NSW North Sea Wrecks - An Opportunity for Blue Growth
Deliverable 4.4 – Clearing *UXO* overview study under North Sea conditions
Deliverable 7.2 – Impact analysis of new cargo and new contaminant types

Discussing Removal Options of Unexploded Ordnance in and near Shipwrecks

The current state of knowledge on analytical processes, monitoring, and legal background

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Discussing Removal Options of Unexploded Ordnance in and near Shipwrecks – The Current state of knowledge on analytical processes, monitoring, and legal background

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Part of:

Deliverable 4.4 – Clearing *UXO* overview study under North Sea conditions and
Deliverable 7.2 – Impact analysis of new cargo and new contaminant types

Content

1. Introduction

The North Sea has been the site of numerous military conflicts throughout history, particularly during the two World Wars. As a result, the seabed of the North Sea is littered with a variety of munitions, including bombs, mines, and chemical weapons, that were dumped there following the wars. These dumped munitions present a significant risk to the environment, marine life, and human health due to the potential for explosions, leakage of toxic substances, and disturbance of the ecosystem.

During both World War I and II, the North Sea saw intense naval battles, air raids, minelaying, and submarine activity, leading to a vast amount of ordnance being deployed. In addition, the post-war period saw the disposal of unwanted munitions at sea as a quick and convenient solution. The exact amount of dumped munitions is unknown, but estimates suggest there could be as many as 1.6 million tons of munitions in the German North and Baltic Seas. These remnants of war can be found near shipwrecks, near wrecks of aircrafts, as bombs dropped in open sea by individual aircraft on their way home, at munition dump sites, and as remnants from minefields, and are responsible for leaking toxic substances into the environment[1].

While some *UXO*s can be safely removed, others require explosive ordnance disposal (EOD), often via detonation on-site using a high-order detonation (blast-in-place; BiP). However, recent studies suggest that this BiP procedure may cause more harm to the environment than leaking. Therefore, it is necessary to assess the available techniques and methods for safely removing *UXO*s and compare them to each other[2].

This study aims to outline these techniques and methods while highlighting the hazards associated with neglecting these remnants of war. The hazards of *2,4,6-trinitrotoluene (TNT)*, which was commonly used in ordnances before and during both World Wars, are thoroughly examined in the next chapter. In chapter three the effects and degradation of Polycyclic Aromatic *Hydrocarbons* (*PAHs*) in seabed conditions are discussed. *PAHs* are present in the oil and fuel of a ships and might still be present in the bunkers of shipwreck. The fourth chapter explains the current technique mostly used in the field for *UXO* removal, including the results of this method. The fifth chapter outlines new techniques and methods currently under review by different EOD disposal teams from different countries. The sixth chapter outlines the techniques for the monitoring of the discussed substances and of the used *UXO* clearance techniques.

Chapter seven addresses the current laws and regulations regarding the removal of (conventional) *UXO*s in European countries bordering the North Sea region, distinguishing between isolated *UXO* finds and those found within the context of a shipwreck. Different regulations may apply to *UXO*s found near or in shipwrecks of cultural and historical value. In chapter eight, a synthesis of the results is presented and summarized in a current state of knowledge. The final chapter advised policymakers and scientists on the next steps to create a safer North Sea Region. The glossary on page 38 provides explanations for any words written in cursive.

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[1] Appel et al., 2018; Baran and Zelt, 2015 ; Beldowski et al., 2019; Böttcher *et al.*, 2011 ; Missiaen et al., 2010; Porter et al., 2004; Robinson et al., 2020, 1 ; Strehse et al., 2017.

[2] Maser and Strehse, 2020; Siebert, 2022

2. Effects and behaviour of *TNT*

The explosive 2,4,6-trinitrotoluene (*TNT*, fig. 1.), is a nitroaromatic energetic compound. It is a major ingredient in almost every munition formulation[3]. *TNT* has been used both as a pure explosive and in *binary mixtures*. The most common *binary mixtures* of *TNT* are with *cyclotrons* (mixtures with *RDX*) and *octyls* (*HMX*). *TNT* has a low melting point and is thermally and chemically stable.

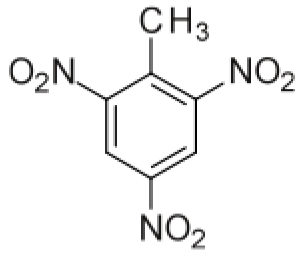

Figure 1: Chemical structure of TNT

2.1. Possible hazards of *TNT*

As a synthetic chemical, *TNT* does not occur naturally in the marine environment. It is a product of human activity, and it can enter the marine environment through various pathways, such as leakages from sea mines, munition dumpsites and World War 1 and 2 shipwrecks. *TNT* as well as its manufacturing impurities and *metabolites* are known to have various negative impairments on human health and are of environmental concern[4]. *TNT* is toxic to all organisms. In humans, *TNT* and its *metabolites* can damage the DNA (mutagenic)[5], it is *carcinogenic*, and it is toxic to the liver, kidneys, eyes, skin, blood system and spleen[6].

Many studies have shown acute and chronic toxic effects on marine species like shrimp, fish, copepods, corals, amphipods, and bivalves[7]. Compared to other aquatic organisms, fish seem to be one of the most sensitive species regarding *TNT*[8]. The *genotoxicity* of *TNT* has been proven by using zebrafish embryos (*Danio rerio*)[9]. Adult mussels such as blue mussels have shown to be the most tolerant species in relation to *TNT* contaminations among other marine and invertebrate species, especially with regard to acute toxic effects. This means, mussels show first acute toxic effects at higher *TNT* water concentrations than other species. Nevertheless, several studies demonstrated negative multilevel biological effects in the Baltic blue mussel (*Mytilus* spp.)[10]. Therefore, negative long-term effects of *TNT* contamination cannot be ruled out for mussels either.

Scientific background – *Carcinogenic*ity of *TNT*

TNT has been tested for *carcinogenic*ity in two-year bioassays in rats and mice. After administration of *TNT* via diet, *carcinoma* of the urinary bladder and *hepatocellular neoplasms* were observed in rats, while malignant lymphoma combined with lymphocytic and granulocytic leukaemia in the spleen significantly increased in mice. US-EPA concluded that *TNT* is a possible human carcinogen (Class C)[6]. A study in humans found elevated levels of chromosomal aberrations in a subset of *TNT*-exposed workers who were also positive for N-acetyltransferase (NAT1) (rapid acetylator) and exhibited the null glutathione-S-transferase (GST) T1 (GSTT1) or GSTM1 genotype[5]. In Germany, *TNT* has been classified as belonging to Group 2 (“substances that are considered to be *carcinogenic* in humans”).

[3] Walsh et al., 1993
[4] EPA, 2021
[5] Sabbioni and Rumler, 2007
[6] Bolt et al., 2006
[7] Lotufo et al., 2016; Nipper et al., 2001; Rosen and Lotufo, 2007; Ek et al., 2008
[8] Lotufo et al., 2021
[9] Koske et al., 2019
[10] Schuster et al., 2021

2.2. Degradation of *TNT* in water

Transformation processes of the munition's residues include *photolysis*, *hydrolysis*, *oxidation*, *reduction*, and biological transformation. Several of these transformation processes take place simultaneously in the waters of the North Sea, but to varying degrees. The various compounds' solubility and the *octanol-water partition coefficient* (K_{OW}) value indicate whether they will diffuse into surrounding water or adsorb to sediment[11]. In natural waters, *TNT* will break down rapidly near the surface through *photodegradation*, i.e., to 1,3,5- trinitrobenzene (*1,3,5-TNB*)[12]. However, the irradiance decreases rapidly with depth by several orders of magnitude within only a few meters of the surface[13]. Hence, *photodegradation* and *photolysis* play only a role in clear or very shallow waters[14].

TNT degradation in coastal marine systems is controlled by seawater circulation in the permeable sediments[15]. When stream water permeated through *anoxic* riverbank sediments *TNT* was degraded under *anoxic* conditions to nitroso or *amino derivatives*[16]. In general, *TNT* degradation in some coastal waters, especially fresh-saline mixing zones, may occur on the order of days to weeks[17]. Degradation experiments using seawater from the North Sea showed slow *mineralization* rates, with a half-life in the order of 5 years. Degradation rates in sediments tend to be faster than those in water[18]. Generally, *TNT* is mineralized less than 10% up to 30% (in some cases) when added to sediment and water slurries[19]. The non-mineralised *TNT* is either metabolised by biota or bacteria, sorbed unmetabolized into the sediment, or distributed by the current. The *metabolites* generated by biota and bacteria can also be adsorbed to sediment or distributed by currents. Interestingly, 80 – 99% of the mineralized carbon from *TNT* is incorporated into the biomass of bacteria[20].

In deeper waters *4-amino-2,6-dinitrotoluene (4-ADNT)*, *2-amino-4,6-dinitrotoluene (2-ADNT)* and 2,4-diamino-6-nitrotoluene (*2,4-DA-6-NT*) appeared to be the most abundant energetic compounds found in all biota samples. The presence of low levels or even the absence of *TNT* itself throughout biota studies is likely a consequence or conversion of *TNT* by biota or bacterial enzymes to *2-ADNT*, *4-ADNT* and *2,4-DA-6-NT*[21].

Scientific background – *mineralization* of *TNT*

Mineralization describes processes in which an organic compound such as *TNT* is transformed into inorganic products. In the case of *TNT* mainly carbon dioxide and nitrogen dioxide as well as alcohols and *ketones* are formed[14]. Hence, *mineralization* of *TNT* also means a ring cleavage of the *aromatic structure*. To date, it has not been possible to clarify how *TNT* can be completely mineralised under natural conditions in the marine environment. It is known that reducing enzymes can also react by *hydride* or *hydroxyl* addition to form Meisenheimer complexes with ring cleavage and release of *nitrite*[14]. Whether and to what extent this happens in the marine environment has not yet been proven.

