept how to select and apply them and how to interpret the results. A risk assessment of dumped munitions in Baltic Sea ecosystems can be achieved with the toolbox. The components of the Ecotox Toolbox together with a short instruction (Kammann 2021) can be downloaded for free via https://www.thuenen.de/de/fi/arbeitsbereiche/meeresumwelt/munition-im-meer/daimon-ecotox-toolbox/

The Thünen Institute hosted an online training on 3 November 2020 with over 40 active participants from politics, authorities, universities and NGOs in Germany. The concept and the practical application of the DAIMON Ecotox Toolbox was explained during the webinar using real examples from dumpsites and suspect areas. Selected methods (tools) were presented by experts and discussed together with the participants. The DAIMON Ecotox Toolbox is an important contribution to future management and remediation of dumped munitions in Germany.

Project execution: Thünen Institute of Fisheries Ecology

Contact: Dr. Ulrike Kammann - ulrike.kammann@thuenen.de

DCF-Bottom-dwelling fish: Dumped munition and their influence on Baltic fish (2019-2021)

Explosives such as TNT are proven to be acutely toxic and genotoxic to fish and may lead to a potential risk for organisms that get in contact with the compounds, such as bottom-dwelling fish. The effects of ongoing corrosion of warfare materials on the stock of bottom-dwelling fish are unclear. For this reason, the Thünen Institute of Fisheries Ecology is working in the pilot project DCF-Bottom-dwelling fish, supported by the European Maritime and Fisheries Fund of the European Union. The project is the first assessment of the contamination of flatfish species such as dab, plaice or flounder with TNT and its toxic degradation products. The results will be used to evaluate the possible influence of explosive compounds on the populations of bottom-dwelling fish species. Flatfish from the vicinity of munitions dumpsites and from reference areas will be studied with LC-MS for TNT and its metabolites. A special analysis method for explosives developed by the Thünen Institute is used to measure both known and unknown TNT metabolites. Results show that TNT and its metabolites as well as other explosives were detected in in bile fluids of fish species used as seafood and caught in the vicinity of known munitions dumpsites. In contrast, fish from reference sites showed low or no contamination. The project used these results to develop relevant methods for chemical monitoring of explosives in fish.

Project execution: Thünen Institute of Fisheries Ecology

Contact: Dr. Ulrike Kammann - ulrike.kammann@thuenen.de

MUNISEE

Anti-aircraft grenades were used on a large scale in the Baltic Sea near the coast during World War II. These anti-aircraft grenades contained highly toxic mercury(II) fulminate as a primary explosive, which now contaminates the Baltic Sea. In a 10 km^2 area near the former marine anti-aircraft gun (FlaK) training centre Dänisch-Nienhof, up to 1.5 million mercury-containing anti-aircraft grenades were fired between 1939 and 1945. Some 70% of these shells detonated during use, releasing up to 2 tons of highly toxic elemental and ionic mercury (Hg^0 and Hg^{2+}) into the environment. Most of this mercury likely accumulated in sediments off Dänisch-Nienhof. Undetonated grenades are also likely present, containing an additional ton of mercury. MUNISEE (Weltkriegsmunition: Quecksilberquelle im Ökosystem Ostsee [World War Munition: Mercury source in the Baltic Sea ecosystem]) investigates the degree of Hg contamination from historical FlaK munitions use in coastal Dänisch-Nienhof. In particular, the release of organic and inorganic Hg from warfare materials-polluted marine sediments in the Bay of Kiel and its transfer into the food chain is investigated.

Project execution: GEOMAR Helmholtz Centre for Ocean Research

Funded by: Schleswig-Holstein Landesinitative “Zukunft Meer” (2018-2021)

Contacts: Prof. Dr. Eric Achterberg – eachterberg@geomar.de; Katherine Gosnell – kgosnell@geomar.de

Pilot study Lübecker Bucht

On behalf of the MELUND (Schleswig-Holstein, Germany) a pilot study was carried out from August 2019 to December 2020 in the Bay of Lübeck. The aim of this study was to establish methods for the routine monitoring of explosives and active ingredients from pharmaceuticals. Water samples were taken monthly at different locations; blue mussels and passive sampling devices were used periodically. The measured values will be evaluated under toxicological guidelines.

5.7.4.5 Past Projects and Activities

The following noteworthy projects and activities that are already finished have been conducted in Germany.

<u>RoBEMM</u>

The project RoBEMM (Robotic underwater salvage and disposal process with the technology to remove explosive ordnance in the sea, in particular in coastal and shallow water) was driven by the idea of developing a procedure that allows the inexpensive clearance of warfare materials from the seabed. It was the target that the clearance should be performed in a partly automated fashion. Another aim was to ensure on-site disposal, which would prevent the transport of hazardous explosive materials both at sea and land. During the project tests for friction and impact sensitivity of explosives were conducted. These indicated that warfare materials needed to be treated in a very sensitive fashion. The main result was a concept for the treatment of warfare materials with a processing unit which allows the safe handling of explosives under water. Furthermore, a quality guideline for the treatment of offshore warfare materials and a concept for a testing ground were developed.

Project Partners: Heinrich Hirdes EOD Services GmbH (Lead), Automatic Klein GmbH, Fraunhofer Institute for Chemical Technology, Institute for Infrastructure and Resources Management of Leipzig University

Funded by: German Federal Ministry for Economic Affairs and Energy (2015-2019)

Contact: hh.hamburg@boskalis.com

<u>UDEMM</u>

The UDEMM (Umweltmonitoring für die Delaboration von Munition im Meer [Environmental monitoring for the remediation/delaboration of munitions on the seabed]) project investigated strategies for monitoring the environmental impact of underwater munitions, before, during, and after remediation. UDEMM focused on 1) hydroacoustic and visual monitoring of warfare materials; 2) oceanographic modelling of munitions chemical transport and dispersion; 3) release, biogeochemical cycling and fate of munitions compounds in water column and sediments; and 4) biological enrichment of munitions compounds in mussels. Study regions included Kolberger Heide, Bay of Kiel, and the southwest Baltic Sea. High resolution seafloor imaging showed extensive but heterogeneous presence of munitions objects throughout the study area Kolberger Heide. Munitions objects showed little movement over the study period; open explosives have been detected in a local area and identified as contamination hotspots. Water column chemical gradients demonstrated unequivocal release and spread of munitions compounds throughout Kolberger Heide but also throughout the southwest Baltic Sea, as it could be measured during a three-week research cruise (POS530). A numerical model incorporating munitions compounds release and degradation successfully predicted the observed regional-scale distribution of munitions compounds. Mussels transplanted to the Kolberger Heide site showed clear bioaccumulation of munitions compounds, highlighting the potential ecological risk of chemical release from underwater munitions. UDEMM resulted in the release of the *Practical Guide for Environmental Monitoring of Conventional Munitions in the Seas*.

Project partners: GEOMAR Helmholtz Centre for Ocean Research (Lead), Institute for Baltic Sea Research Warnemünde, Institute for Toxicology and Pharmacology for Natural Scientists of Kiel University

Funded by: German Federal Ministry of Education and Research (2015-2019)

Contact: Prof. Jens Greinert – jgreinert@geomar.de

Further information: https://udemm.geomar.de

<u>Mercury and dimethylmercury pollution in the ecosystem of the Kiel Fjord as a result of historical use of air defence munitions</u>

The project determined the distribution of mercury (Hg) in the waters and sediments of the southwest Baltic Sea derived from munitions deployed over 70 years ago, and how much has moved into the food chain. The study focused on a region off Kiel where more than 1.2 million mercury-containing anti-aircraft grenades were shot from World War II artillery training grounds which now litter the seabed. Seafloor magnetometer data and multibeam imaging indicated a large number of likely munitions objects on the seafloor in the Bay of Kiel and at Dänisch-Nienhof. Higher concentrations of Hg were measured in sediments and biota from munitions-contaminated regions compared with control sites. Concentrations and isotope signatures of Hg and methyl-Hg in fish indicated bioaccumulation of suspected munitions-derived pollution, although natural isotope fractionation processes were also evident in the data.

Project partners: GEOMAR Helmholtz Centre for Ocean Research (Lead), Ministry of Energy, Agriculture, the Environment, Nature and Digitalization of Schleswig-Holstein, Institute for Toxicology and Pharmacology for Natural Scientists of Kiel University

Funded by: Future Ocean CP16; Christian-Albrechts-Universität Kiel (2016-2017)

Contact: Prof. Dr. Eric Achterberg – eachterberg@geomar.de

<u>MUNITECT</u>

Munitect was established in 2016 as a network of SMEs and research institutes that share the vision of a high-performance and cost-effective sensor platform to facilitate efficient, safe and risk-free detection of old military munitions. An improved accuracy of classification, as well as targeted development of procedures for cost-efficient end systems, is a challenge the network partners would like to take on. The partners represent the manufacturers and customers during activities regarding warfare materials in the economic exploitation of the North and Baltic Seas. The Federal Ministry for Economic Affairs and Energy of Germany has supported Munitect for the past four years as an R&D-orientated (ZIM-) network. The almost 20 partners approach the complex issue of warfare materials with different working teams who share a joined innovation roadmap and meet frequently. Munitect is supported by an advisory committee from different public sector institutions. In the near future Munitect shall be the nucleus to establish a German industry association for munition in the sea.

Funded by: German Federal Ministry for Economic Affairs and Energy (2016-2020)

Contact: info@munitect.de

Further information: https://www.munitect.de

SOAM

The project SOAM (Berührungsfreie Sondierung von Gewässeruntergründen zwecks Auffindung von Altmunition und anderen Gefahrstoffen zur Gewährleistung der gefahrenlosen Gründung von Offshore-Windenergieanlagen (WEA) [Contactless investigation of the ground of bodies of water in order to detect explosive remnants of war and other hazardous materials with the aim of ensuring hazard free foundation of offshore wind farms]) focused on the technical investigation of warfare material. The aim was to test appropriate sensors and to establish intelligent data evaluation. An AUV should be equipped with integrated analytical sensor technologies so its detection capabilities could be tested.

Project partners: Clausthaler Umwelttechnik-Institut GmbH (Lead), Challenger Technologies Dr.-Ing. Klaus Koehler, Michael Clemens + Ingenieure, ATLAS ELEKTRONIK GmbH, Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) in Eckernförde

Funded by: German Federal Ministry for Economic Affairs and Energy (2012-2015)

CHEMSEA (Dumped chemical munitions and ecological effects in the Baltic Sea, 2011-2014)

In the framework of the EU-funded CHEMSEA project, the Thünen Institute of Fisheries Ecology, together with project partners, carried out studies on effects of dumped CWAs on the health status of fish in the Baltic Sea. During five seagoing cruises onboard RV *Walther Herwig III* in the years 2011-2013, scientist studied cod (*Gadus morhua*) for the occurrence a range of health and fitness parameters. This was done in the main dumpsite in the Bornholm and Gotland Basisn as well as in areas suspected to be dumpsites and in non-impacted reference areas. The studies focused on externally visible diseases, parasites, pathological liver alterations and fitness indices. The Thünen Institute of Fisheries Ecology was in charge of the studies. Cod from the major dumpsite for chemical munitions and CWAs east of the Island of Bornholm showed a worse health status and decreased fitness values compared to fish from unimpacted reference areas in the western and eastern Baltic Sea. However, cod from other known and suspected dumpsites were not different from fish sampled in the reference areas.

Project execution: Thünen Institute of Fisheries Ecology

Contact: Dr. Jörn Scharsack

DAIMON (Decision aid for marine munitions 2017-2019)

DAIMON aimed on better evaluation of the risks and benefits of various management options for marine munitions. The environmental effects of CWAs and conventional munitions were assessed in order to make proper risk assessments. DAIMON 1 developed techniques for the assessment of impacts of the dumped warfare materials on ecosystem, maritime activities and humans as seafood consumers. The Thünen Institute of Fisheries Ecology contributed to field studies (with research vessels *Walther Herwig III* and *Clupea*), laboratory experiments and caging studies with fish. Thünen researchers investigated dabs caught close to the munitions dumpsite Kolberger Heide and from reference sites. Fish pathology and parasites were investigated as well as the blood: 25% of dabs from the dumpsites exhibited liver tumours. In contrast dabs from the reference sites showed tumour rates below 5% - a significant difference. In vitro experiments conducted by Thünen researchers showed that TNT and its main metabolites damage the DNA of fish – a possible explanation for the high tumour prevalence. By means of chemical trace analysis several specific metabolites of TNT could be identified – including so far unknown substances. It could be shown that 48% of the dabs from the dumpsites were positive for one or more metabolites of explosives. In reference sites the positive results were significantly lower or at 0%. The results show that fish can degrade explosives like TNT to potential toxic metabolites. Later, the metabolites can be used as markers for exposition of fish to TNT even if TNT itself is no longer detectable. The biological responses of the Atlantic hagfish to CWAs from contaminated wrecks were studied. The results show differences in biomarker response between hagfish collected next to a wreck containing a large amount of CWA munitions compared to the reference sites, indicating negative biological impacts caused by the CWAs.