[11] Goodfellow, 1983
[12] EPA, 2012
[13] Wozniak and Dera, 2007 from Beck at al. 2018
[14] Beck et al., 2018
[15] Santos et al., 2012
[16] Zheng et al., 2009
[17] Montgomery et al., 2014
[18] Beck et al., 2018; Harrison and Vane, 2010
[19] reported in Montgomery et al., 2011
[20] Montgomery et al., 2014
[21] Hawari et al. 2000

2.3. Degradation of munitions compounds by bacteria – biodegradation of *TNT*

According to the literature, "degradation" of *TNT* often means *oxidation* and/or *reduction* of the NH_3- or NO_2- moieties of the *TNT* ring, respectively, while the aromatic ring system of *TNT* itself remains uncleaved. However, all these ring-structured "*metabolites*" of *TNT* are still (or even more) toxic and *carcinogenic*, thereby keeping their threat to the environment and/or the human seafood consumer. While animals are not able to naturally *detoxify TNT* and other ring-structured chemicals, it is known that bacteria can perform the complete degradation of ring-structured chemicals like steroids and *PAHs*. Thus, bacteria are unique to express *ring cleavage dioxygenase enzymes*, which enable them to completely metabolize ring-structured chemicals into CO_2 and H_2O.

Due to differences in physiological properties and niche preferences among community members, bacteria respond in specific ways to environmental drivers, potentially resulting in distinct microbial fingerprints for a given environmental state. In an effort to identify bacteria that have possibly adapted to munition compound contaminated areas, machine learning was used to detect microbial fingerprints indicating the presence of the energetic compound *2,4,6-trinitrotoluene (TNT)* in southwestern Baltic Sea sediments. Over 40 environmental variables including grain size distribution, elemental composition, and concentration of munition compounds (mostly at $pmol \cdot g^{-1}$ levels) from 150 sediments collected at the near-to-shore munition dumpsite Kolberger Heide by the German city of Kiel were combined with 16S rRNA *gene amplicon sequencing* libraries. Although the major aim was to use the microbial community on site to predict the presence of *TNT* contamination, the data could also pave the way for identifying bacteria that live on *TNT* as a source of carbon, nitrogen and energy and may therefore be used for *TNT* remediation in the marine environment[22].

A recent study isolated six different bacterial species from the Baltic Sea and the Chinese Sea that are capable of metabolizing *TNT*. The researchers found that one type of bacteria, *Buttiauxella* sp. S19-1, has the strongest ability to degrade *TNT*. They also discovered that a gene called BuP34O is critical in breaking down *TNT*[23]. In fact, the knockout of this gene in the S19-1 mutant strain resulted in a marked *reduction* in *TNT* degradation efficiency compared to the wildtype strain. Furthermore, the researchers found that a *recombinant protein* called P34O, which is expressed by the BuP34O gene, may catalyze downstream reactions in the *TNT* degradation pathway. Another gene called BuMO was also found to be central to *TNT* degradation[24]. The researchers discovered that the importance of *Buttiauxella* sp. S19-1 in *TNT* degradation was further supported by a transcriptome analysis, which revealed the significance of the BuMO gene in the *TNT* degradation pathway. These findings indicate that these bacteria have enormous potential for the restoration of *TNT*-contaminated seas, but a present it is part of further investigations how to use them under environmental conditions.

[22] Janßen *et al.*, 2021
[23] Xu *et al.*, 2021
[24] Xu *et al.*, 2023

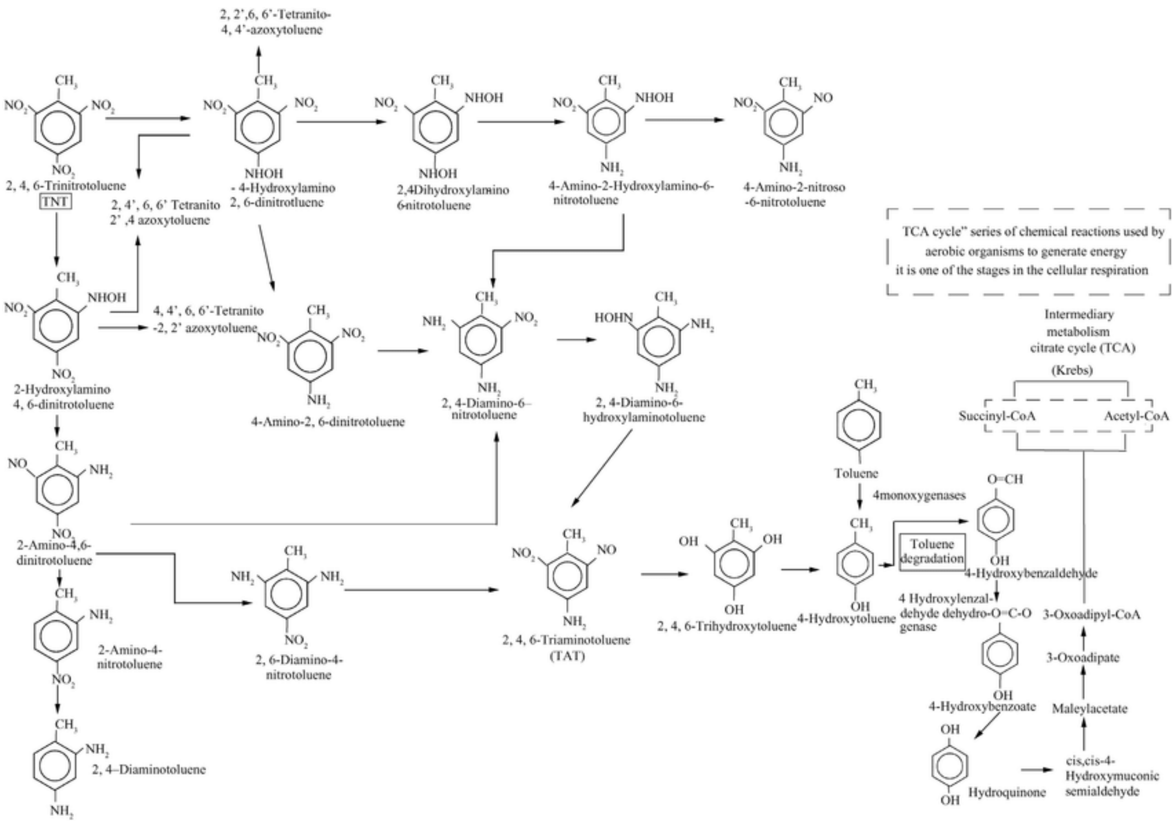

Figure 2: TNT degradation pathway, the scheme is based on EAWAG biocatalysts/biodegradation database[25]

Scientific background – bacterial *metabolization* of *TNT*

In the study by Xu *et al.*, 2021, six different bacterial species were isolated from the Baltic Sea and from the Chinese Sea that can metabolize *TNT*. Screening for *TNT* degradation by six selected bacteria revealed that *Buttiauxella* sp. S19-1 possesses the strongest degrading ability. Moreover, *BuP34O* (a gene encoding for protocatechuate 3,4-dioxygenase – P34O, a key enzyme in the *β-ketoadipate pathway*) was upregulated during *TNT* degradation. A knockout of *BuP34O* in S19-1 to generate an S-M1 mutant strain caused a marked reduction in *TNT* degradation efficiency compared to the S19-1 wildtype strain. Additionally, the EM1 mutant strain (*Escherichia coli* DH5α transfected with *BuP34O*) showed higher degradation efficiency than DH5α. Gas chromatography-mass spectrometry (GC-MS) analysis of *TNT* degradation by S19-1 revealed *4-amino-2,6-dinitrotoluene (4-ADNT)* as the intermediate metabolite of *TNT*. Furthermore, the recombinant protein P34O (rP34O) expressed the activity of 2.46 µmol/min*mg. These findings suggest that P34O could catalyse downstream reactions in the *TNT* degradation pathway[23].

The importance of the bacterium *Buttiauxella* sp. S19-1 in *TNT* degradation was further supported by a transcriptome analysis which revealed another gene in this strain being central for *TNT* degradation, the monooxygenase gene (*BuMO*). *BuMO* was significantly up-regulated during *TNT* degradation. While a *BuMO* knockout strain (S-Δ*MO*; absence of *BuMO* gene in the S19-1 mutant) degraded *TNT* 1.66-fold less efficiently than strain S19-1 (from 71.2% to 42.9%), an E-*MO* mutant (*Escherichia coli BuMO*-expressing strain) increased the efficiency of *TNT* degradation 1.33-fold (from 52.1% to 69.5%). In this study, the three-dimensional structure of the enzyme was predicted, the recombinant protein purified, and the importance of BuMO in the *TNT* degradation pathway was highlighted[24].

[25] MacFarlan 1998 In Serrano González *et al.* 2018

3. Effects and behavior of *PAHs*

PAHs are organic compounds that have two or more condensed aromatic rings, and are widely distributed in the air, water, and soil. *PAHs* can derive from fuels from bunkers of sunken (war)ships which leak into the aquatic environment. Consequently, addressing *PAHs* pollution becomes crucial alongside the mitigation of munitions compounds as they both contribute to the overall contamination. *PAHs* pollution is toxic to marine organisms[26].