Project execution: The Thünen Institute of Fisheries Ecology

Contact: Dr. Jörn Scharsack

<u>MODUM (Towards the Monitoring of Dumped Munitions Threat, 2011-2013)</u>

The NATO-funded international MODUM project developed concepts and strategies for monitoring and assessment of ecological risks posed by dumped chemical munitions in the Baltic Sea. The applicability of moored sensor installations, ROVs and AUVs for identification and characterisation of munitions and warfare agents was evaluated. Furthermore, ecological risks were analysed by studying biological effects of CWAs in fish. Four Baltic Sea areas were studied that are either official dumpsites of chemical munitions (Bornholm Basin, Gotland Basin, Little Belt) or are suspected to have been used as areas for dumping operations (inner Flensburg Fjord, Gdanks Deep). ROVs and AUVs were employed for identification and characterisation of dumped munitions. Furthermore, studies on the health status of Baltic Sea were conducted in dumping and reference areas. The Thünen Institute of Fisheries Ecology contributed to the project through the use of RV *Walther Herwig III* as one of the research platforms and was responsible for studies on fish diseases.

Project execution: The Thünen Institute of Fisheries Ecology

Contact: Dr. Jörn Scharsack

5.8 Latvia

Latvia did not provide any information on past, present or future activities.

Military Mine Counter Measures

Latvia participated in numerous OPEN SPIRIT, Baltic Sweep and MCOMLAT and MCOMLIT operations.

5.9 Lithuania

This chapter was last updated before January 1, 2022.

5.9.4.1 Authorities and Legal Situation

Responsible for aspects concerning warfare materials in the sea

The following authorities are responsible or relevant for aspects concerning warfare materials in the Baltic Sea:

- Ministry of National Defence of the Republic of Lithuania (www.kam.lt)
- Ministry of Environment of the Republic of Lithuania (www.am.lt)
- Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania (www.gamta.lt)

Responsible for the treatment of incidents

In case an incident occurs with warfare materials in the sea, the following institutions are responsible:

- Lithuanian Armed Forces (Maritime Rescue Coordination Center)
- Klaipeda State Sea Port Authority
- The State Border Guard Service at the Ministry of the Interior of the Republic of Lithuania
- The Fire and Rescue Department under the Ministry of the Interior of the Republic of Lithuania
- Municipal administration

Laws and regulations

The following laws and regulations apply to warfare materials in the sea:

- Law on the protection of the environment of the Republic of Lithuania
- Marine Environmental Protection Law (Baltic Sea Environmental Strategy, Regional cooperation, Pollution prevention requirements, Pollution incident liquidation)
- Work plan for the elimination of pollution incidents in the maritime area

Action plan for the implementation of water field development 2017–2023 programme

The Environmental Protection Agency plans to carry out monitoring of the effects of the chemical weapons dumped in the Baltic Sea, to take part in the activities of international organisations to share experience and information, to evaluate monitoring data regarding the effects of chemical weapons and to initiate coordinated activities in the Baltic Sea region to solve the problem.

5.9.4.2 Current Projects

DAIMON 2

The Lithuanian Environmental Protection Agency is an Associated Organisation of the Interreg Baltic Sea Region project Decision Aid for Marine Munitions - Practical Application (DAIMON2), running from 2019 until 2021. The aim of the DAIMON 2 is to cooperate closer with the target group, offering methodologies from the scientifically renewed DAIMON EcoTox Toolbox. These have the capacity to become the new Standard Operation Procedures for the environmental impact assessments (EIA) of offshore economy projects in areas contaminated by dumped munitions.

Project execution: Environmental Protection Agency

5.9.4.3 Past Projects and Activities

TC project RER/0/016

A part of the chemical warfare materials dumpsite in the Gotland Basin within the western part of the Lithuanian exclusive economic zone was investigated for the first time in the scope of a national Lithuanian project. It is located 70 nm (roughly 130 km) from the Lithuanian coast (on the Klaipėda-Ventspilis plateau slope). Expeditions took place in October 2002, June 2003 and August 2004. The aim was to confirm whether chemical warfare materials were dumped in the waters of the Lithuanian EEZ and to perform an environmental impact assessment by evaluating the condition of the environment and biota in the area under investigation. Arsenic in sediment samples from the chemical munitions dumpsite was assessed together with scientists from the Marine Environment Laboratory, the International Atomic Energy Agency and Monaco (TC project RER/0/016). Studied parameters did not show changes in the environmental state at the dumpsite. Higher arsenic concentrations were found at the dumpsite compared to other sites. However, arsenic concentrations were low relative to other investigations of sediments in the Baltic and North Seas.

Project partners: Ministry of National Defence of the Republic of Lithuania, Ministry of Environment of the Republic of Lithuania, the Centre of Marine Research (now: Environment Research Department of the Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania) and the Institute of Geology and Geography

CHEMSEA

Using data that was obtained during cruises to chemical munitions dumpsites, an assessment of the potential hazard of chemical munitions at the dumpsite in the Lithuanian EEZ was made. Sediment and water samples were taken during the cruise with research vessel *Vėjūnas* in 2013 and arsenic concentrations in sediments, which act as an indicator of contamination by warfare agents, were assessed. Warfare agents were analysed in sediment samples by the VERIFIN

(Finland) laboratory. As a result, arsenic concentrations in sediments of the chemical munitions dumpsite were in line with the concentrations found during a previous study of the dumpsite in 2003. It was furthermore found that the number of the macrozoobenthos species has decreased notably (from 10 in 1981–1993 to 3 in 2013). Additional CWAs (Clark I/II-related; Triphenylarsine and PDCA-related) were also found in sediments in one of investigated stations.

Project execution: Marine Research Department of the Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania

MODUM

The MODUM (Towards the Monitoring of Dumped Munitions Threat) project, funded by NATO Science for Peace and Security (SPS) programme, started in 2013 and ended in 2016. The project studied the establishment of a monitoring network observing chemical weapons dumpsites in the Baltic Sea, using AUVs and ROVs, and utilizing existing research vessels of partner institutions as launch platforms. Two cruises (in 2014 and 2015) to the chemical munitions dumpsite in Gotland were undertaken by R/V *Vėjūnas*. New equipment for the monitoring of dumped chemical warfare materials such as an AUV was successfully tested.

Project execution: Marine Research Department of the Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania

DAIMON

DAIMON (Decision Aid for Marine Munitions), a flagship project of the EU Baltic Sea Region Strategy, was financed by EU Baltic Sea Region Interreg. It started in 2016 and ended in 2019. DAIMON has focused on the evaluation of risks associated with individual munitions, categorization of threats and possible remediation methods. Risk assessment and categorization methods were applied in field studies in the Gulf of Finland, Bornholm and Gdansk Deeps, Little Belt and Skagerrak to produce evaluation examples in different regions of the Baltic Sea. As the main result, an easy-to-use software Decision Support System (DSS), based on the research carried out within the project, was created and presented to stakeholders in the Baltic Sea countries, including Lithuania, to provide them with a tool for the efficient management of the problem in their respective EEZs. The tool aims at making the knowledge gained in previous projects related to dumped munitions available to decision makers in the Baltic Sea area. Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania was a Project Partner of DAIMON.

Project execution: Environmental Protection Agency under the Ministry of Environment of the Republic of Lithuania

Military Mine Counter Measures

Lithuania participated in numerous OPEN SPIRIT, Baltic Sweep and MCOMLAT and MCOMLIT operations.

5.10 Poland

This chapter was last updated on August 10, 2022.

5.10.4.1 Authorities and Legal Situation

The issue of warfare materials in marine areas is extremely complicated and therefore requires interdisciplinary cooperation between many authorities.

Ministry of National Defence

The institution responsible for the clearance of warfare materials in Polish maritime areas is the Ministry of National Defence and organizational units subordinated to it or supervised by it. Pursuant to Part A of the National Crisis Management Plan, the Navy is responsible for the identification and elimination of threats related to dumped chemical warfare. Also, in accordance with the order of the Navy Commander No. 148/SIM of 30 October 2013, the 3rd Coastal Defence Flotilla and 8th Coastal Defence Flotilla are the bodies responsible for the clearance of warfare materials from the Polish maritime areas. These bodies have the capabilities, scientific and research potential, and command of specialized forces that monitor various threats, including those arising from the presence of warfare materials and other hazardous objects on the seabed of Polish maritime areas.

Ministry for the Environment

At the same time, it should be noted that in accordance with the *Law of 4 September 1997 on government administration departments*, the Ministry for the Environment is the body responsible for monitoring compliance with environmental protection requirements and examining the state of the environment. In accordance with *Law of 20 July 1991 on the Inspection of Environmental Protection*, the Inspection of Environmental Protection was established to monitor compliance with environmental protection regulations and to examine and assess the state of the environment. In accordance with the provisions of *Law of 4 September 1997 on government administration departments*, the Ministry for the Environment is the body responsible for environmental protection and the rational use of its resources, as well as the management of natural resources. In addition, pursuant to *Law on the Inspection Inspector of Environmental Protection*, the Chief Inspector of Environmental Protection conducts environmental monitoring and laboratory activities. In accordance with the Part A of National Crisis Management Plan, the Ministry for the Environment conducts general supervision over environmental protection, including marine environment protection, while in accordance with Part A of National Crisis Management Plan, the Chief Inspector for Environmental Protection is responsible for monitoring and assessing the quality of the marine environment. With reference to the issue of identification and monitoring of hazardous materials in Polish marine areas and assessment of the scale of the threat, the role of the State Environmental Monitoring created by the *Law of 10 July 1991 on the Inspection of Environmental Protection* should also be indicated.

Maritime Administration

According to the provisions of *Law of 21 March 1991 on maritime areas of the Republic of Poland and maritime administration* the maritime administration authorities are responsible for the prevention of pollution of the marine environment as a result of sea-based activities.

Maritime Offices

Under the *Regulation of the Minister of Infrastructure and Development of 7 May 2015 on the determination of objects, devices and installations included in the infrastructure providing access to the port with a basic significance for the national economy* the directors of maritime offices are responsible for identification of hazardous materials in territorial waters and to monitor water bodies with the purpose of determining where shipping and offshore infrastructure (fairways, anchorages, breakwaters, quays, etc.) are to be located. The detailed scope of the control is regulated by the *Regulation of the Minister of Maritime Economy of 23 October 2006 on the technical conditions of use and the detailed scope of inspections of offshore hydrotechnical constructions*. The directors of maritime offices also monitor the areas in the vicinity of selected wrecks which may pose a threat or potentially contain fuel. These activities are implemented by air surveillance and satellite monitoring, which enable the detection of pollution on the sea surface.

5.10.4.2 Ongoing Management Activities

Various offshore projects

Various hydrotechnical works are carried out in Polish ports. As a result of these activities, commercial business entities and the Polish Navy are gradually cleaning the warfare materials from those areas.

New findings of torpedoes, mines and other warfare materials appeared during hydrographic works, especially in vicinity of the port of Gdansk and Gdynia. Cleaning activities are carried out when needed.

The Director of the Maritime Office in Szczecin is responsible for the investment project titled Modernization of the Swinoujście-Szczecin fairway to a depth of 12.5 m. For the purpose of this undertaking the *Safety Plan for Shipping* was developed, which contains procedures that were agreed upon with the contractor in the event of finding and handling hazardous materials. Before the implementation of investments, under which dredging works are carried out, Szczecin and Swinoujscie Seaports Authority SA commissions the execution of a magnetic survey of the seabed in the port area. The aim of these works is the detection and identification of objects that may pose a threat to people and equipment (warfare materials and other hazardous objects). In 2019, these works were carried out in the Dębicki Channel and in the Kaszuby Basin in the port of Szczecin as part of improving the access to the port in Szczecin in the area of the Dębicki channel and of improving the access to the port in Szczecin in the area of the Kashubian Basin. Removal of the warfare materials is carried out by the construction works contractor. These works are financed from funds allocated for the implementation of the above investments.

Mobile Floating Platform

Since 2019 Poland conducts a project regarding innovative technology for locating, removal and destruction of sea-dumped chemical munitions with the use of a mobile floating platform. The project is financed from the EU regional development fund, in the frame of operational programme Intelligent Growth. Currently the project is at the finishing stage of the design period and entering the prototype building phase.

5.10.4.3 Other Ongoing Activities

Interdepartmental Working Group

In 2021 the Ministry of Infrastructure (responsible for the maritime economy) established an interdepartmental Working Group for dealing with the threats resulting from dumped hazardous materials based on the on the Ordinance No. 42 of the Prime Minister of The Republic of Poland (dated 14 July 2021). The Group started its works in June 2021.