3.1. Possible hazards of PAH

PAHs bioaccumulate in aquatic animals, including invertebrates, where they act as endocrine disruptors and cause tissue-specific toxicity, including developmental toxicity, *genotoxicity*, *immunotoxicity*, and *oxidative stress*.

The most concerning toxicity of *PAHs* is their *carcinogenic*ity. Within an organism, *PAHs* are transported into cells and activate certain enzymes that break them down into other harmful substances. Some of these substances can bind to DNA and cause mutations that can lead to cancer. A number of specific types of *PAHs* have been classified as probably *carcinogenic* by the International Agency for Research on Cancer (*IARC*). The US Environmental Protection Agency monitors the emissions of 16 different *PAHs* because they are persistent pollutants that can accumulate in the environment and harm marine life. *PAHs* can also increase the toxicity of other hazardous chemicals in sunken war ships.

Scientific background - *Carcinogenic*ity of PAH

The *IARC* classified a number of PAHs as being probable *carcinogenic* chemicals including benzo[a]anthracene (BaA), benzo[a]pyrene (BaP), and dibenz[a,h]anthracene. The *carcinogenic* properties of PAHs have been examined in English sole (*Parophrys vetulus*) and flounder (*Platichthys stellatus*). The level of BaP binding to *hepatic DNA* was 10 times higher in juvenile sole compared with adult sole and 90 times higher in juvenile sole than in Sprague Dawley rats, a species that is resistant to BaP-induced hepatocarcinogenesis. Additionally, fish embryos are particularly sensitive to dispersed crude oil which is of relevance in sunken war ships because shipwrecks provide an ideal fish spawning and nursery grounds. For example, the embryos of Atlantic haddock (*Melanogrammus aeglefinus*) were fouled by crude oil droplets adhering to the chorion when exposed to concentrations of more than 0.7 µg/L tPAH. This correlated with an increase in toxicological responses (malformations and cardiotoxicity) and shows that the early development of fish is influenced by PAHs.

3.2. Degradation of fuel contaminants by bacteria – biodegradation of PAH

PAHs are environmental pollutants with harmful effects on living organisms, making the degradation of these compounds crucial for environmental remediation. Biological methods have gained wide attention for *PAHs* remediation, followed by integrated methods, and chemical *oxidation*. Among all biological methods for *PAHs* remediation, bacteria- and fungi-assisted degradation has been widely studied[27].

Several bacterial strains have been identified to break down *PAHs* using different metabolic pathways depending on whether oxygen is present or not. These different mechanisms to break down the

[26] Honda and Suzuki, 2020

[27] Patel *et al.*, 2020

complex structures of *PAHs* include ring-opening, *hydroxylation*, and *deoxygenation*[28]. *Aerobic* degradation uses oxygen as a final electron acceptor, while *anaerobic* degradation uses alternative electron acceptors. The degradation process involves enzymatic reactions, which breaks down the complex structures of *PAHs* into simpler components[27]. Bacterial consortia have also been shown to be effective in the complete degradation of *PAHs*, using these *hydrocarbons* as a source of energy, breaking them down into simpler components and finally mineralizing them to carbon dioxide and water. However, the *bioremediation* process can be affected by factors such as nutrient availability, oxygen concentration, and temperature[29].

The use of *bioremediation*, including biodegradation of *PAHs*, has been explored as a cost-effective and efficient alternative to traditional clean-up methods such as excavation and removal. *Bioremediation* techniques have been shown to be effective in degrading hydrocarbon contaminants in soil and water and numerous studies have demonstrated the ability of bacterial strains to degrade *PAHs* from various sources. However, the effectiveness of biodegradation may depend on factors such as the availability of nutrients, oxygen, and temperature, as well as the presence of other compounds[30]. This is regardless of how long wrecks and their cargoes have been on the seabed. In conclusion, it can be said that wrecks would benefit from a *bioremediation* approach that targets both *PAHs* and munition compounds [31,32].

Scientific background - bacterial degradation of PAH

Bacteria have unique metabolic versatility for the degradation of PAHs. During bacterial *aerobic* PAHs degradation, the oxygen works as the final electron acceptor and also as a co-substrate for the *hydroxylation* and oxygen-mediated cleavage of the aromatic ring, whereas bacterial *anaerobic* PAHs degradation utilizes an entirely diverse approach to break and open the aromatic ring depending on the reductive reaction type and alternative final electron acceptors Briefly, the bacteria perform *aerobic* PAHs degradation using oxygenase-facilitated metabolism (comprising monooxygenase and *dioxygenase enzymes*). The first step in the *aerobic* PAHs degradation is the *hydroxylation* of the aromatic ring through *dioxygenase enzymes* and the formation of the *cis-dihydrodiol*, which ultimately oxidizes to *diol intermediates* with the help of *dehydrogenase* enzymes[30].

While research on the *aerobic* biodegradation of PAHs has been extensively performed, only limited data are available on the a*naerobic* biodegradation of PAHs. Bacterial *anaerobic* PAHs degradation utilizes an entirely diverse approach to break and open the aromatic ring than *aerobic* biodegradation, depending on the reductive reaction type and alternative final electron acceptors. However, microbial degradation of PAHs under *anaerobic* conditions is important and gains more and more attention due to the presence of *anoxic* conditions in diverse environmental niches such as the phreatic zone, deep aquatic sediment, and water-flooded soil or, important for the present documentation, the inner side of shipwrecks. One of the limitations in *anaerobic* PAH degradation research is the slow growth rate of *anaerobic* bacteria living on PAHs and the low energy yield in the metabolic processes. Indeed, some *anaerobic* bacteria degrade PAHs under reducing conditions[31]. *Anaerobic* degradation of PAH has been demonstrated in several microcosm studies with nitrate, ferric iron, or sulfate as electron acceptors and under methanogenic conditions[31].

Interestingly, an enhanced or complete PAHs degradation can be achieved by mixed bacterial cultures and bacterial consortia as a result of collaborative catabolic activities of participants and possibly the presence of diverse degradation pathways[32].

[28] Kong *et al.,* 2017
[29] Haritash and Kaushik, 2009
[30] Haritash and Kaushik, 2009; Kong et al., 2017
[31] Dhar *et al.,* 2020
[32] Cao *et al.*, 2022

4. Currently used clearance technique

4.1. Blast-in-Place using high-order detonations

Currently, the most often used technique in the North Sea region is a controlled Blast-in-Place (BiP) procedure. During this procedure, a contact donor charge is placed on the to be removed *UXO*. These primary explosives are readily ignited or detonated by an electrical or mechanical stimulus. The donor charge is set to explode and subsequently detonates the targeted *UXO* by the initial shock. An explosion is an event of a chemical reaction where the nitrogen and oxygen molecules separate and then unite with carbon and hydrogen as shown in figure 3[33].

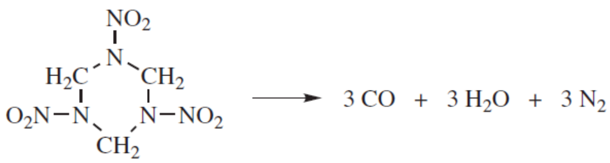

Figure 3: Chemical reaction within an explosion. The energetic compound is separated into carbon monoxide (CO), water (H_2O) and nitrogen (N_2)[33].

An explosion is a rapid release of a substantial amount of energy, typically accompanied by the sudden expansion of a significant volume of hot gas. It requires an *exothermic* reaction generating a large quantity of gas and a rapid propagation of the reaction. The velocities of the detonation shockwave are in the range of 5000-9000 m/s. The speed of explosion processes in detonating explosives is always supersonic[33]. This also results in a high peak in sound pressure, and thus in kinetic power. It has been measured that a high-order detonation of 13 kg of *TNT* produces a 283 dB re 1 µPa[34], which is 63 dB re 1 µPa higher than the Beluga whale call at a 1-meter distance and above the marine mammal sound exposure level parameter threshold, which is > 170-198 dB re 1 µPa. Thus, this shock and noise pollution results in permanent damage to the affected marine mammals[35]. Additionally, the shockwave from the explosion might also damage the wreck at which the *UXO* was found, adding to the already done damage.

After the deliberate detonation of an *UXO*, residues remain on the seabed or are distributed in the water. In addition to metal parts of the casing, this also includes residues of *energetic compounds*, such as *TNT*. How much of the various components of an *UXO* remain, the size of the residues and also the distribution radius depends very much on the method used to detonate the *UXO*. It has been shown that after BiP operations fine particles of explosive materials remain on the seabed[36]. These residues can be sized from grain to several centimetres. Even though *TNT* is hardly soluble in water, more and more of it goes into solution over time and, thus, can be taken up by marine species[37].

4.1.1. supportive methods to avoid underwater noise

To protect the sensitive hearing of fish and mammals such as porpoises and seals, the so-called bubble curtain technique is used in some countries as a supportive method for underwater blasting operations. Bubble curtains are considered the best available technique to reduce the impact of sound and shock waves on marine wildlife. A bubble curtain is created by compressed air forming a ring of

[33] Akhavan, 2018
[34] Robinson at al., 2020. 7
[35] Siebert et al., 2022a
[36] Kampmeier et al., 2020; Strehse et al., 2017
[37] Beck et al., 2022; Maser and Strehse, 2020; Strehse et al., 2017

bubbles rising from a nozzle pipe lying on the seabed (figure 4)[38]. The efficiency of bubble curtains depends on their diameter, width and shape, effective airflow, bubble size, currents, and water depth. At the moment, deployment depths are limited to about 40 to 50 metres. To intensify the effectiveness of bubble screens, several parallel rings can be used. The pipe system is designed as a closed circular system around the *UXO* to be blasted. The diameter is around 70 metres, according to individual requirements. Depending on the sound propagation, a bubble curtain can reduce the danger zone for porpoises, fish, or birds by up to 99%. If an *UXO* has a high loading, a double bubble curtain can also be used to improve the noise and shock-reducing effect accordingly (figure 4). The bubble curtain systems currently in use are reusable. All handling of the bubble curtain can be done from just one vessel and without a diver. In the German EEZ, the use of bubble curtains is mandatory upon carrying out blasting operations when explosive ordnance disposal companies are working on offshore construction sites. In other countries, however, the use of a bubble curtain is not mandatory. It is argued that it takes a lot of effort, preparation time, and money, to use this technique, especially if only one *UXO* has to be cleared.