The working group terms of reference were established as follows:

- Analysis of available materials and collected information about threats.
- Conducting detailed analysis of public administration tasks.
- Preparation of terms of reference for the risk monitoring system.
- Preparation of an economic analysis of the costs of activities related to counteracting the threats resulting from the deposition of CWAs and their decomposition products, conventional weapons, as well as the fuel and other mineral oils still remaining in wrecks.
- Developing recommendations for the Council of Ministers regarding further actions.

The work of the Group was completed in January 2022. As a result, a number of recommendations were prepared for further decisions. Currently, based on these recommendations, new regulations on governmental level regarding proceeding with hazardous materials in Polish sea areas are being prepared.

SONATINA – NCN grant no. 2021/40/C/NZ8/00125, Warsaw University

In 2021 the National Science Centre in Poland funded a SONATINA scientific grant that studies the sublethal effects of exposure to CWAs by a model aquatic organism – *Daphnia magna*. Simultaneously, metagenomic and metabolomic analyses of CWA exposure effects on Prokaryotic assemblages from the Baltic Sea CW dumpsites sediments will be performed. Project is coordinated by the Department of Biology of Warsaw University and will last until 2024.

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PRELUDIUM – NCN grant no. 2020/37/N/NZ8/04099, Warsaw University

A small ongoing project is funded by the National Science Centre in Poland. The main goal of this project is to quantify basic toxicity thresholds (NOEC, LC50, LC100) of arsenoorganic CWAs during different life stages of fish (embryos, larvae, juveniles) in both acute and chronic toxicity assays according to standards from the OECD library. This project also focuses on studying the intestinal health of wild Baltic cod in a chemical warfare dumpsite near Bornholm (Wilczynski et al., 2022).

5.10.4.4 Past Projects and Activities

Removal of WWII explosives conducted by Navy in cooperation with maritime administration

During the past few years several actions were taken. As a result:

- 70 post-German (partly armed) torpedoes from the area of Gulf of Gdansk were removed. Recovery of 92 another torpedoes, newly located and identified in the Gulf of Puck, is still in progress.
- 14 German and British sea mines were liquidated through the process of replacing and deflagration.
- In October 2020, one of the largest air bombs in the history of World War II was neutralized - the British DP-12000-IB bomb with a weight of about 5,400 kg (the so-called Tallboy), located at the bottom of the Piastowski Canal in the Świnoujście region.
- Numerous unexploded conventional warfare were removed during construction works in Gdańsk and Szczecin – Świnujście regions.

Fishermen's Guide

In 2019 a group of experts updated the *Instructions for the crews of fishing vessels in the event of passively fished or the removal of chemical warfare agents from the sea*.

PATROL 18

On 17 October 2018, the nationwide exercises PATROL 18 took place in Dziwnów. During the exercise, activities were carried out that would be implemented in case of a threat of chemical, biological and radioactive contamination. The main purpose of the exercise was to improve the procedures for activating the individual elements of the National System of Contamination Detection and Alarming by exercising scenarios of crisis events to develop expert assessments and analyses, recommendations for further proceedings, to check information exchange procedures, and to coordinate the activities carried out by individual services and institutions. One of the elements of the exercise was to respond to the case of finding barrels with unknown substances in fishing nets, which lead to the contamination of the crew and the equipment. The exercise considered the effects of the substance on humans and the possibility of contamination of the unit with CWAs.

PRELUDIUM – NCN grant no. 2017/27/N/NZ8/02813, IO PAN

Between 2018 and 2020, the National Science Centre in Poland funded a PRELUDIUM scientific grant to estimate the acute toxicity of CWAs and their degradation products to a model aquatic organism – *Daphnia magna*. Simultaneously, the first study was conducted of Prokaryotic communities from marine sediments from Baltic Sea chemical weapons dumpsites. The results from the project were published in four scientific publications (Vanninen et al. 2020, Brzeziński et al. 2020, Czub et al. 2020 and Czub et al. 2021).

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5.11 Sweden

This chapter was last updated before September 10, 2021.

5.11.4.1 Authorities and Legal Situation

Swedish Armed Forces

The Swedish armed forces assist civil authorities (i.e. police, coast guard and emergency services) in munitions clearance of warfare materials in the sea. Munitions or other warfare materials that cannot be classified, and finds at sea that cannot be identified, are not allowed not be cleared without permission from and according to the regulations of the armed forces. The marine tactical staff is responsible to assist the coast guard and emergency services with finds located at sea. If the find or object containing CWAs is deemed to also contain an explosive substance, the Swedish armed forces (marine tactical staff) are furthermore obliged to support in locating, identifying, indicating, decontaminating and neutralizing it. The Swedish EOD and Demining Centre is responsible to assist police, coast guard and emergency services with finds located on land. Furthermore, the Swedish armed forces are responsible for the disposal of warfare materials inside a military area or an area that is closed off for military activities. The role of the Swedish armed forces are governed by the Regulation (2002:375) of support to the society by the Swedish armed forces (Förordning (2002:375) om Försvarsmaktens stöd till samhället).

Swedish Coast Guard

The Swedish coast guard is responsible for disposing of CWAs in Swedish territorial sea and EEZ as well as the lakes Vänern, Vättern, and Mälaren. In addition, they are responsible for disposing of CWAs on a ship which is not located inside a port area. If the find or object is deemed to contain an explosive substance, the Swedish armed forces (marine tactical staff) are obliged to support in locating, identifying, indicating, decontaminating and neutralizing it.

Swedish Police

The Swedish police is responsible for the disposal of warfare materials, of civilian as well as military origin, on civilian land. They are also responsible for munitions clearance of warfare materials in connection with a crime or suspicion of a crime, including inside a military area or an area that is closed off for military activities. The armed forces can support the police after a request for assistance. After an accident with military explosives on civilian land, the decision of clearance or other action is taken by the police.

Relevant Legal Documents

Swedish Armed Forces. 2017. Reglemente – Verksamhetssäkerhet, ammunition och minröjning (Regulations – operational safety, munition and mine clearance).

Swedish Coast Guard. 2007. Kemiska stridsmedel till sjöss (Chemical warfare agents at sea).

Swedish National Police. 2007. Rikspolisstyrelsens författningssamling, rikspolisstyrelsens föreskrifter och allmänna råd om polisens åtgärder med misstänkt farligt föremål (Swedish national police statutes, regulations and general guides regarding police measures concerning suspicions dangerous objects).

5.11.4.2 Ongoing Management Activities

Management of Wrecks

The Swedish Agency for Marine and Water Management (SwAM) is responsible for coordinating the investigations as well as the recovery of environmentally hazardous substances and lost fishing gear (ghost nets) from shipwrecks in Swedish waters. There are about 17,000 shipwrecks along the coasts of Sweden and the Swedish Maritime Administration classified 3,000 of these as possibly hazardous for the environment, 300 as hazardous for the environment and 30 of them as an acute environmental threat. Shipwrecks leaking oil or petroleum products pose risk to marine life in Swedish waters. In addition to shipwrecks containing oil there are wrecks containing CWAs in Swedish waters. In an area west of the island of Måseskär in Skagerrak, 28 ships were scuttled after World War II. Over the years, low levels of CWAs were detected in sediment and in fish, indicating that the ships contain dumped CWAs. In 1992, low concentrations of Sulfur mustard were detected in the sediments in the area, and in 2016 and 2017 low concentrations of the CWA Clark I was found in Norwegian lobster, flatfish and shrimps. Degradation products of Clark I were found in approximately 12% of the sampled organisms. Further studies are performed to investigate which wrecks contain CWAs, the extent of the contamination and their potential impact on the environment. In 2019 SwAM performed additional exploratory fishing, both in the Måseskär area and in the Gotland deep. At Måseskär fishing for Norwegian lobster, shrimp and hagfish were performed close to three wrecks not yet investigated. At the Gotland deep cod and flatfish were fished close to known positions of dumped CWA objects. In the Måseskär area low concentrations of Clark I and Clark II was found in hagfish (*Myxine glutinosa*) and Clark I, II and Arsine oil were found in cod (*Gadhus morhua*) in the Gotland deep area. In addition, Clark I, Clark II, Arsine oil and Adamsite were found in all sediment samples taken during the same study. The concentrations of the detected CWAs were below levels of quantification (SwAM, 2020).

5.11.4.3 Current Projects

Sweden is part of the DAIMON 2 project, with Chalmers University of Technology as a partner.

5.11.4.4 Past Projects and Activities

CHEMSEA

The Swedish Maritime Administration (SMA) was a partner of the CHEMSEA project. During the CHEMSEA project the SMA conducted several research cruises with the vessel *Baltica* to detect and verify CWAs in the Gotland deep.

DAIMON

During the DAIMON project Sweden participated with Chalmers University of Technology as a partner and SwAM as an associated partner.

In the DAIMON project Chalmers University of Technology developed the risk assessment tool VRAKA-CWA. VRAKA-CWA is a risk-based decision support tool that combines measured or collected dumping ground specific information with expert knowledge on how a leakage event may occur due to anthropogenic and natural underwater activities, e.g. construction work, trawling, anchoring, diving and landslides. The risk is calculated using well-established methods, Bayesian updating, applied in environmental risk assessment and other fields. Parameters considered are the probability of release, the toxicity of the specific CWA and the amount of CWAs on the sea-floor at the location in question. The result can be used to e.g. compare and rank different contaminated sites, identify the human activities and natural phenomena that are most likely to cause damage to and leakage from the warfare materials on the sea-floor and to identify and evaluate possible mitigation measures.

6. Findings and Conclusions

Warfare materials are one of many types of hazardous submerged object in the Baltic Sea. They are legacy point sources of pollution that are located in the areas of responsibility of shipping administration, maritime spatial planning offices and national marine protection authorities. Besides being sources of pollution, warfare materials pose a risk to maritime workers and recreational users. Due to their hazardous properties, they are not treated as sources of pollution under the Marine Strategic Framework Directive (MSFD). In 2021, the Contracting Parties adopted an update to the Baltic Sea Action Plan and included action S 34 for a comprehensive risk assessment and action S 35 to "*Maintain the HELCOM thematic assessment on hazardous submerged objects as a living document, including munitions and wrecks and regularly update the information in the HELCOM Map and Data Service*". By doing so, HELCOM recognized the results of research projects targeting munitions compounds, such as CHEMSEA, DAIMON, UDEMM, and ExPloTect. Based on data that was collected during offshore project development, as part of MSFD efforts or for other reasons, comprehensive site-specific risk assessments appear possible and affordable. Based on such assessments, resources could be deployed in the future to focus on the most urgent sites for remediation operations.

Over the last decade, some EUR 35 million of public funding have been allocated to research projects in the field of munitions in the seas in Europe alone. The majority of research focused on the Baltic Sea to understand the status and effects of warfare materials. These projects are summarized in chapter 5 of this report. They resulted in a summary of findings and conclusions to locate, identify, assess, and monitor relevant marine areas, as well as to inform decision makers.

There are three major areas of concern relating to the issue of warfare materials. These are the explosive hazard of the warfare materials, consequences of direct contact with munitions objects, and environmental effects of munitions compounds. Especially thinly cased naval mines, torpedo heads, depth charges and airborne bombs appear increasingly fragile. Ageing changes the properties of previously stable and safe-to-handle explosives, making them difficult to handle, which limits options for remediation over time. In addition, the probability of detonations due to unintentional external kinetic impacts, e.g. by anchor dropping, trawling or ploughing for underwater cable laying, increases. Besides the risk to humans, targeted analysis detected mutagenic and carcinogenic munitions compounds in wide parts of the Baltic Sea. They were also measured in marine biota. CWAs were already addressed in depth in HELCOM CHEMU and HELCOM MUNI. Conventional warfare materials are covered for the first time in great detail in this assessment in HELCOM.

It is well known that noise pollution from blasting can harm marine vertebrates such as harbor porpoises. Wherever possible, detonations should be avoided. For unavoidable detonations, it is important to model the sound and shock wave propagation prior to the blast in order to be able to assess the potential for damage to the environment and the range of injury for animals and implement effective mitigation measures. Further, it is important to carry out accompanying measurements of impulsive noise and measure explosive residues in water samples when detonations are carried out in order to verify the efficiency of mitigation and identify potential consequences of release and spread of contaminants following detonations. Contracting Parties are invited to share their data obtained in this way in order to jointly develop verified models to predict noise and shock wave propagation and release of energetic material and identify best practices for mitigation.

The above findings are only a fraction of the great number of findings described in chapters 2, 3 and 4.