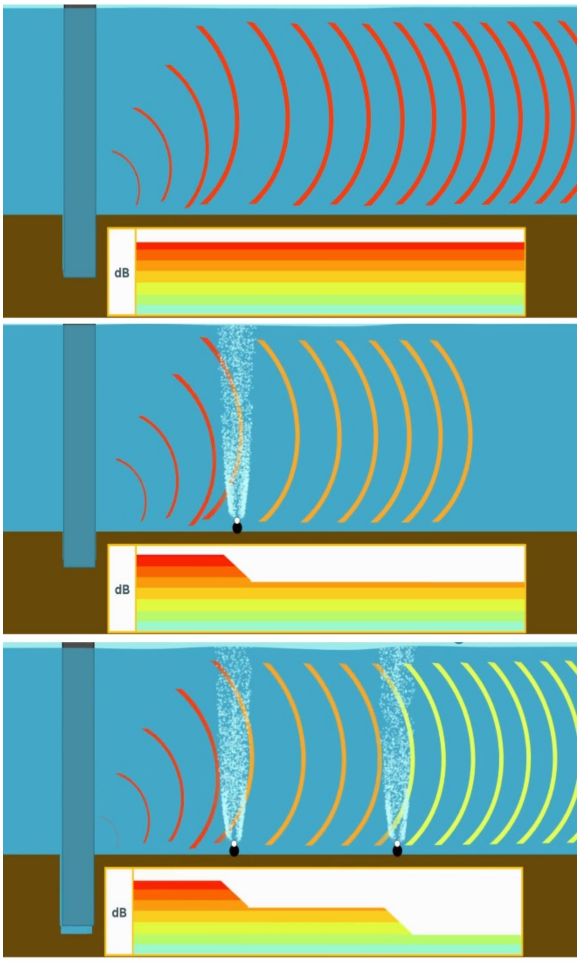

Figure 4: The effects of the bubble curtain on underwater dB-levels. Top – no bubble curtain; middle – one curtain; bottom – two curtains[38]

Another option is the use of seal scarer. These acoustic warning devices generate a high-frequency noise to scare mammals from an area. Seal scarer are used alone or in combination with a bubble curtain. A disadvantage of seal scarer is the possibility of causing reversible shifts in hearing thresholds[39].

To avoid underwater noise, it is also possible that transportable *UXO*s are towed to a sandbank and blown up there. However, there is also the problem that the explosive is not fully converted into carbon monoxide (CO), water (H_2O), and nitrogen (N_2) during the explosion and remnants of the energetic material and gasses dispersed in the surrounding area and atmosphere. Due to the later onset of the tide, these residues are then distributed in the marine environment, as is also the case with underwater BiP operations on the seabed.

[38] https://www.bubbletubing.com/bubble-tubings-solutions/bubble-curtain-with-bubble-tubing/

[39] Siebert et al. 2022b

5. New techniques & Methods

5.1. Low-order/*deflagration* techniques

Deflagrating explosives burn faster and more violently than ordinary combustible materials. They burn with a flame or sparks, or a crackling or hissing noise. In contrast to other combustible materials, they do not need a supply of oxygen to sustain the burning[40].

Detonations are characterized by a shock wave that initiates chemical reactions as it propagates through the explosive charge. The shock wave and reaction zone have the same supersonic velocity; a fraction of the chemical energy is used to support the shock. Unlike the detonation wave, the *deflagration* wave is subsonic, and consequently a precursor shock is propagated in front of the reaction zone. Its intensity and velocity depend on the chemical energy released and on the boundary conditions (figure 5). Some explosives exhibit two different detonation velocities, depending on the diameter of the cartridge and the initial ignition energy[40].

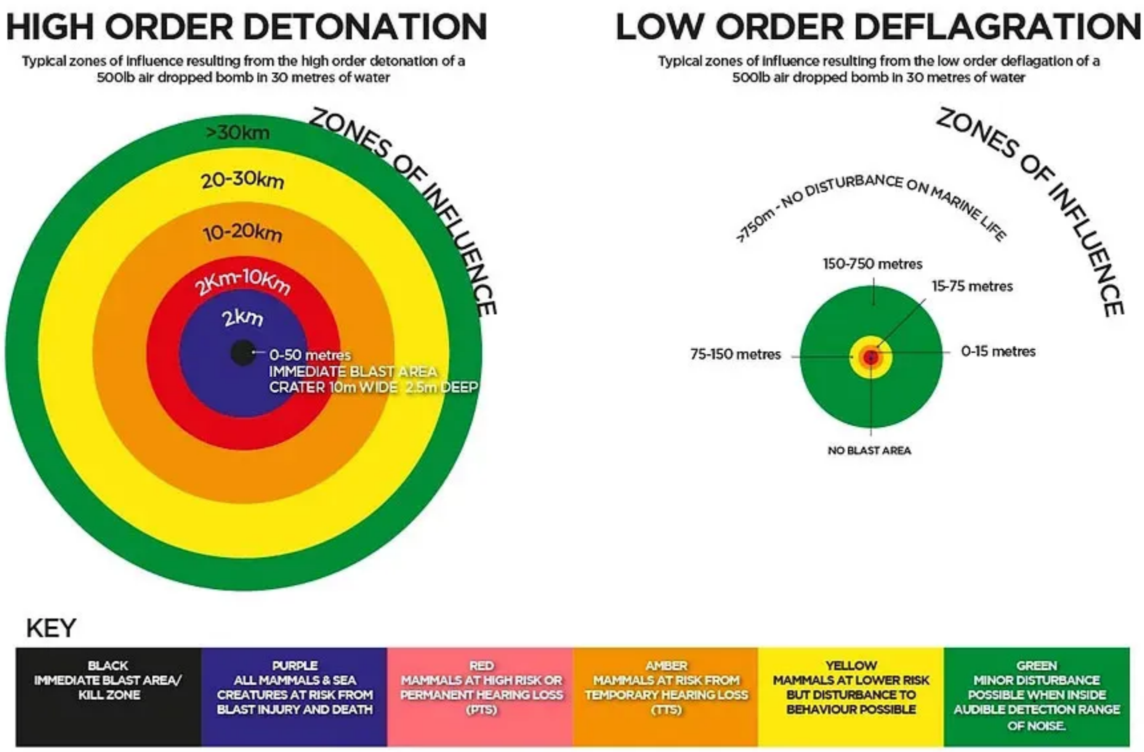

Figure 5: typical zones of influence from a high order detonation vs low order deflagration[41]

A *deflagration* can generate a shock wave, which is propagated in the unreacted medium, and if strong enough, can initiate reactions and become a detonation wave. The transition to detonation occurs as the pressure of the gas formed behind the *deflagration* zone becomes high enough to generate a shock wave. Detonation occurs when the shock wave reaches the front of the *deflagration* wave. If a deflagrating explosive is initiated completely enclosed in a casing, the gaseous products will not be able to escape. As a consequence, the pressure will increase as well as the rate of d*eflagration*. When the rate of *deflagration* reaches a velocity of 1000–1800 m s^{-1} it becomes classed as a low-order detonation. For comparison – at a velocity of 5000 m s^{-1} the detonation becomes classed as a high-

[40] Akhavan, 2018; Novak, 2022

[41] https://uk.eodexgroup.com/news/low-order-deflagration/

order detonation. The propagation of an explosion reaction through a deflagrating explosive is therefore based on thermal reactions. These thermal reactions are relatively slow. The explosive material surrounding the initial exploding site is warmed above its decomposition temperature resulting in small explosions. The transfer of energy through the deflagrating explosive is by thermal means through a temperature difference and depends very much on external conditions such as ambient pressure[40].

One of the major disadvantages of *TNT* is the *exudation* (leaching out) of the isomers dinitrotoluenes and trinitrotoluenes when the explosives are stored over a longer period or are exposed to a higher temperature or higher ambient pressure. This causes the formation of cavities and cracks leading to a *reduction* in its density and premature detonation[40]. Thus, an intended low-order clearing operation of a *TNT* containing *UXO* may result in a high-order detonation.

Low-order and *deflagration* techniques are already used in different countries. In Denmark and Norway commercial kits, such as Pluton Maritime EOD (PLMEOD) Kit™, are used to deflagrate different kinds of *UXO*s. The Pluton Maritime EOD (PLMEOD) Kit™ (ALFORD technologies) is a specialist 65mm shaped charge system developed for underwater or waterline use. The kit contains three Pluton™ Tool Roll Sets which each contain three complete charge systems with projectiles, along with supporting ancillary items to assist in positioning and attachment to the target. The PLMEOD Kit™ is primarily used for countermining and *deflagration*. The kit is placed at the *UXO* by divers. The explosive is burnt inside the *UXO* in this way. Underwater noise is significantly less compared to a high-order detonation and also the disturbance on the seafloor such as the formation of craters and sediment eruption above the surface during the operation. Depending on how well the *deflagration* goes, however, different amounts of explosives may remain and, in the worst case, may also be dispersed in the environment - on the seabed or in the water.

In Germany, an *UXO* that cannot be transported is defused by the state EOD service with a low-order technique to make it transportable. The fuze set of the *UXO* is removed with the help of a cutting charge - consisting of two metres of Semtex® Razor, which is a flexible linear shaped charge. The disarmed *UXO* can then be recovered or transported to a munition dump site. Prior to the blasting, acoustic devices will be deployed within a 400-metre radius to scare animals such as harbour porpoises away from the area.

5.2. Recovery techniques

To minimize the impact on the marine environment in terms of pollutants and noise, many *UXO* clearance companies aim to recover munitions directly without blasting. To be sure that the munitions are safe to handle, extensive surveys must be carried out beforehand. This includes the exact localization of objects. The following equipment and methods are used for this purpose: 3-*axis gradiometer* (TFG), *total field magnetometer*, electromagnetic technology, video cameras, LED lights, Blue-View sonar, Ultra-Short Baseline Positioning System (USBL), Remote Operated Air Lift (ROAL), Remotely Operated Vehicle (ROV) with manipulators, water nozzle and airlift and the use of divers[42]. Objects can be identified from information collected by sensors, using video recording, or by visual inspection by divers. For instance, within the identification procedure performed by the company SeaTerra, an object is assessed exclusively by a qualified offshore explosives expert. Once an object

[42] https://seaterra.de/web/UXO/start/index.php?page=Kampfmittelraeuumung_Offshore

has been identified and deemed safe to handle, there are several ways to recover the object. SeaTerra, for instance, uses the following techniques: Recovery using ROVs, recovery by divers, recovery using remote-controlled and video/BlueView-monitored arms and relocation of *UXO*s using ROVs or lifting bags[42].

The newest technique used by SeaTerra is *UXO* clearance with the help of a crawler[43] (figure 6). It plays an important role as a multifunctional tool for relocating, uncovering, identifying, and transporting munition objects. The use of a multi-tool such as the crawler has the advantage to clear more objects in a shorter period. This is interesting for the clearance of munition dumping sites. Here, several objects are normally located close to each other which are not easy to clear using one of the other mentioned techniques. SeaTerra's crawler can work continuously at current speeds of up to three knots for three days without interruption. The crawler is powered, remotely controlled, and monitored from a work platform in the sea. It has a multitude of different sensors, e.g., with sensors to detect metallic objects, to enable all the necessary steps of clearance with the help of two mobile arms – from investigating to exposing, identifying and transporting the munition objects. The system also works reliably in low visibility conditions, which are not uncommon in the North and Baltic Seas for various reasons, by using acoustic imaging methods and cameras, such as BlueView/Aris, for the identification of the investigated objects. The movements of the crawler are recorded by sensors and visualized in real time as a 3D animation in the operations centre on the work platform. To locate the crawler underwater a USBL system and a gyro-compass are used. Investigated objects are uncovered with the help of a suction device that removes the surrounding sediment. The handling of transportable munition objects is carried out by the multi-axis mobile claw arm of the crawler which is loading the objects to transport baskets on the seabed. The use of different transport baskets allows the sorting of different types of munitions already on the seabed. In the final step, the baskets are brought onshore, and the munition objects are delivered to specific destruction or disposal processes[43].

After the recovery and brought onshore, munitions have to be further processed such as recycling of the munition contents. For instance, in Germany the company "GEKA" (Gesellschaft zur Entsorgung von chemischen Kampfstoffen und Rüstungsaltlasten mbH[44]) is responsible for the combustion of *energetic compounds* and chemical warfare agents. The company is a federally owned company in the portfolio of the Federal Ministry of Defence, and it operates three incineration plants, a soil washing plant and dismantling plants for conventional and chemical munitions up to two tons of *TNT* equivalent. Although this is one method of processing *UXO*s onshore, there are several more, i.e., explosives, steaming, chemical extraction. These methods come with their own benefits and challenges and there is limited information available on them.

[43] https://seaterra.de/web/UXO/start/index.php?page=Crowler

[44] https://www.geka-munster.de/home/

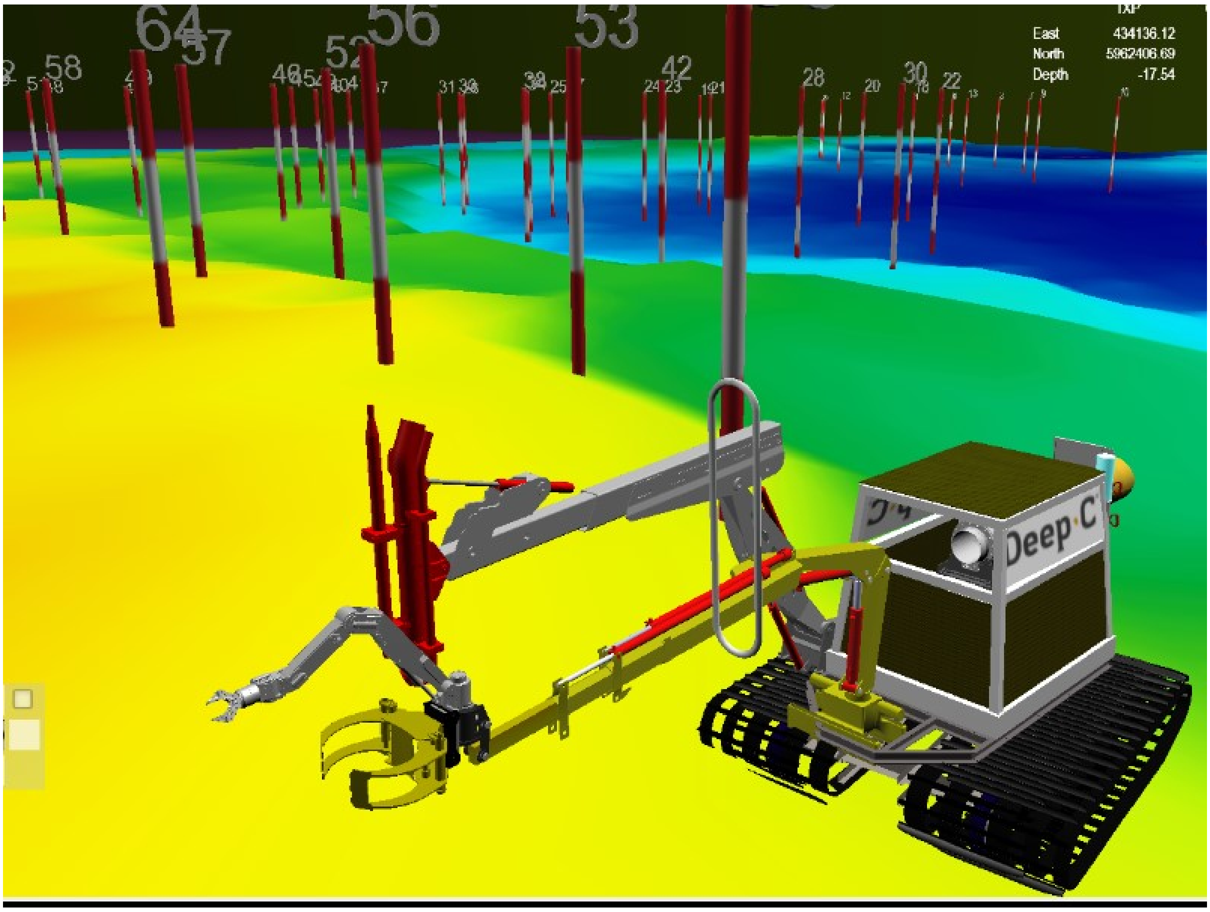

Figure 6: The SeaTerra crawler[43]

6. Monitoring techniques

For an efficient protection of the North Sea and other oceans, comprehensive monitoring of all its ecosystem elements is of fundamental importance. Monitoring comprises the acquisition of biological, chemical, physical, hydrological, and morphological data of the ecosystem to assess its status[45]. Indicators address specific measurable attributes of selected ecosystem elements, allowing to monitor spatial or temporal changes of these elements[45]. Regarding submerged munitions in the sea, the monitoring of the condition of the munition items itself is as important as the evaluation of possible negative effects caused by these objects on the marine environment as well as an environmental monitoring of the used remediation techniques to clear *UXO*s and other submerged munitions.

This chapter will present monitoring strategies related to marine munitions. These include assessing the current state of an area's ecosystem and the condition of the munitions present, monitoring an area over a period of time to detect changes caused by munitions, and monitoring the effects of clearance operations such as underwater blasting or the recovery of munitions objects.

6.1. Acoustic and visual methods

Acoustic mapping methods and photo and video acquisition are suitable for recording the nature of the seabed and the quantities of munitions present in an area. Common tools for installing different kinds of observation techniques are autonomous underwater vehicle (AUVs) and remotely operated underwater vehicles (ROVs). They can be equipped with different kinds of sensors and instruments, for instance for bathymetric surveys or the identification and defence of *UXO*s. In 1999, for instance, a munition dumpsite in the Eastern Scheldt estuary, Netherlands, was visually observed using a ROV and munition items were identified using side scan sonar[46].

In the “UDEMM” project, detailed monitoring strategies were developed for munitions in the seas[47]. For instance, *multibeam echosounder* surveys are recommended for unburied objects of a minimum size of 0.5 × 1 m^2 in shallow waters of less than 30 m. As the aim of monitoring is to detect changes over time, very high precision in positioning is required. *Multibeam echosounder* provides a tool for three different applications which are the detailed bathymetry of the dumping ground for object detection and monitoring, detailed backscatter map of the dump for seafloor classification and monitoring, and automated object and change detection[47]. More details regarding the technical requirements and the mapping procedure can be found in the practical guide of the UDEMM project[47].