Despite great efforts, knowledge gaps exist and additional research on warfare materials in the Baltic Sea is required. For example, military archives contain valuable entry information for research. In addition, more information regarding biological effects and risks of munitions compounds (such as uptake and transfer in the marine food webs, ecosystem effects, chronic effects in organisms and residues in sea food) is needed. Further research is also required to understand if they present a risk to humans and the environment.

HELCOM successfully established relevant cooperation on warfare materials, like ongoing exchange of information with the Baltic Ordnance Safety Board (BOSB) and with the Council of the Baltic Sea States (CBSS). Data collection and sharing on all warfare materials encounters in the region are needed to better address possible risk and identify areas of action. The Contracting Parties are invited to discuss the need and the advantages of a Baltic Sea-wide dataset. To overcome existing gaps, strategic linkages between HELCOM and other institutions and fora become important and should be intensified and promoted. Especially the cooperation and exchange with regional partners such as BOSB, CBSS and the Baltic Sea Parliamentary Conference (BSPC) should be further advanced. Intensifying the strategic partnership with the European Commission and OSPAR holds great potential to solve issues regarding munitions in the sea and realize the economic potential as outlined in this assessment report.

In the coming years, implementation of state-of-the art technology and further development of automated and autonomous detection technologies and approaches should be addressed to increase mapping efficiency. Funding for technology development projects can further increase the efficiency of clearance and disposal technologies, which also need to be improved. Investment into clearance and disposal are encouraged to achieve a sustainable, safe and cost-effective growth of the Blue Economy in the Baltic Sea area.

The HELCOM EG Submerged will continue working within its mandate towards finding solutions to address the risks associated with hazardous submerged objects. The 2021 Baltic Sea Action Plan and the Terms of Reference of the group provide a clear way forward in achieving this objective. This includes acting as a platform for discussion and information sharing and updating the HELCOM *Submerged Assessment* based on the latest knowledge. It also, however, includes important measures such as developing best environmental practices and best available techniques for managing the associated risks, as well as conducting site-specific risk assessments, prioritizing affected areas and coordinating mitigation efforts.

List of References

Abbondanzieri, M., Klein, T., Frey, T., Müller, P. (2018) RoBEMM. Robotisches Unterwasser-Bergungs- und Entsorgungsverfahren inklusive Technik zur Delaboration von Munition im Meer, insbesondere im Küsten- und Flachwasserbereich. In: *Tagungsband der Statustagung 2018*. At: Statustagung Maritime Technologien 2018. Berlin. 13.12. Zentralbibliothek, Verlag. Jülich. Schriftenreihe Forschungszentrum Jülich. 159–167.

Ahvo A., Lehtonen K.K., Lastumäki A., Straumer K., Kraugerud M., Feist S.W., Lang T., Tørnes J.A. (2020) The use of Atlantic hagfish (*Myxine glutinosa*) as a bioindicator species for studies on effects of dumped chemical warfare agents in the skagerrak. 2. Biochemical biomarkers. *Mar Environ Res*. 162, 105097, DOI: 10.1016/j.marenvres.2020.105097.

Aguilar de Soto, N., Delorme, N., Atkins, J., Howard, S., Williams, J., Johnson, M. (2013) Anthropogenic noise causes body malformations and delays development in marine larvae. *Scientific Reports*. 3, 2831. DOI: 10.1038/srep02831.

Ahlborg, G. Jr, Einistö, P., Sorsa M. (1988) Mutagenic activity and metabolites in the urine of workers exposed to trinitrotoluene (TNT). *Br J Ind Med*. 45 (5), 353–358. DOI: 10.1136/oem.45.5.353.

Álvarez-Muñoz, D., Rodríguez-Mozaz, S., Maulvault, A.L., Tediosi, A., Fernández-Tejedor, M., Van den Heuvel, F., Kotterman, M., Marques, D. Barceló, A. (2015) Occurrence of pharmaceuticals and endocrine disrupting compounds in macroalgaes, bivalves, and fish from coastal areas in Europe. *Environmental Research*. 143, Part B, 5-64. DOI: 10.1016/j.envres.2015.09.018.

Amato, E., Alcaro, L., Corsi, I., Della Torre, C., Farchi, C., Focardi, S., Marino, G., Tursi, A. (2006) An integrated ecotoxicological approach to assess the effects of pollutants released by unexploded chemical ordnance dumped in the southern Adriatic (Mediterranean Sea). *Marine Biology*. 149, 17–23. DOI: 10.1007/s00227-005-0216-x.

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S., Houégnigan, L. (2011) Low-frequency sounds induce acoustic trauma in cephalopods. *Front Ecol Environ*. 9, 489–493. DOI: 10.1890/100124.

Appel, D., Strehse, J. S., Martin, H. J., Maser, E. (2018) Bioaccumulation of 2, 4, 6-trinitrotoluene (TNT) and its metabolites leaking from corroded munition in transplanted blue mussels (M. edulis). *Marine pollution bulletin*. 135, 1072-1078. DOI: 10.1016/j.marpolbul.2018.08.028.

Arbeitskreis Arbeitshilfen Kampfmittelräumung (AK AH KMR) (2018) *Baufachliche Richtlinien Kampfmittelräumung (BFR KMR). Arbeitshilfen zur Erkundung, Planung und Räumung von Kampfmitteln auf Liegenschaften des Bundes*. September 2018. Berlin, Bonn. Bundesministerium des Innern, für Bau und Heimat (BMI), Bundesministerium der Verteidigung (BMVg). https://tinyurl.com/ctm9wmnv (2024-02-28).

Ariyarathna, T., Vlahos, P., Tobias C., Smith R. (2016) Sorption kinetics of TNT and RDX in anaerobic freshwater and marine sediments: Batch studies. *Environmental Toxicology and Chemistry*. 35 (1), 47-55. DOI: 10.1002/etc.3149.

Ballentine, M., Tobias, C., Vlahos, P., Smith, R., Cooper, C. (2015) Bioconcentration of TNT and RDX in Coastal Marine Biota. *Arch Environ Contam Toxicol*. 68 (4), 718-728. DOI: 10.1007/s00244-014-0104-9.

Bundesarchiv. Abteilung Militärarchiv. *BM 1/2392*.

Bundesarchiv. Abteilung Militärarchiv. *BM 1/8922*.

Bundesarchiv. Abteilung Militärarchiv. *BW 1/25453*.

Bundesarchiv. Abteilung Militärarchiv. *RL 4/16*.

Bundesarchiv. Abteilung Militärarchiv. *RM 7/1486*.

Bundesarchiv. Abteilung Militärarchiv. *RM 7/1587*.

Bundesarchiv. Abteilung Militärarchiv. *RM 7/1489*.

Bundesarchiv. Abteilung Militärarchiv. *RM 7/1952*.

Bundesarchiv. Abteilung Militärarchiv. *RM 45 I/189*.

Bundesarchiv. Abteilung Militärarchiv. *RM 54/28*.

Bundesarchiv. Abteilung Militärarchiv. *RM 60 II/v 39*.

Bundesarchiv. Abteilung Militärarchiv. *RM 70/1*.

Bundesarchiv. Abteilung Militärarchiv. *RM 70/6*.

Bundesarchiv. Abteilung Militärarchiv. *RM 94/232*.

Bundesarchiv. Abteilung Militärarchiv. *RM 94/143*.

Baršiene, J., Butrimaviciene, L., Grygiel, W., Lang, T., Michailovas, A., Jackunas, T. (2014) Environmental genotoxicity and cytotoxicity in flounder (*Platichthys flesus*), herring (*Clupea harengus*) and Atlantic cod (*Gadus morhua*) from chemical munitions dumping zones in the southern Baltic Sea. *Mar Environ Res*. 96, 56–67. DOI: 10.1016/j.marenvres.2013.08.012.

Barton, J.V., Porter, J.W., Torres, C., Bush, P.B. (2004) Radiological, Chemical, and Environmental Health Assessment of the Marine Resources of the Isla de Vieques Bombing Range, Bahia Salina del Sur, Puerto Rico, Puerto Rico, 8 March 2004.

Beck, A.J., van der Lee, E.M., Eggert, A., Stamer, B., Gledhill, M., Schlosser, C., Achterberg, E.P. (2019) In situ measurements of explosive compound dissolution fluxes from exposed munition material in the Baltic Sea. *Environmental science & technology*. 53 (10), 5652-5660. DOI: 10.1021/acs.est.8b06974.

Beck, A.J., Gledhill, M., Schlosser, C., Stamer, B., Böttcher, C., Sternheim, J., Greinert, J., Achterberg, E.P. (2018) Spread, Behavior, and Ecosystem Consequences of Conventional Munitions Compounds in Coastal Marine Waters. *Frontiers in Marine Science*. DOI: 10.3389/fmars.2018.00141.

Bełdowski J., Lang, T., Reuter, M., Vanninen, P., Brenner, M., Popiel, S., Szala, M., Fabisiak, J., Tengberg, A., Garnaga-Budre, G., Bełdowska, M. (2020) Dumped munitions as a pressure factor for the Baltic Ecosystem. In: *Earth system changes and Baltic Sea coasts*. Köppen, S., Reckermann, M. 3rd Baltic Earth Conference. Online. 1-2.

Bełdowski J, Szubska M, Siedlewicz G, Korejwo E, Grabowski M, Bełdowska M, Kwasigroch U, Fabisiak J, Łońska E, Szala M, Pempkowiak J. (2019) Sea-dumped ammunition as a possible source of mercury to the Baltic Sea sediments. *Sci Total Environ*. 674, 363-373. DOI: 10.1016/j.scitotenv.2019.04.058.

Bełdowski, J., Klusek, Z., Szubska, M., Turja, R., Bulczak, A.I., Rak, D., Brenner, M., Lang, T., Kotwicki, L., Grzelak, K., Jakacki, J., Fricke, N., Ostin, A., Olsson, U., Fabisiak, J., Garnaga, G., Nyholm, J.R., Majewski, P., Broeg, K., Soderstrom, M., Vanninen, P., Popiel, S., Nawala, J., Lehtonen, K., Berglind, R., Schmidt, B. (2016b) Chemical Munitions Search & Assessment—An evaluation of the dumped munitions problem in the Baltic Sea. *Deep-Sea Res Part II Top Stud Oceanogr*. 128, 85–95. DOI: 10.1016/j.dsr2.2015.01.017.

Bełdowski, J., Szubska, M., Emelyanov, E., Garnaga, G., Drzewińska, A., Bełdowska, M., Vanninen, P., Östin, A., Fabisiak, J. (2016a) Arsenic concentrations in Baltic Sea sediments close to chemical munitions dumpsites. *Deep-Sea Res Part II Top Stud Oceanogr*. 128, 114–122. DOI: 10.1016/j.dsr2.2015.03.001.

Bełdowski, J., Potrykus, J., Szubska, M., Klusek, Z., Anu, L., Lehtonen, K., Turja, R., Fabisiak, J., Michalak, J., Olejnik, A., Pączek, B., Lang, T., Fricke, N., Bickmeyer, U., Brenner, M., Garnaga-Budrė, G., Malejevas, V., Popiel, S., Östin, A, Fidler, J. (2014) *CHEMSEA Findings – Results from the CHEMSEA project (chemical munitions search and assessment)*. http://tinyurl.com/2s3bdxky (2024-02-29).

Bell, T, Barrow, B., Steinhurst, D., Harbaugh, G., Friedrichs, C., Massey, G. (2018) *Empirical Investigation of the Factors Influencing Marine Applications of EMI*. SERDP Project MR-2409. Department of Defense Strategic Environmental Research and Development Program (SERDP). Arlington, Alexandria. http://tinyurl.com/2p53rvvn (2024-02-28).

Bellmann, M. A., May, A., Wendt, T., Gerlach, S., Remmers, P., Brinkmann, J. (2020) *Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values*. ITAP GmbH. Oldenburg. http://tinyurl.com/sfezx5xx (2024-02-29).

Bickmeyer, U., Meinen I., Meyer S., Kroner S., Brenner M. (2020) Fluorescence measurements of the marine flatworm *Macrostomum lignano* during exposure to TNT and its derivatives 2-ADNT and 4-ADNT. *Marine Environmental Research*. 161, 105041. DOI: 10.1016/j.marenvres.2020.105041.

Bundesamt für Naturschutz (BfN) (2022) Meidung und Minderung von Umweltschäden bei der Beseitigung von Munition im Meer. Putbus. http://tinyurl.com/yc75uyne (2024-02-29).

Bjørnø, L. (2013) Developments in Sonar Technologies and their Applications. *IEEE International Underwater Technology Symposium (UT) 2013*. Tokyo. 05.03.-08.03. Institute of Electrical and Electronics Engineers; IEEE International Underwater Technology Symposium, UT, International Symposium on Underwater Technology. Piscataway.

Bolt, H.M., Degen, G.H., Dorn, S.B., Plöttner, S., Harth, V. (2006) Genotoxicity and Potential Carcinogenicity of 2,4,6-TNT Trinitrotoluene: Structural and Toxicological Considerations. *Reviews on the Environmental Health*. 21 (4), 217-228. DOI: 10.1515/reveh.2006.21.4.217.

Böttcher, C., Knobloch, T., Rühl, N.-P., Sternheim, J., Wichert, U., Wöhler, J. (2011) Munitionsbelastung der deutschen Meeresgewässer - Bestandsaufnahme und Empfehlungen (Stand 2011). Sekretariat Bund/Länder-Messprogramm für die Meeresumwelt von Nord- und Ostsee (BLMP), Bundesamt für Seeschifffahrt und Hydrographie (BSH). Hamburg. https://tinyurl.com/3zdwrhsh (2024-02-28).

Bourne, N.K., Eastwood, D.E., Marussi, S., Parker, G., Dickson, P.M., Atwood, R.C., Connolley, T., Martinez, A., Wagstaff, D. (2020) The transit to detonation in high explosives. In: *AIP Conference Proceedings*. 2272 (1). DOI: 10.1063/12.0000904.

Brzeziński, T., Czub M., Nawała J., Gordon, D., Dziedzic, D., Dawidziuk, B., Popiel, S., Maszczyk P. (2020) The effects of chemical warfare agent Clark I on the life histories and stable isotopes composition of *Daphnia magna*. *Environmental Pollution* 266 (3) DOI: 10.1016/j.envpol.2020.115142.

Bünning T.H., Strehse J.S., Hollmann A.C., Bötticher T., Maser E. (2021) A Toolbox for the Determination of Nitroaromatic Explosives in Marine Water, Sediment, and Biota Samples on Femtogram Levels by GC-MS/MS. *Toxics Mar*. 16 9 (3), 60. DOI: 10.3390/toxics9030060.

Butler, D.K., Cespedes, E.R., Cox, C.B., Wolfe, P.J. (1998) *Multisensor methods for buried unexploded ordnance detection, discrimination, and identification*. Vicksburg, Miss. U.S. Army Engineer Waterways Experiment Station: United States Army Corps of Engineers (Technical report, SERDP-98-10). http://tinyurl.com/3jfvtamt (2024-02-28).

Chabert, A. *Recent developments in marine geophysical methods for UXO detection*. The Hydrographic Society UK - UXO surveys Seminar. http://tinyurl.com/4a4hpkn6 (2016-09-02).

Chappell, M.A., Porter, B.E., Price, C.L., Pettway B.A., George R.D. (2011) Differential kinetics and temperature dependence of abiotic and biotic processes controlling the environmental fate of TNT in simulated marine systems. *Mar Pollut Bull*. 62 (8), 1736-1743. DOI: 10.1016/j.marpolbul.2011.05.026.

Chmielińska, K., Hube, D., Bausinger, T., Simon, M., Reviere, G., Fauser, P., Sanderson, H. (2019) Environmental contamination with persistent cyclic mustard gas impurities and transformation products. *Global Security: Health, Science & Policy*. 4 (1),14-23. DOI: 10.1080/23779497.2019.1699848.

Christensen, I.M.A., Sanderson, H., Baatrup, E., Storgaard, M.S., Fauser, P., Hansen, S.F. (2016) Acute toxicity of sea-dumped chemical munitions: Luminating the environmental toxicity of legacy compounds. *Global Security: Health, Science and Policy*. 1 (1), 39-50. DOI: 10.1080/23779497.2016.1219962.

Cooper, P.W. (1996): *Explosives Engineering*. New York. Wiley-VCH.

Cybulska, K., Łońska, E., Fabisiak, J. (2020) Bacterial benthic community composition in the Baltic Sea in selected chemical and conventional weapons dump sites affected by munition corrosion. *Science of The Total Environment*. 709. DOI: 10.1016/j.scitotenv.2019.136112.

Czub, M., Kotwicki, L., Lang, T., Sanderson, H., Klusek, Z., Grabowski, M., Szubska, M., Jakacki, J., Andrzejewski, J., Rak, D., Bełdowski, J. (2018) Deep sea habitats in the chemical warfare dumping areas of the Baltic Sea. Science of the Total Environment, 616–617, 1485–1497. DOI: 10.1016/j.scitotenv.2017.10.165.

Czub, M., Nawała, J., Popiel, S., Dziedzic, D., Brzeziński, T., Maszczyk, P., Sanderson, H., Fabisiak, J., Bełdowski, J., Kotwicki, L. (2020) Acute aquatic toxicity of Sulfur mustard and its degradation products to *Daphnia magna*. *Marine Environmental Research*. 161, 105077. DOI: 10.1016/j.marenvres.2020.105077.

Czub, M., Nawala, J., Popiel, S., Brzezinski, T., Maszczyk, P., Sanderson, H., Maser, E., Gordon, D., Dziedzic, D., Dawidziuk, B., Pijanowska, J., Fabisiak, J., Szubska, M., Lang, T., Vanninen, P., Niemikoski, H., Missiaen, T., Lehtonen, K.K., Bełdowski J., Kotwicki. L. (2021) Acute aquatic toxicity of arsenic-based chemical warfare agents to *Daphnia magna*. *Aquatic Toxicology*. 230, 105693. DOI: 10.1016/j.aquatox.2020.105693.

Dawidziuk, B., Nawała, J., Dziedzic, D., Gordon, D., Popiel, S. (2018) Development, validation and comparison of three methods of sample preparation used for identification and quantification of 2, 4, 6-trinitrotoluene and products of its degradation in sediments by GC-MS/MS. *Anal Methods*. 10 (43), 5188-5196. DOI: 10.1039/C8AY01939H.

Dimitriu, R.G., Shtirkov, I., Barbu, M.-B. (2017) UXO Search in Burgas: A High Resolution Marine Magnetic Survey Prior to the Start of the Second Phase Harbor's Expansion. 17th International Multidisciplinary Scientific GeoConference (SGEM 2017), 17th International Multidisciplinary Scientific GeoConference (SGEM 2017). Albena 29.06-05.07. International Multidisciplinary Scientific GeoConference, SGEM. Red Hook: Curran Associates Inc. 475–482.

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman W.J., Talley, L.D. (2012) Climate change impacts on marine ecosystems. *Ann Rev Mar Sci*. 4, 11-37. DOI: 10.1146/annurev-marine-041911-111611.

Dontsova, K.M., Yost, S.L., Šimunek, J., Pennington, J.C., Williford, C.W. (2006) Dissolution and Transport of TNT, RDX, and Composition B in Saturated Soil Columns. *J Environ Qual*. 35, 2043–2054. DOI: 10.2134/jeq2006.0007.

DW-Shipconsult (2020) *Dokumentation von Minendetonationen, Fehmarnbelt - August 2019* (English: Documentation of mine detonations, Fehmarnbelt - August 2019). Bundesamt für Naturschutz. Schwentinental. http://tinyurl.com/5fftzryy (2024-02-29).

Edwards, M.H., Shjegstad, S.M., Wilkens, R., King, J.C., Carton, G., Bala, D., Bingham, B., Bissonnette, M.C., Briggs, C., Bruso, N.S., Camilli, R., Cremer, M., Davis, R.B., DeCarlo, E.H., DuVal, C., Fornari, D.J., Kaneakua-Pia, I., Kelley, C.D., Koide, S., Mah, C.L., Kerby, T., Kurras, G.J., Rognstad, M.R., Sheild, L., Silva, J., Wellington, B., van Woerkom, M. (2016) The Hawaii Undersea Military Munitions Assessment. *Deep Res Part II Top Stud Oceanogr*. 128, 4–13. DOI: 10.1016/j.dsr2.2016.04.011.

Esteve-Nuñez, A., Caballero, A., Ramos, J.L. (2001) Biological degradationof 2,4,6-trinitrotoluene. *Microbiol Mol Biol Rev*. 65, 335-352. DOI: 10.1128/MMBR.65.3.335-352.2001.

Ewing, L.L., Mattison, D.R. (1987) Introduction: Biological Markers of Male Reproductive Toxicology. *Environmental Health Perspectives*. 74 (11). DOI: 10.2307/3430429.

Fabisiak J., Olejnik A. (2012) Amunicja chemiczna zatopiona w Morzu Bałtyckim – poszukiwania i ocena ryzyka – projekt badawczy CHEMSA (English: Chemical ammunition dumped in the Baltic Sea - exploration and risk assessment - CHEMSEA research project). Polish Hyperbaric Research 2 (39), 25–52.

Fabisiak, J., Jurczak, W., Szubrycht, G., Zaremba, M. (2018) Ecological safety of the Baltic Sea in the aspects of corrosive reprocessing of containers with toxic warfare agents. *Journal of KONBiN*. 45 (1) 27-44. DOI: 10.2478/jok-2018-0002.

Farrington, J.W., Tripp, B.W., Tanabe, S., Subramanian, A., Sericano, J.L., Wade, T.L., Knap, A.H. (2016) Edward D. Goldberg's proposal of "the Mussel Watch": Reflections after 40 years. *Mar Pollut Bull*. 110 (1), 501-510. DOI: 10.1016/j.marpolbul.2016.05.074.

Fauser, P., Pedersen, E.A., Christensen, I. (2018) Weight-of-Evidence Environmental Risk Assessment. In: *Towards the Monitoring of Dumped Munitions Threat (MODUM). A Study of Chemical Munitions Dumpsites in the Baltic Sea*. Bełdowski, J., Been R., Turmus, E.K. Springer. Dordrecht. NATO Science for Peace and Security Series C. 183–212.

Fickett, W., Davis, W.C. (1979) *Detonation - Theory and Experiment*. Dover Puplications, Inc.

Francken, F., Hafez, A.M. (2009) A case study in modeling dispersion of yperite and CLARK I and II from munitions at Paardenmarkt, Belgium. *Marine Technology Society Journal*. 43 (4), 52-61. DOI: 10.4031/MTSJ.43.4.3.

Frey, T., Fischer, J.-U., Holländer, R. (2019) *Qualitätsleitfaden Offshore-Kampfmittelbeseitigung*. 1. Aufl. Berlin. Logos Verlag (Studien zu Infrastruktur und Ressourcenmanagement 10).

Gallus, A. (2020) *Auswirkungen von Unterwassersprengungen auf die akustische Anwesenheit von Schweinswalen*. Deutsches Meeresmuseum, Stralsund.

German Bundestag (2018) *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Cornelia Möhring, Dr. Gesine Lötzsch, Lorenz Gösta Beutin, weiterer Abgeordneter und der Fraktion DIE LINKE*. Drucksache 19/4511 Verwendung von Blasenschleiern beim Sprengen von Altmunition. Berlin.

German Bundestag (2019) *Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Steffi Lemke, Claudia Müller, weiterer Abgeordneter der Fraktion BÜNDNIS90/DIE GRÜNEN*. BT Drucksache 19/13878. Sprengungen von Munitionsaltlasten und Kampfmitteln in Meeresschutzgebieten. Berlin.

Gitschlag, G.R., Schirripa, M.J., Powers, J.E. (2000) *Estimation of Fisheries Impacts Due to Underwater Explosives Used to Sever and Salvage Oil and Gas Platforms in the U.S. Gulf of Mexico*. Minerals Management Service. New Orleans. http://tinyurl.com/y8jtm39e (2024-02-29).

Glasby, G.P. (1997) Book review. *Sci Total Environ*. 208 145–147.

Gledhill, M., Beck, A.J., Stamer, B., Schlosser, C., Achterberg, E.P. (2019) Quantification of munition compounds in the marine environment by solid phase extraction–ultra high performance liquid chromatography with detection by electrospray ionisation–mass spectrometry. *Talanta.* 200, 366-372. DOI: 10.1016/j.talanta.2019.03.050.

Goldberg, E.D. (1986) The Mussel Watch concept. *Environmental Monitoring and Assessment*. 7, 91–103 DOI: 10.1007/BF00398031.

Granbom, P.O. (1994) Dumped Chemical Ammunition in the Baltic: A Rejoinder. *Secur Dialogue*. 25 105–110. DOI: 10.1177/0967010694025001009.

Greenberg, M.I., Sexton, K.J., Vearrier, D. (2016) Sea-dumped chemical weapons: environmental risk, occupational hazard. *Clin Toxicol (Phila)*. 54 (2), 79-91. DOI: 10.3109/15563650.2015.

Greinert, J. (2019) *Practical Guide for Environmental Monitoring of Conventional Munitions in the Seas - Results from the BMBF funded project UDEMM "Umweltmonitoring für die Delaboration von Munition im Meer"*. Version 1.1. GEOMAR Report. GEOMAR Helmholtz Centre for Ocean Research. Kiel. DOI: 10.3289/GEOMAR_REP_NS_54_2019.