Visual observations can be performed using different kinds of cameras in diving or AUV operations. This can be towed camera systems (OFOS) coupled with ultra-short-baseline navigation (USBL)[47]. In the UDEMM project, for instance, four different types of platforms were used for visual inspection: An online camera and a GoPro mounted in a towing frame, video and photo footage recorded by scientific divers, an HD video camera equipped CTD, and a Girona-500 AUV[47]. The visual observation enables the identification of habitat classes as well as the direct identification of *UXO*s and allows us to differentiate them from other submerged non-*UXO* objects. It is also possible to use the resulting images for building a 3D photomosaic. Geo-reference mosaic containing additional covering landmarks can be built by the inclusion of acoustic data[47]. Photomosaic has the advantage to provide

[45] Mack et al., 2019
[46] den Otter et al., 2023
[47] UDEMM, 2019

detailed information about areas of interest to allow for repeated monitoring surveys about the same spot[47].

6.2. Field sampling

To investigate the condition and possible level of contamination in an area, different types of samples can be taken on-site. These include water, sediment and various biota living in the area such as mussels. Fish are also suitable for analyses. Examination of the samples taken can be used to record the current status of possible contaminations in an area and, when carried out at regular intervals, also enables changes to be detected at an early stage. This enables rapid intervention to prevent negative impacts on the marine environment as early as possible. In addition to *energetic compounds*, heavy metals and fuels can also be analysed, as these can also occur in connection with submerged munitions in an area. For example, fuel can leak from almost undetectable micro-cracks in the ship's tanks. These substances could then possibly be found in sediment. Here, analysing sediment samples would serve as a monitoring strategy and early warning system for oil spills. The samples can be collected by divers or can be taken from a vessel with tools such as a CTD for water samples or Van Veen surface grab for sediment and biota samples. The type and quantity of samples collected, as well as the number and frequency of collection, will depend on the size of the study area, the quantities of submerged munitions present, and the suspected level of potentially critical changes in the area being studied.

Water and sediment samples can be analysed for the content of different pollutants. The various biota can also be analysed for the content of these pollutants. Furthermore, the biota should be analysed for health impairments. These are mainly chronic effects on health, which are mainly caused by rather low pollutant concentrations. These include impaired growth and reproduction, cancer and general signs of (oxidative) stress. The latter can be detected, for example, with a multi-biomarker approach as described in Schuster et al., 2021, or with specific biomarkers such as the expression of the *carbonyl reductase* gene[48]. Studies on fish and mussels are particularly suitable for this.

6.3. Active (bio-)monitoring

Active biomonitoring is suitable for recording long-term changes in a study area and for monitoring targeted measures such as clearance operations. For this purpose, living organisms such as blue mussels or passive samplers are selectively deployed in an area for a defined period (figure 7)[49]. The advantage of this method is that it is possible to determine exactly how long the material under investigation has been on site and the location of exposure. Depending on the size of the area to be investigated, the number of exposed organisms and/or passive samplers can be adjusted accordingly.

Blue mussels and other bivalves are due to their sedentary behaviour and their capability for survival under diverse environmental conditions made them become one of the most common used species in cage experiments. In addition to analysing mussel flesh for various pollutants such as *energetic compounds* and heavy metals, various biomarkers and the general health status of the mussels can also be recorded at the same time. Thus, it is possible to gain insights into the harmful effects of munition components on the fitness and health of the mussels. To estimate health impairments, it is important to always include mussels from non-contaminated reference areas in the investigations.

[48] Strehse et al., 2020

[49] Maser & Strehse, 2020.

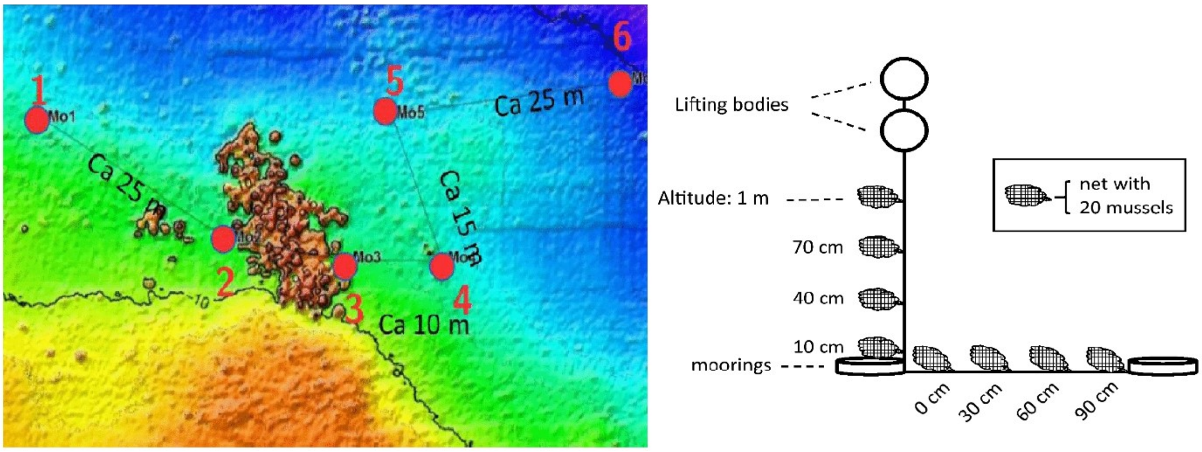

Figure 7: Example of a biomonitoring setup around a mine mount (left) and the construction scheme of the moorings (right) which are indicated by red dots on the left side[50]

Passive Samplers like Chemcatcher® and POCIS (Polar Organic Chemical Integrative Sampler) are collecting contaminants based on molecular diffusion and sorption to a binding agent. They are such as mussels deployed at a specific location and accumulate the contaminants in the surrounding environment over time. The Chemcatcher® collects in-/organic substances of polar or non-polar nature while the POCIS is selective for polar organic chemicals. In contrast to living organisms, passive samplers have the advantage that they do not metabolise the analytes. They therefore directly reflect the *energetic compounds* present in the water. For active monitoring, the simultaneous use of passive samplers and mussels has proven effective. This has also been demonstrated here in the NSW project.

6.4. Using molecular biomarkers for monitoring of explosive compounds

It is known that the mechanism of toxicity and *carcinogenic*ity of *TNT* and its derivatives occurs through its capability of inducing *oxidative stress* in the target biota. Interestingly, *TNT* can induce the gene expression of *carbonyl reductase* in blue mussels. *carbonyl reductase*s are members of the short-chain *dehydrogenase*/reductase (SDR) superfamily. They metabolize *xenobiotics* bearing *carbonyl* functions, but also endogenous signal molecules such as steroid hormones, *prostaglandins*, *biogenic amines*, as well as sugar and *lipid peroxidation* derived reactive *carbonyl*s, the latter providing a defense mechanism against *oxidative stress* and reactive oxygen species (ROS). A bioinformatic approach, combined with gene cloning and both laboratory and field studies showed that *TNT* induces a strong and concentration dependent induction of gene expression of *carbonyl reductase* in the blue mussel *Mytilus* spp. *Carbonyl reductase* may thus serve as a biomarker for *TNT* exposure on a molecular level which is useful to detect *TNT* contaminations in munition dumping sites or ship wrecks and to perform a risk assessment both for the ecosphere and the human sea food consumer[51].

6.5. Other monitoring techniques

Depending on the specific issue, there are additional monitoring approaches feasible, such as *(e)DNA metabarcoding*. *Environmental DNA* (eDNA) metabarcoding is a powerful molecular method that can be used to identify the presence of different species in a given environment based on their DNA. In the article by Mack et al. (2020), the authors highlight the potential of eDNA metabarcoding as a monitoring technique for marine biodiversity. This method involves the collection of water samples

[50] Maser & Strehse, 2020

[51] Strehse *et al.,* 2020

from a particular area, followed by the extraction and amplification of DNA from the organisms present in the sample. The amplified DNA is then sequenced and compared to existing DNA databases to identify the different species present in the sample. This technique can provide a rapid and cost-effective method for monitoring marine biodiversity and has been used successfully to detect a wide range of organisms in different aquatic environments. In the context of the Baltic Sea, eDNA metabarcoding could be used to monitor the presence and distribution of different species, including those that are difficult to detect using traditional methods. This information could be used to inform management and conservation efforts, and to track changes in the composition and diversity of the Baltic Sea ecosystem over time[52]

In addition, machine learning could be used to identify bacteria that have possibly adapted to munition compound contaminated areas, or to detect microbial fingerprints indicating the presence of the munition compounds in munition dumping sites[53]. Also here, environmental variables including grain size distribution, elemental composition, and concentration of munition compounds from sediments can be collected at munition dumping sites or ship wrecks and be evaluated combined with 16S rRNA *gene amplicon sequencing* libraries. With this approach, microbial communities on site can be predicted for identifying bacteria that live on *TNT* as a source of carbon, nitrogen and energy and may therefore be used for *TNT* remediation in the marine environment.

[52] Mack *et al.,* 2020

[53] Janßen *et al.,* 2021

7. Laws and regulations of European Union North Sea Region Member States

This chapter focuses on the current laws and regulations regarding the removal of (conventional) *UXO*s currently in use in European countries bordering the North Sea region. It starts with an outline of what research has been done and what advice has been given in previous studies in the Baltic Sea.