Guerra, Á., González, Á.F., Pascual, S., Dawe, E.G. (2011) The giant squid *Architeuthis*: an emblematic invertebrate that can represent concern for the conservation of marine biodiversity. *Biol Conserv*. 144 (7), 1989-1997. DOI: 10.1016/j.biocon.2011.04.021.

HELCOM (2007) *HELCOM Baltic Sea Action Plan*. Kralow.

HELCOM (2021) *HELCOM Baltic Sea Action Plan*. 2021 Update. Helsinki. http://tinyurl.com/45e9kpwv (2024-02-28).

HELCOM CHEMU (1994) *Report to the 16th Meeting of Helsinki Commission 8 - 11 March 1994 from the ad hoc Working Group on Dumped Chemical Munition (HELCOM CHEMU)*.

HELCOM MUNI (2013) *Chemical Munitions Dumped in the Baltic Sea. Report of the ad hoc Expert Group to Update and Review the Existing Information on Dumped Chemical Munitions in the Baltic Sea (HELCOM MUNI)*. Helsinki. HELCOM. https://tinyurl.com/4dpa4vh2 (2024-02-28).

Höher, N., Turja, R., Brenner, M., Rattfelt Nyholm, J., Östin, A., Leffler, P., Butrimavičienė, L., Baršienė, J., Halme, M., Karjalainen, M., Niemikoski, H., Vanninen, P., Broeg, K., Lehtonen, K.K., Berglind, R. (2019) Toxic effects of chemical warfare agent mixtures on the mussel *Mytilus trossulus* in the Baltic Sea: a laboratory exposure study. *Marine Environmental Research*. 145, 112-122. DOI: 10.1016/j.marenvres.2019.02.001.

Hollyer, G., Racic, L., Butler, D.K. (2008) *Enhancing Geophysical Data Acquisition, Quality Control, Processing, Analysis and Visualization for UXO Detection, Characterization and Discrimination*. Geosoft Inc., US Army Corps of Engineers (USACE). http://tinyurl.com/4jyy37ws (2024-02-28).

Hordoir, R., H. E. M. Meier (2012) Effect of climate change on the thermal stratification of the Baltic sea: a sensitivity experiment. *Climate Dynamics*. 38 (9-10), 1703-1713. DOI:10.1007/s00382-011-1036-y.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri, R.K., Meyer., L.A. Geneva, Switzerland, IPCC Core writing team. 151.

Jakacki, J., Andrzejewski, J., Przyborska, A., Muzyka, M., Gordon, D., Nawała, J., Popiel, S., Golenko, M., Zhurbas, V., Paka, V. (2020) High resolution model for assessment of contamination by chemical warfare agents dumped in the Baltic Sea. *Marine Environmental Research*. 161, 105079, DOI: 10.1016/j.marenvres.2020.105079.

Johnson, L.R., Davenport, R., Balbach, H., Schaeffer, D.J. (1994) Phototoxicology. 2. Near-ultraviolet light enhancement of microtox assays of trinitrotoluene and aminodinitrotoluenes. *Ecotoxicology and environmental safety*. 27 (1), 23-33. DOI: 10.1006/eesa.1994.1004.

Johnson, M.S., Milchie, M.W., Bazar, M.A., Salice, C.J., Gogal, R.M. (2005) Responses of Oral 2,4,6-Trinitrotoluene (TNT) Exposure to the Common Pigeon (*Columba livia*): A Phylogenic and Methodological Comparison. *Int J Toxicol*. 24 (4), 221–229. DOI: 10.1080/10915810591000686.

Jurczak, W., Fabisiak, J. (2017) Corrosion of ammunition dumped in the Baltic Sea. *J. KONBiN*. 41, 227–246. DOI: 10.1515/jok-2017-0012.

Kalinowski R., Chrzanowska, E., Brytan, M. (2013) Do environmental quality standards for selected nerve agents ensure safety of the ecosystem. *Ochrona Środowiska i Zasobów Naturalnych*. 24, 39-41. DOI: 10.2478/oszn-2013-0008.

Kammann U. (2021) *DAIMON Ecotox Toolbox in a nutshell - Short practical guidance to explain and apply the Ecotox Toolbox (in simple version)*. http://tinyurl.com/5hynbekj (2024-02-28).

Kampmeier, M., van der Lee, E.M., Wichert, U., Greinert, J. (2020) 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. DOI: 10.1016/j.csr.2020.104108.

Kiciński, R., Szturomski, B. (2020) Pressure Wave Caused by Trinitrotoluene (TNT) Underwater Explosion—Short Review. *Appl. Sci*. 10 (10), 3433. DOI: 10.3390/app10103433.

Kibong K., Tsay O.G., Atwood, D.A., Churchill D.G. (2011) Destruction and Detection of Chemical Warfare Agents. *Chemical Reviews.* 111 (9), 5345-5403. DOI: 10.1021/cr100193y.

Klapötke, T.M. (2009) *Chemie der hochenergetischen Materialien*. Walter de Gruyter. Berlin.

Koch, M. (2009) *Subaquatische Kampfmittelaltlasten in der Ostsee: Neubewertung des Status Quo, Risikopotenziale und resultierende Handlungsszenarien*. Dissertation. Leuphana Universität. Lüneburg.

Köhler, J., Meyer, R., Homburg, A. (2008) *Explosivstoffe* (English: Explosive Materials). WILEY-VCH Verlag. Weinheim.

Komissarov, P.V., Borisov A.A., Sokolov G.N., Lavrov V.V. (2015) Experimental Comparison of Shock and Bubble Heave Energies from Underwater Explosion of ideal HE and Explosive Composite Mixtures Highly Enriched with Aluminum. Physics Procedia 72, 333-337, Conference of Physics of Nonequilibrium Atomic Systems and Composites, PNASC 2015.

Korotenko, K.A. (2003) Chemical warfare munitions dumped in the Baltic Sea: Modeling of pollutant transport due to possible leakage. *Oceanology*. 43 (1), 16-29.

Koschinski, S. (2011) Underwater Noise Pollution from Munitions Clearance and Disposal, Possible Effects on Marine Vertebrates, and Its Mitigation. *Marine Technology Society Journal*. 45 (6), 80-88. DOI: 10.4031/MTSJ.45.6.2.

Koske, D., Goldenstein, N.I., Kammann, U. (2019) Nitroaromatic compounds damage the DNA of zebrafish embryos (Danio rerio). *Aquatic Toxicology*. 217, 105345. DOI: 10.1016/j.aquatox.2019.105345.

Koske D., Straumer K., Goldenstein N.I., Hanel R., Lang T., Kammann U. (2020) First evidence of explosives and their degradation products in dab (*Limanda limanda L.*) from a munition dumpsite in the Baltic Sea. *Mar Pollut Bull*. 155, 111131. DOI: 10.1016/j.marpolbul. 2020.111131.

Kotwicki, L., Grzelak K., Bełdowski J. (2016) Benthic communities in chemical munitions dumping site areas within the Baltic deeps with special focus on nematodes. *Deep-Sea Research Part II-Topical Studies in Oceanography*. 128, 123-130. DOI: 10.1016/j.dsr2.2015.12.012.

Kunde, T., Held, P., Sternberg, H., Schneider von Deimling, J. (2018) Ammunition detection using high frequency multibeam snippet backscatter information. *Marine pollution bulletin*. 133, 481–490. DOI: 10.1016/j.marpolbul.2018.05.063.

Lagadic, L., Caquet, T., Amiard, J.C., Ramade, F. (1997) Biomarqueurs en Ecotoxicologie (English: Biomarkers in Ecotoxicology). Aspects Fonda-mentaux. Masson. Paris.

Landesarchiv Schleswig-Holstein. *Abt 617 188*.

Lang, T., Kotwicki L., Czub M., Grzelak, K., Weirup L., Straumer K. (2018) The Health Status of Fish and Benthos Communities in Chemical Munitions Dumpsites in the Baltic Sea. In: *Towards the Monitoring of Dumped Munitions Threat (Modum): A Study of Chemical Munitions Dumpsites in the Baltic Sea*. Bełdowski, J., Been, R., Turmus, E.K. 129-152.

Lauritzen, E.K. (2013) *Desk Study UXO Horns Rev 3. Offshore wind farm site*. Version 3. ENERGINET.DK; NIRAS A/S. Alleroed. http://tinyurl.com/f5p2xm42 (2016-01-12).

Leipe, T., Moros, M., Kotilainen, A., Vallius, H., Kabel, K., Endler, M., Kowalski, N. (2013) Mercury in Baltic Sea sediments — Natural background and anthropogenic impact. *Geochemistry*. 73 (3), 249–259. DOI: 10.1016/j.chemer.2013.06.005.

Lewis, J.A. (1996) *Effects of underwater explosions on life in the sea*. Dept. of Defence, Defence Science and Technology Organisation. Melbourne.

Lima, D.R.S., Bezerra, M.L.S., Neves, E.B., Moreira, F.R. (2011) Impact of ammunition and military explosives on human health and the environment. *Reviews on environmental health*. 26 (2), 101-110. DOI: 10.1515/reveh.2011.014.

Lisichkin, G.V. (1996) Chemical weapons on the seabed. In: *Sea-Dumped Chemical Weapons: Aspects, Problems and Solutions*. Kaffka A.V. Springer. Dordrecht. 121–128.

Lotufo, G.R. (2012) Ecotoxicity of Explosives. In: *Encyclopedia of Aquatic Ecotoxicology*. Férard, J.F., Blaise, C. 328-336.

Lotufo, G.R., Nipper, M., Carr, R.S., Conder, J.M. (2009) Fate and toxicity of explosives in sediments. In: *Ecotoxicology of Explosives*. Sunahara, G.I., Lotufo, G.R., Kuperman, R.G., Hawari, J. CRC Press. Boca Raton (FL). 117–134. DOI: 10.1201/9781420004342.ch5.

Lynch, J.C., Myers, K.F., Brannon, J.M. & Delfino, J.J. (2001) Effects of pH and Temperature on the Aqueous Solubility and Dissolution Rate of 2,4,6-Trinitrotoluene (TNT), Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX). *J Chem Eng Data*. 46 (6), 1549–1555. DOI: 10.1021/je0101496.

MacLeod, I. D. (2016) In-situ Corrosion Measurements of WWII Shipwrecks in Chuuk Lagoon, Quantification of Decay Mechanisms and Rates of Deterioration. *Front Mar Sci*. 3, 38. DOI: 10.3389/fmars.2016.00038.

Magnusson, R., Nordlander, T., Östin, A. (2016) Development of a dynamic headspace gas chromatography–mass spectrometry method for on-site analysis of Sulfur mustard degradation products in sediments. *J Chromatogr A.* 1429, 40-52. DOI: 10.1016/j.chroma.2015.12.009.

Majcher, J., Grabowski, M., Bełdowski, J. (2017) Determining hotspots of sonar targets related to chemical munitions dumped in Bornholm Deep and Gotland Deep using GIS. *Hydroacoustics*. (20), 121–128.

Malyshev, L.P. (1996) Technological questions of safe elimination of CW dumps on the Baltic sea bed. In *Sea-Dumped Chemical Weapons: Aspects, Problems and Solutions*. Kaffka A.V. Springer. Dordrecht. 93–104.

Marine Estates, The Crown Estate, Mineral Products Association, British Marine Aggregate Producers Association (2010) *Dealing with munitions in marine sediments*. Guidance Note March 2010. London. The Crown Estate. http://tinyurl.com/44sb7rvr (2016-08-02).

Mariussen, E., Stornes, S.M., Bøifot, K.O., Rosseland, B.O., Salbu, B., Heier, L.S. (2018) Uptake and effects of 2, 4, 6-trinitrotoluene (TNT) in juvenile Atlantic Salmon (*Salmo salar*). *Aquat Toxicol*. 194, 176–184. DOI: 10.1016/j.aquatox.2017.11.016.

Maser, E., Strehse, J.S. (2020) "Don't Blast": blast-in-place (BiP) operations of dumped World War munitions in the oceans significantly increase hazards to the environment and the human seafood consumer. *Archives of Toxicology*. DOI: 10.1007/s00204-020-02743-0.

Maser E, Strehse J.S. (2021) Can seafood from marine sites of dumped World War relicts be eaten? *Arch Toxicol*. 95 (7), 2255-2261. DOI: 10.1007/s00204-021-03045-9.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield T. (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. G. S. World Meteorological Organization.

Meier, H.E.M., Hoglund A., Eilola K., Almroth-Rosell, E. (2017) Impact of accelerated future global mean sea level rise on hypoxia in the Baltic Sea. *Climate Dynamics*. 49 (1-2), 163-172.

Melkonov J. (2003) *Батареи Моонзунда* (English: The Batteries of Moonzund). Riga. RTC BASK.

Melkonov J. (2005) *Батареи Моонзунда* (English: Guns of Kurland Coast). Riga. GVARDS.

Menzel, P., Schütt, C., Wranik, H., Paschen, M., Drews, A. (2018) Towards a general prediction-model for the current-induced mobilisation of objects on the sea floor. *Ocean Engineering*. 164, 160-167. DOI: 10.1016/j.oceaneng.2018.06.047.

Menzel, P., Wranik, H., Govindan, S. N., Paschen, M. (2017) Prediction of the initial movement of objects on the sea floor. *OCEANS 2017*. Aberdeen. IEEE. DOI: 10.1109/OCEANSE.2017.8084925.

Metillo, E.B., Boco, S.R.E., Malugao, M.E.D. (2016) Effects of in situ firecrackers explosion on copepods (*Crustacea*, *Copepoda*) and *Siganus guttatus* (*Pisces*, *Siganidae*) larvae. *Asian Journal of Biological and Life Sciences*. 5 (2), 135-140.

Missiaen, T., Feller, P. (2008) Very-high-resolution seismic and magnetic investigations of a chemical munition dumpsite in the Baltic Sea. *Journal of Applied Geophysics*. 65 (3–4), 142–154. DOI: 10.1016/j.jappgeo.2008.07.001.

Missiaen, T., Henriet, J. P. (2002) Chemical munition dump sites in coastal environments: a border-transgressing problem. In: *Chemical Munition Dump Sites in Coastal Environments*. Missiaen, T., Henriet J.P. Brussels. Federal Office for Scientific, Technical and Cultural Affairs (OSTC), Federal Ministry of Social Affairs, Public Health and the Environment. 1–12.

Missiaen, T., Noppe, L. (2009) Detailed seismic imaging of a chemical munition dumpsite in the Bornholm Basin, south-western Baltic. *Environ Earth Sci*. (60), 81–94. DOI: 10.1007/s12665- 009-0171-9.

Missiaen, T., Paka, V., Emalyanov, E. (2006) Modelling of Ecological Risks Related to Sea-Dumped Chemical Weapons: Synthesis report of the available data. MERCW.

Missiaen, T., Söderström, M., Popescu, I., Vanninen, P. (2010) Evaluation of a chemical munition dumpsite in the Baltic Sea based on geophysical and chemical investigations. *Science of the total environment*. 408 (17), 3536-3553. DOI: 10.1016/j.scitotenv.2010.04.056.

Monteil-Rivera, F., Deschamps, S., Ampleman, G., Thiboutot, S., Hawari, J. (2010) Dissolution of a new explosive formulation containing TNT and HMX: Comparison with octol. *J Hazard Mater*. 174 (1-3), 281–288. DOI: 10.1016/j.jhazmat.2009.09.048.

Nawała, J., Jóźwik, P., Popiel, S. (2019) Thermal and catalytic methods used for destruction of chemical warfare agents. *Int J Environ Sci Technol*. 16, 3899–3912. DOI: 10.1007/s13762-019-02370-y.

North, N., Macleod I. (1987) Corrosion of metals. In: *Corrosion of Marine Archaeological Objects*. Pearson. C. Butterworths. London. 68-98. DOI: 10.1016/B978-0-408-10668-9.50010-1.

Nawała, J., Gordon, D., Dziedzic, D., Rodziewicz, P., Popiel, S. (2021) Why does Clark I remain in the marine environment for a long time? *Science of The Total Environment*. 774, 145675. DOI: 10.1016/j.scitotenv.2021.145675.

Niemikoski, H., Söderström, M., Vanninen, P. (2017) Detection of Chemical Warfare Agent-Related Phenylarsenic Compounds in Marine Biota Samples by LC-HESI/MS/MS. *Analytical chemistry*. 89 (20), 11129-11134. DOI: 10.1021/acs.analchem.7b03429.

Niemikoski, H., Straumer, K., Ahvo, A., Turja, R., Brenner, M., Rautanen, T., Lang, T., Lehtonen, K.K., Vanninen, P. (2020a) Detection of chemical warfare agents-related phenylarsenic compounds and multi-biomarker responses in cod (*Gadus morhua*) from chemical munition dumpsites in the Baltic Sea. Marine Environmental Research. 162, 105160. DOI: 10.1016/j.marenvres.2020.105160.

Niemikoski, H., Söderström, M., Kiljunen, H., Östin, A., Vanninen, P. (2020b) Identification of Degradation Products of Sea-Dumped Chemical Warfare Agent-Related Phenylarsenic Chemicals in Marine Sediment. *Anal Chem.* 92 (7), 4891–4899. DOI: 10.1021/acs.analchem.9b04681.

Niemikoski, H., Lehtonen, K. K., Ahvo, A., Heiskanen, I., Vanninen, P. **(2021)** Metabolism and cytotoxicity of diphenylarsinic acid, a degradation product of sea-dumped chemical warfare agents, in a rainbow trout liver cell line RTL-W1. *Aquat Toxicol.* 241, 105993. DOI: 10.1016/j.aquatox.2021.105993.

Nipper, M., Carr, R.S., Biedenbach, J.M., Hooten, R.L., Miller, K., Saepoff, S. (2001) Development of Marine Toxicity Data for Ordnance Compounds. *Arch Environ Contam Toxicol*. 41, 308–318. DOI: 10.1007/s002440010253.

Nipper, M., Carr, R.S., Lotufo, G.R. (2009) Aquatic toxicology of explosives. In: *Ecotoxicology of Explosives*. Sunahara, G.I., Lotufo, G., Kuperman, R.G., Hawari, J. Boca Raton (FL). CRC Press. 77-115. DOI:10.1201/9781420004342.ch4.

Nixon, E. (2009) *Assessment of the Impact of Dumped Conventional and Chemical Munitions*. OSPAR Commission. http://tinyurl.com/5n8bb9f3 (2024-02-29).

Nützel, B. (2008) *Untersuchungen zum Schutz von Schweinswalen vor Schockwellen* (English: Studies on the protection of porpoises from shock waves). Report Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik (FWG). Kiel.

Overfield, M. L., Symons, L. C. (2009) The Use of the RUST Database to Inventory, Monitor, and Assess Risk from Undersea Threats. *Mar Technol Soc J*. 43 (4), 33–40. DOI: 10.4031/MTSJ.43.4.9.

Pfeiffer, F. (2012) *Bericht über die in-situ-Begleituntersuchungen zur Munitionssprengung in der Ostsee vom 18.2.2009*. https://tinyurl.com/5n8d4mpv (2024-02-28).

Porter, J.W., Barton, J.V., Torres, C. (2011) Ecological, radiological, and toxicological effects of naval bombardment on the coral reefs of Isla de Vieques, Puerto Rico. In: *Warfare Ecology*. Machlis, G.E., Hanson T., Špirić, Z., McKendry, J.E. Springer. Dordrecht. 65-122. DOI: 10.1007/978-94-007-1214-0_8.

Reckermann, M., Omstedt, A., Soomere, T., Aigars, J., Akhtar, N., Bełdowska, M., Bełdowski, J., Cronin, T., Czub, M., Eero, M., Hyytiäinen, K. P., Jalkanen, J.-P., Kiessling, A., Kjellström, E., Kuliński, K., Larsén, X. G., McCrackin, M., Meier, H. E. M., Oberbeckmann, S., Parnell, K., Pons-Seres de Brauwer, C., Poska, A., Saarinen, J., Szymczycha, B., Undeman, E., Wörman, A., Zorita, E. (2022) Human impacts and their interactions in the Baltic Sea region. *Earth Syst Dynam*. 13 (1), 1–80. DOI: 10.5194/esd-13-1-2022.

Rennie, S.E., Brandt, A., Friedrichs, C.T. (2017) Initiation of motion and scour burial of objects underwater. *Ocean Engineering*. 131, 282-294. DOI: 10.1016/j.oceaneng.2016.12.029.

Reynolds, J.M. (2011) *An introduction to applied and environmental geophysics*. WileyBlackwell. 2nd ed. Chichester, Hoboken.

Robidoux, P.Y., Hawari, J., Thiboutot, S., Sunahara, G.I. (2003) Eco-toxicological risk assessment of an explosives-contaminated site. In: *Environmental Analysis of Contaminated Sites*. Sunahara, G.I., Renoux, A.Y., Thellen, C., Gaudet, C.L., Pilon, A. John Wiley and Sons. New York. 335–359.

Robinson, S.P., Wang, L., Cheong, S.H., Lepper, P.H., Marubini, F., Hartley, J.P. (2020) Underwater acoustic characterisation of unexploded ordnance disposal using deflagration. *Marine Pollution Bulletin*. 160, 111646. DOI: 10.1016/j.marpolbul.2020.111646.

Rodacy, P.J., Reber, S.D., Walker, P.K., Andre, J.V. (2001) *Chemical sensing of explosive targets in the Bedford Basin, Halifax Nova Scotia*. Sandia National Laboratories. Albuquerque, Livermore. https://tinyurl.com/p55wmpxm (2024-02-29).

Røen, B.T., Unneberg, E., Tørnes, J.A., Lundanes, E. (2010) Headspace-trap gas chromatography–mass spectrometry for determination of sulphur mustard and related compounds in soil. *J Chromatogr A*. 1217 (14), 2171-2178. DOI: 10.1016/j.chroma.2010.01.088.

Rosen, G., Lotufo, G.R. (2010) Fate and effects of Composition B in multispecies marine exposures. *Environmental Toxicology and Chemistry*. 29 (6), 1330–1337. DOI: 10.1002/etc.153.

Rossland, H.K., Johnsen, A., Karsrud, T.E., Parmer, M.P., Larsen, A., Myran, A., et al. (2010) *Forurensning fra Ammunisjon i Akvatisk Miljø og på Kystfort -Innledende Undersøkelser* (English Translation: Pollution from ammunition in the aquatic environment and the coastal forts: Initial investigations). Forsvarets forskningsinstitutt (FFI), FFI-rapport 2010/00239. FFI.

Ruffell, A., Pringle, J.K., Cassella, J.P., Morgan, R.M., Ferguson, M., Heaton, V.G., Hope C., McKinley, J.M. (2017) The use of geoscience methods for aquatic forensic searches. *Earth-Science Reviews*. 171, 323–337. DOI: 10.1016/j.earscirev.2017.04.012.

Salazar, M.H., Salazar, S.M. (1995) In-Situ Bioassays using Transplanted Mussels: I. Estimating Chemical Exposure and Bioeffects with Bioaccumulation and Growth. *Environ Toxicol Risk Assess*. 216-241. DOI: 10.1520/STP12693S.

Sanderson H., Fauser P. (2015) *Environmental Assessments Of Sea Dumped Chemical Warfare Agents: CWA report*. No. 174. Danish Cent Environ Energy, Aarhus University. Aarhus. http://dce2.au.dk/pub/SR174.pdf (2024-02-28).

Sanderson, H., Fauser, P., Stauber, R.S., Christensen, J., Løfstrøm, P., Becker, T. (2017) Civilian exposure to munition specific carcinogens and resulting cancer risks for civilians on the Puerto Rican island of Vieques following military exercises from 1947-1998. *Glob Secur Heal Sci Policy*. 2 (1), 40–61. DOI: 10.1080/23779497.2017.1369358.

Sanderson, H., Fauser, P., Thomsen, M., Vanninen, P., Soderstrom, M., Savin, Y., Khalikov, I., Hirvonen, A., Niiranen, S., Missiaen, T., Gress, A., Borodin, P., Medvedeva, N., Polyak, Y., Paka, V., Zhurbas, V., Feller, P. (2010) Environmental hazards of sea-dumped chemical weapons. Environ. Sci. Technol. 44 (12), 4389-4394. DOI: 10.1021/es903472a.

Scharsack, J.P., Koske, D., Straumer K., Kammann U. (2021) Effects of climate change on marine dumped munitions and possible consequence for inhabiting biota. *Environmental Sciences Europe*. 33 (1), 102. DOI: 10.1186/s12302-021-00537-4.

Schuster, R., Strehse, J.S., Ahvo, A., Turja, R., Maser, E., Bickmeyer, U., Lehtonen, K.K., Brenner, M. (2021) Exposure to dissolved TNT causes multilevel biological effects in Baltic mussels (*Mytilus spp*.). *Marine Environmental Research*. 167, 105264. DOI: 10.1016/j.marenvres.2021.105264.

Schmidtke, E. (2010) *Schockwellendämpfung mit einem Luftblasenschleier zum Schutz der Meeressäuger*. DAGA conference 2010. Berlin. 689-690. http://tinyurl.com/4p8nbbbc (2024-02-29).

Schmidtke, E. (2012) *Schockwellendämpfung mit einem Luftblasenschleier im Flachwasser*. DAGA conference 2012. Darmstadt. 949-950. http://tinyurl.com/mwrp6uew (2024-02-29).