7.1. Previous research on legal aspects of marine munition management

Within the Baltic Sea region, a similar project as the NSW project has been executed under the Interreg program. The DAIMON (Decision Aids for Marine Munition) project had partners found in the countries that border the Baltic Sea, these include Germany, Denmark, and Norway. As part of the DAIMON project the International Dialogue on Underwater Munitions (IDUM) has published a report on the Legal Aspects of Marine Munitions Management: Decision Making in the Face of Uncertainty and Risk (hereafter the IDUM report)[54]. After analysing the applicable national, regional, and international law on munitions in the Baltic Sea, the report concludes:

“The various national and international laws on underwater munitions management are fragmented and uneven with relatively no consistency in legislation, any common language, regulations, or mandates”.

And:

“While many international agreements touch on certain aspects of the issues (environmental protection, hazardous materials and/or explosives handling) surrounding the dumping of chemical munitions, none address it specifically nor provide mechanisms for international cooperation or enforcement. As such, there is a need for a comprehensive international agreement specifically for underwater munitions management.”

The conclusions from the IDUM report are valid for the North Sea Wrecks project at least as far as it concerns States covered by both projects (Germany, Denmark, and Norway). Further research is required for the remaining NSW States, the Netherlands and Belgium. Before doing so, further analysis is made of the relevance of international and EU legislation for *UXO*.

7.2. International law

Explosives may have an impact on the marine environment, safety of navigation and food safety. The right and/or duty of states to protect these interests depend on the maritime zones, as described in the United Nations Convention of the Law of the Sea (UNCLOS), in which the explosives are located. The location of explosives in one maritime zone or another also has an impact on the applicability of other international conventions and national laws. For example, the UNESCO Convention on the Protection of Underwater Cultural Heritage, 2001 is applicable as a whole in the EEZ of State Parties such as Belgium and France. In the territorial waters and the contiguous zone of these State Parties, only the Rules from the Convention apply. In non-State Parties, the UNESCO Convention does not apply. As an example of national law, the UK Protection of Wrecks Act 1973 applies in UK territorial waters but does not apply to the UK contiguous zone and other maritime zones.

[54] legalaspects_daimon__final_5mar_.pdf (daimonproject.com)

In the territorial sea (12-mile zone), the coastal state has sovereign rights[55]. The coastal state may adopt laws and regulations in relation to such as the safety of navigation, the conservation of the living resources of the sea and the preservation of the environment of the coastal State and the prevention, *reduction*, and control of pollution thereof[56].

In the contiguous zone (24-mile zone), the coastal state may exercise the control necessary to prevent infringement of its customs, fiscal, immigration or sanitary laws and regulations within its territory or territorial sea. The coastal state may in the contiguous zone also punish infringement of the aforementioned laws and regulations committed within its territory or territorial sea[57].

In the Exclusive Economic Zone (200-mile zone), the coastal state has sovereign rights for conserving and managing the natural (living and non-living) resources and jurisdiction with regard to the protection and preservation of the marine environment[58]. In exercising its rights and performing its duties in the EEZ, the coastal state shall have due regard to the rights and duties of other states[59].

On the High Seas states shall cooperate with each other in the conservation and management of living resources in the areas of the high seas[60].

According to Article 194 UNCLOS, states shall take all measures that are necessary to prevent, reduce, and control pollution of the marine environment from any source, using for this purpose the best practicable means at their disposal and in accordance with their capabilities, and they shall endeavour to harmonize their policies in this connection. These measures shall deal with all sources of pollution of the marine environment and shall include, *inter alia*, those designed to minimize to the fullest possible extent the release of toxic, harmful, or noxious substances, especially those which are persistent, by dumping[61].

With regard to dumping, states shall adopt laws and regulations to prevent, reduce and control pollution of the marine environment by dumping and shall take other measures as may be necessary to prevent, reduce, and control such pollution[62]. More detailed regulation on dumping has been incorporated in the 1996 Protocol to the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Protocol) and the Chemical Weapons Convention (CWC). The objective of the London Dumping Protocol is to protect and preserve the marine environment from all sources of pollution and take effective measures, according to their scientific, technical, and economic capabilities, to prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea of wastes or other matter. Where appropriate, they shall harmonize their policies in this regard. The regulations do not cover any form of pollution that originates from a site which pre-dates the ratifications dates of the regulations. Hence, de regulations do not cover WW 1 and 2 dump sites in the marine environment.

According to the CWC each state party undertakes to destroy chemical weapons it owns or possesses, or that are located in any place under its jurisdiction or control, in accordance with the provisions of this Convention[63].

[55] Article 2 UNCLOS.
[56] Article 21 UNCLOS.
[57] Article 31 UNCLOS.
[58] Article 56 (1) UNCLOS
[59] Article 56 (2) UNCLOS.
[60] Article 112 UNCLOS.
[61] Article 194 (2) UNCLOS.
[62] Article 210 UNCLOS.
[63] Article I (2) CWC.

OSPAR Recommendation 2010/20 sets a framework for reporting encounters with conventional and chemical munitions in the OSPAR Maritime Area. This recommendation does not cover analyzation of risks related to *UXO* nor remuneration measures.

7.3. EU legislation

According to Article 4 of the Treaty on the Functioning of the European Union (EU) (the EU Treaty) the EU shares competence with the Member States inter alia in the areas relevant for munition:

(d) Agriculture and fisheries, excluding the conservation of marine biological resources;
(e) Environment;
(f) Consumer protection;
(k) Common safety concerns in public health matters, for the aspects defined in the EU Treaty.

7.3.1. Foods safety

The EU food safety policy is mainly governed by Articles 168 (public health) and 169 (consumer protection) of the EU Treaty.

Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety provides the basis for the assurance of a high level of protection of human health and consumers' interest in relation to food. It establishes common principles and responsibilities in matters of food and feed safety. It applies to all stages of production, processing and distribution of food and feed. The general principles include:

General objective: Food law shall pursue one or more of the general objectives of a high level of protection of human life and health and the protection of consumers' interests, including fair practices in food trade, taking account of, where appropriate, the protection of animal health and welfare, plant health and the environment

Risk analysis: In order to achieve the general objective of a high level of protection of human health and life, food law shall be based on risk analysis except where this is not appropriate to the circumstances or the nature of the measure. Risk assessment shall be based on the available scientific evidence and undertaken in an independent, objective, and transparent manner.

Precautionary principle: In specific circumstances where, following an assessment of available information, the possibility of harmful effects on health is identified but scientific uncertainty persists, provisional risk management measures necessary to ensure the high level of health protection chosen in the Community may be adopted, pending further scientific information for a more comprehensive risk assessment[64].

According to Article 14 of Regulation 178/2002 food shall not be placed on the market if it is unsafe. Food shall be deemed to be unsafe if it is considered to be injurious to health and/or unfit for human consumption. In determining whether any food is unsafe, regard shall be had:

[64] Communication from the European Commission on the precautionary principle: Microsoft Word - DGSanco-PO-COM_2000_1-99-3401-precaut_EN_ACTE.doc (europa.eu)

"To the normal conditions of use of the food by the consumer and at each stage of production, processing and distribution, and to the information provided to the consumer."

In determining whether any food is injurious to health, regard shall be had:

(a) not only to the probable immediate and/or short-term and/or long-term effects of that food on the health of a person consuming it, but also on subsequent generations;
(b) to the probable cumulative toxic effects;
(c) to the particular health sensitivities of a specific category of consumers where the food is intended for that category of consumers.

Food that complies with specific Community provisions governing food safety shall be deemed to be safe insofar as the aspects covered by the specific Community provisions are concerned. Conformity of a food with specific provisions applicable to that food shall not bar the competent authorities from taking appropriate measures to impose restrictions on it being placed on the market or to require its withdrawal from the market where there are reasons to suspect that, despite such conformity, the food is unsafe. Where there are no specific Community provisions, food shall be deemed to be safe when it conforms to the specific provisions of national food law of the Member State in whose territory the food is marketed.

Specific Community provisions for food safety exist in relation to physical, chemical and (micro)biological risks. Food safety risks related to *UXO* qualify as a chemical risk. EU legislation on chemical risks provides inter alia rules on methods of sampling and protection from persistent organic pollutants[65]. EU legislation also contains specific rules on contaminants. Regulation (EC) 1881/2006 sets maximum levels for certain contaminants in foodstuffs. These regulations cover metals which can be present in the shells and chemical mixtures which are present in *UXO*s, and it covers the *PAHs* that originate from oil and fuel leakage from shipwrecks[66]. However, both regulations do not cover *TNT* and its *metabolites*.

7.3.2. Protection of the environment

The 2008 Marine Strategy Framework Directive (MSFD) obliges EU Member States to develop and implement marine strategies in order to:

(a)protect and preserve the marine environment, prevent its deterioration or, where practicable, restore marine ecosystems in areas where they have been adversely affected;

(b)prevent and reduce inputs in the marine environment, with a view to phasing out pollution as defined in Article 3(8), so as to ensure that there are no significant impacts on or risks to marine biodiversity, marine ecosystems, human health, or legitimate uses of the sea.

[65] Council decision on the Stockholm Convention on Persistent Organic Pollutants (2006/507/EC). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:22006A0731(01)&from=EN

[66] Regulation 1881/2006 covers the following contaminants, in addition, to the already mentioned: mycotoxins (aflatoxins, ochratoxin A, Fusarium toxins, patulin and citrinin, ergot alkaloids), 3-monochloropropane-1,2-diol (3-MCPD) and its fatty acid esters and glycidyl fatty acid esters, dioxins and polychlorinated biphenyls (PCBs), melamine, erucic acid, hydrocyanic acid, tropane alkaloids, pyrrolizidine alkaloids, nitrates and perchlorate.