Schmidtke, E., Nützel, B., Ludwig, S. (2009) Risk mitigation for sea mammals - The use of air bubbles against shock waves. NAG/DAGA 2009. Rotterdam. 269-270. http://tinyurl.com/4wsxrwv7 (2024-02-29).

Schwartz, A., Brandenburg, E. (2009) An Overview of Underwater Technologies for Operations Involving Underwater Munitions. *Marine Technology Society Journal*. 43 (4), 62–75. DOI: 10.4031/MTSJ.43.4.12.

Siebert, U., Morell, M., Lakemeyer, J., Schaffeld, T. (2020) *Untersuchungen von Schweinswalen aus der Ostsee auf mögliche Effekte durch Sprengungen. Bericht an das Bundesamt für Naturschutz,* Institut für Terrestrische und Aquatische Wildtierforschung. Büsum. http://tinyurl.com/3hhd8e3r (2024-02-29).

Siebert, U., Stürznickel, J., Schaffeld, T., Oheim, R., Rolvien, T., Prenger-Berninghoff, E., Wohlsein, P., Lakemeyer, J., Rohner, S., Schick, L. A., Gross, S., Nachtsheim, D., Ewers, C., Becher, P., Amling, M., Morell, M. (2022)

Blast injury on harbour porpoises (*Phocoena phocoena*) from the Baltic Sea after explosions of deposits of World War II ammunition. *Environ Int*. 159, 107014. DOI: 10.1016/j.envint.2021.107014.

Silva, J.A.K., Chock, T. (2016) Munitions integrity and corrosion features observed during the HUMMA deep-sea munitions disposal site investigations. *Deep Res Part II Top Stud Oceanogr*. 128, 14–24. DOI: 10.1016/j.dsr2.2015.09.001.

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., André, M. (2013a) Ultrastructural damage of *Loligo vulgaris* and *Illex coindetii* statocysts after low frequency sound exposure. *PLoS ONE*. 8 (10), e78825. DOI: 10.1371/journal.pone.0078825.

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., André, M. (2013b) Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? *Deep Sea Res Part II: Topical Studies in Oceanography*. 95, 160-181. DOI: doi.org/10.1016/j.dsr2.2012.10.006.

Strahle, W.C. (1988) *Conventional Weapons Underwater Explosions*. Georgia Institute of Technology. Atlanta. http://tinyurl.com/23sd3shr (2024-02-28).

Strategic Environmental Research and Development Program (SERDP), Environmental Security Technology Certification Program (ESTCP) (2007) *SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environments*. https://tinyurl.com/6pc96x78 (2024-02-28).

Straumer K., Kraugerud M., Feist S.W., Ahvo A., Lehtonen K., Lastumäki A., Ljønes M., Tørnes J.A., Lang T. (2020) The use of Atlantic hagfish (*Myxine glutinosa*) as a bioindicator species for studies on effects of dumped chemical warfare agents in the Skagerrak. 1: Liver histopathology. *Mar Environ Res*. 161, 105046, DOI: 10.1016/j.marenvres.2020.105046.

Strehse, J.S., Appel, D., Geist, C., Martin, H.-J., Maser, E. (2017) Biomonitoring of 2,4,6-trinitrotoluene and degradation products in the marine environment with transplanted blue mussels (*M. edulis*). *Toxicology*. 390 117–123. DOI: 10.1016/j.tox.2017.09.004.

Strehse, J.S., Maser, E. (2020) Marine bivalves as bioindicators for environmental pollutants with focus on dumped munitions in the sea: A review. *Mar Environ Res*. 105006. DOI: 10.1016/j.marenvres.2020.105006.

Strehse J.S., Brenner M., Kisiela M., Maser E. (2020) The explosive trinitrotoluene (TNT) induces gene expression of carbonyl reductase in the blue mussel (*Mytilus spp*.): a new promising biomarker for sea dumped war relicts? *Arch Toxicol*. 94 (12), 4043-4054 DOI: 10.1007/s00204-020-02931-y.

Sućeska, M. (Hg.) (1995): *Test Methods for Explosives*. Springer Verlag. New York.

Sun, Q., Chen, Z., Yuan, D., Yu, C.P., Mallavarapu, M., Naidu, R. (2011) On-line SPE Coupled with LC–APCI–MS for the Determination of Trace Explosives in Water. *Chromatographia*, 73 (7-8), 631-637. DOI: 10.1007/s10337-011-1964-z.

Surikov, B.T. (1996) How to save the Baltics from ecological disaster. In: *Sea-Dumped Chemical Weapons: Aspects, Problems and Solutions*. Kaffka A.V. Springer. Dordrecht. 67–70.

Sutolovic, C. (2004) *Overview of Perspectives for the Destruction of Toxic Chemicals and CWA According to the Chemical Weapons Convention*.

Ahlsén, J., Bergkvist, J., Granmo, Å. (2020) *Undersökning av biota och sediment i anslutning till dumpningsområden av kemisk ammunition på väst- och östkusten 2019* (English: Investigation of biota and sediment in connection to chemical warfare dump sites on the west and east coast of Sweden 2019.). SwAM report 2020:15. http://tinyurl.com/2ncj4acj (2024-02-28).

Szarejko, A., Namieśnik, J. (2009) The Baltic Sea as a dumping site of chemical munitions and chemical warfare agents. *Chemistry and Ecology*. 25 (1), 13-26. DOI: 10.1080/02757540802657177.

Szubska M. (2020) *Variability and Sources of Arsenic Concentration in Baltic Sea Sediments*. PhD Thesis. Institute of Oceanology PAS. Sopot.

Talmage, S.S., Opresko, D.M., Maxwell, C.J., Welsh, C.J., Cretella, F.M., Reno, P.H., Daniel, F.B. (1999) Nitroaromatic munition compounds: environmental effects and screening values. *Rev Environ Contam Toxicol*. 161, 1–156. DOI: 10.1007/978-1-4757-6427-7_1.

The National Archives of the UK *ADM 228-24*.

Tornero, V., Hanke, G. (2016) Chemical contaminants entering the marine environment from sea-based sources: A review with a focus on European seas, *Mar Pollut Bull*. 112 (1–2), 17–38. DOI: 10.1016/j.marpolbul.2016.06.091.

Tornero, V., Hanke, G. (2017) *Potential chemical contaminants in the marine environment*. JRC 108964. European Union. DOI: 10.2760/337288.

Tørnes, J. A., Voie, Ø. A., Ljønes, M., Opstad, A. M., Bjerkeseth, L. H., Hussain, F. (2002) *Investigation and risk assessment of ships loaded with chemical ammunition scuttled in Skagerrak*. FFI/Rapport-2002/04951. FFI. Kjeller. http://tinyurl.com/y729nw89 (2024-02-29).

Tørnes, J.A., Vik, T., Kjellstrøm, T.T. (2020) Leakage rate of the nerve agent tabun from sea-dumped munition. *Marine Environmental Research*. 161, 105052. DOI: 10.1016/j.marenvres.2020.105052.

U.S. Environmental Protection Agency (US EPA) (2012) *EPA Federal Facilities Forum Issue Paper: Site Characterization For Munitions Constituents*. EPA-505-S-11-001. http://tinyurl.com/2j3kwrz6 (2024-09-29).

Videla, H.A. (2000) An overview of mechanisms by which sulphate-reducing bacteria influence corrosion of steel in marine environments. *Biofouling*. 15 (1-3), 37-47. DOI: 10.1080/08927010009386296.

Vanninen, P., Östin, A., Bełdowski, J., Pedersen, E.A., Söderström, M., Szubska, M., Grabowski, M., Siedlewicz, G., Czub, M., Popiel, S., Nawała, J., Dziedzic, D., Jakacki, J., Pączek, B. (2020) Exposure Status of Sea-Dumped Chemical Warfare Agents in the Baltic Sea. *Marine Environmental Research*. 161, 105112. DOI: 10.1016/j.marenvres.2020.105112.

von Benda-Beckmann, A.M., Aarts, G., Sertlek, Ö., Lucke, K., Verboom, W.C., Kastelein, R.A., Ketten, D.R., van Bemmelen, R.S.A., Lam, F.P.A., Kirkwood, R., Ainslie, M.A. (2015a) Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (*Phocoena phocoena*) in the Southern North Sea. *Aquatic Mammals*. 41 (4), 503-523. DOI: 10.1578/AM.41.4.2015.503.

von Benda-Beckmann, A.M., Aarts, G.M., Lucke, K., Verboom, W.C., Kastelein, R.A., van Bemmelen, R.S.A., Geelhoed, S.C.V., Kirkwood, R.J. (2015b) *Assessment of impact of underwater clearance of historical explosives by the Royal Netherlands Navy on harbour porpoises in the North Sea*. TNO. The Hague. http://tinyurl.com/yeser9wp (2024-02-29).

Wang, P.-F., George, R.D., Wild, W., Liao, Q. (2013) *Defining Munition Constituent (MC) Source Terms in Aquatic Environments on DoD Ranges*. Technical Report 1999. SSC Pacific. San Diego (CA). http://tinyurl.com/2abyw85s (2024-02-29).

Wang, P.-F., Liao, Q., George, R., Wild, W. (2011) Release rate and transport of munitions constituents from breached shells in marine environment. In: *Environmental Chemistry of Explosives and Propellant Compounds in Soils and Marine Systems: Distributed Source Characterization and Remedial Technologies*. Chappell M.A., Price, C.L. 317–340. DOI: 10.1021/bk-2011-1069.ch016.

Warren, J.K., Vlahos, P., Smith, R., Tobias, C. (2018) Investigation of a new passive sampler for the detection of munitions compounds in marine and freshwater systems. *Environ Toxicol Chem.* 37 (7), 1990-1997. DOI: 10.1002/etc.4143.

Wilczynski, W., Radlinska, M., Wysujack, K., Czub, M., Brzeziński, T., Kowalczyk, G., Bełdowski, J., Nogueira, P., Maszczyk, P. (2022) Metagenomic Analysis of the Gastrointestinal Microbiota of *Gadus morhua callarias* L. Originating from a Chemical Munition Dump Site. *Toxics*. 10, 206. DOI: 10.3390/toxics10050206.

Winkelmann, K. (2014) State of the Art in Commercial Offshore UXO Detection. *Underwater Acoustics 2014*. Rhodes 23.06.2014.

Winkelmann, K., Fischer, A. (2009) *"Tiefenreichweite" bei der Kampfmittelsuche mit Magnetometern*. SENSYS. https://tinyurl.com/yu92dpkf (2024-02-28).

Yelverton, J.T., Richmond, D.R., Hicks, W., Sounders, H., Fletcher, E.R. (1975) *The Relationship between Fish Size and Their Response to Underwater Blast*. Topical Report AD-AO15 970. Lovelace Foundation for Medical Education and Research. Albuquerque (NM). https://tinyurl.com/2nmrs5pe (2024-02-29).

Young, G.A. (1991) *Concise methods for predicting the effects of underwater detonations on marine life*. Naval Surface Warfare Center, Silver Spring (MD). http://tinyurl.com/ynh5xe4b (2024-02-29).

Zampoukas, N., Palialexis, A.,Duffek, A., Graveland, J., Giorgi, G., Hagebro, C., Hanke, G., Korpinen, S., Tasker, M., Tornero, V., Abaza, V., Battaglia, P., Caparis, M., Dekeling, R., Frias Vega, M., Haarich, M., Katsanevakis, S., Klein, H., Krzyminski, W., Laamanen, M., Le Gac, J.C., Leppanen, J.M., Lips, U., Maes, T., Magaletti, E., Malcolm, S., Marques, J.M., Mihail, O., Moxon, R., O'Brien, C., Panagiotidis, P., Penna, M., Piroddi,C., Probst, W.N., Raicevich, S., Trabucco, B., Tunesi, L., van der Graaf, S., Weiss, A., Wernersson, A.S., Zevenboom, W. (2014) *Technical guidance on monitoring for the Marine Stategy Framework Directive*. Report EUR 26499 EN. Joint Research Centre. Ispra. DOI: 10.2788/70344.

Zhang, X., Hester, K.C., Mancillas, O., Peltzer, E.T., Walz, P.M., Brewer, P.G. (2009) Geochemistry of chemical weapon breakdown products on the seafloor: 1, 4-Thioxane in seawater. *Environmental science & technology*. 43 (3), 610-615. DOI: 10.1021/es802283y.

Zukas, J.A., Walters, W.P. (1998) *Explosive Effects and Applications*. Springer Verlag. New York.

Zuykov, M., Pelletier, E., Harper, D.A.T. (2013) Bivalve mollusks in metal pollution studies: From bioaccumulation to biomonitoring. *Chemosphere*. 93 (2), 201-208. DOI: 10.1016/j.chemosphere.2013.05.001.

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