Pollution as defined in Article 3 (8) MSFD means the direct or indirect introduction into the marine environment, as a result of human activity, of substances or energy, including human-induced marine underwater noise, which results or is likely to result in deleterious effects such as harm to living resources and marine ecosystems, including loss of biodiversity, hazards to human health, the hindering of marine activities, including fishing, tourism and recreation and other legitimate uses of the sea, impairment of the quality for use of sea water and *reduction* of amenities or, in general, impairment of the sustainable use of marine goods and services. This broad definition of pollution in the Marine Strategy Framework Directive includes the introduction into the marine environment of contaminants leaking from explosives.

7.4. The Netherlands

Within the Dutch legislation the process of detection, classification, approaching and removing an *UXO* is regulated through and by the "*Certificatieschema opsporen ontplofbare oorlogresten*" (hereafter *CS-OOO*); in English: Certification Scheme for the Detection of Explosive Remnants of War. This certification scheme is included in Annex XII of the Working Conditions Regulations, and OCE-companies are obliged to have and work following this certification. Within the *CS-OOO* the process of detection, classification, and clearing is described. Within the schema, no differentiation is made between *UXO*s found on land or in water, and it describes the process leading up to removal for both environments. The process consists out of preliminary research, a risk assessment, tracking down and detection, and approach. It does not denote the process of removal because this is done by the Explosive Ordnance Disposal (EOD) team of the Dutch military.

The preliminary (desktop) research must be conducted for every *UXO*-research in the Netherlands, if one has to make alteration in or on the soil. The goal of this research is to assess the probability on the presence of *UXO*s in the area, but not to locate them. The outcome of the research can either be that the research area is not expected to have *UXO*s in the area or that the research area is expected to have them. The employee that writes this report must be a Certified OCE-Assistant, furthermore the report must be verified by a certified Senior OCE-expert.

The second phase of the research is the project-related risk analysis (PRA). The aim of the PRA is to assess the different risks the expected *UXO*s might pose to the future of the project area. Simply put, is there a change an *UXO* will explode due to the planned activities or use of the project area. The PRA include scenarios needed to manage these risks and its content must be checked by a Senior OCE-expert and be agreed upon by a Senior OCE -expert and an authorized member of the organisation’s management.

The third and final phase of the schema is the detection and removal phase. The hired OCE-organisation must plan, prepare, and execute the processes for the realization of the detection and removal of the *UXO*s. The detection must be done by an OCE-expert. While underwater, both the diver and the back-up diver must at least be an assistant OCE-expert while also be authorized to dive following the Dutch Working Conditions Regulations. These divers should be in contact with at least an OCE-expert. These people may not remove the suspected *UXO*, this can only be done by the EOD team, and be organised by a Senior OCE-expert.

Working conditions rules related to *UXO* can be found in Artikel 4.10 Arbeidsomstandighedenbesluit (Working Conditions Decree) and Paragraaf 4.2b Arbeidsomstandighedenregeling (Working Conditions Regulation).

In all cases where there may be a danger to the safety or health of employees due to the possible presence of explosive remnants of war, an exploratory investigation shall be carried out before work is started. If the exploratory investigation does not rule out the possible presence *UXO* that could endanger the safety or health of employees, a further investigation will be initiated. If the further investigation shows that there is a danger to the safety or health of employees due to the presence of *UXO*, those explosive remnants of war shall be traced, or other appropriate measures shall be taken to prevent this danger. The detection of *UXO* is exclusively performed by a company that, for the work to be performed, is in possession of a certificate for the detection of explosive remnants of war issued by the Minister of Defence or a certifying institution designated by him.

The work for the purpose of detecting *UXO* is only performed by a qualified person who is registered in the Register Safe Working with Explosive Substances or "Register Veilig Werken met Explosieve Stoffen" or by a person whose professional qualifications have been checked and found to be adequate in accordance with the General Act on the Recognition of EU Professional Qualifications and who carries out this work under the constant supervision of a suitably qualified person who is registered in the Safe Register working with explosive substances. The removal of *UXO* is performed exclusively by explosive ordnance disposal units of the Ministry of Defence.

7.4.1. Territorial Waters Netherlands – Germany

The location of a wreck is of significance for the determination of the rights and duties of a coastal state vis-a-vis that wreck. For that reason, it is important to know the extent of the territorial waters of a coastal state. This is especially the case when a wreck is situated near the sea border between two neighbouring states. The Netherlands and Germany have entered into bilateral agreements on the determination of the sea border between them, both near the coast and further at sea:

- Verdrag tussen het Koninkrijk der Nederlandsen en de Bondsrepubliek Duitsland inzake de zijdelingse begrenzing van het continentale plat in de nabijheid van de kust, Bonn, 1964[67];
- Verdrag tussen het Koninkrijk der Nederlanden en de Duitse Bondsrepubliek inzake de begrenzing van het continentaal plat onder de Noordzee, Kopenhagen, 1971[68];
- Verdrag tussen het Koninkrijk der Nederlanden en de Bondsrepubliek Duitsland betreffende het gebruik en beheer van de territoriale zee van 3 tot 12 zeemijlen, (Westereems Treaty) 2014[69].

Despite the existence of these instruments, no agreement exists as of yet on the border in the Ems-estuary. Nevertheless, a treaty is in place that contains agreements on cooperation between both states: the Ems-Dollard Treaty[70]. This treaty is accompanied by a Supplementary Agreement (on the exploration and production of petroleum and natural gas). The Ems-Dollard Treaty states that The

[67] http://verdragenbank.overheid.nl/verdragen/004342
[68] http://verdragenbank.overheid.nl/verdragen/002720
[69] http://verdragenbank.overheid.nl/verdragen/012557
[70] http://verdragenbank.overheid.nl/verdragen/008887

Netherlands and Germany shall co-operate in a spirit of good neighbourliness in the Ems Estuary, recognizing their common interests and taking into account the special interests of the other State, in order to ensure a connection of their ports with the sea which meets the changing requirements. According to the Ems-Dollard Treaty, this aim should be achieved - while maintaining mutual legal positions with regard to the course of the State border - by means of a practical settlement of the questions which concern both States. Based on this agreement Germany and The Netherlands should cooperate and look for a practical settlement with regard to wrecks in the contested area. The Westereems Treaty 2014 includes a specific provision on wrecks. According to Article 13 of the Westereems Treaty each of the parties is authorized to remove obstacles to navigation including wrecks in the fairway and shall issue the required permits for this purpose. These activities will be carried out by and at the expense of the initiating Contracting Party, unless otherwise agreed. The domestic law of the executing Contracting Party shall apply to works in accordance with the first sentence.

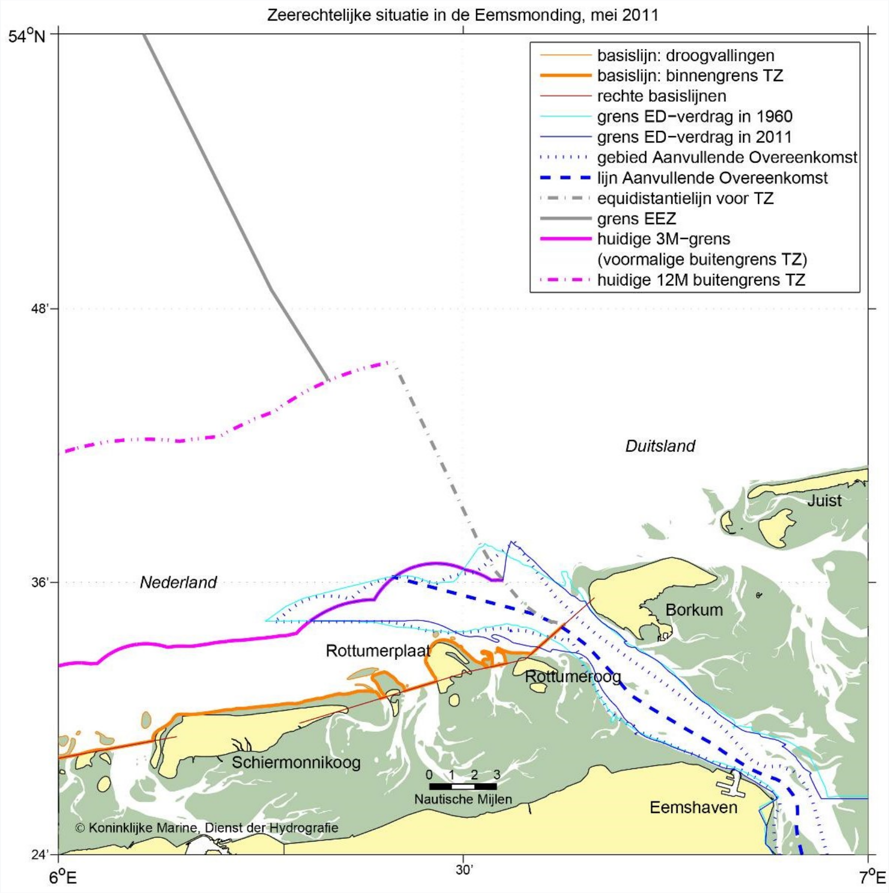

Figure 8: Maritime situation in the Ems estuary – text is in Dutch. © Dutch Department of Defense

7.5. Belgium

Belgium is party to the UNESCO Convention on the Protection of the Underwater Cultural Heritage and applies OSPAR Recommendation 2010/20 on an OSPAR framework for reporting encounters with conventional and chemical munitions in the OSPAR Maritime Area. The content of both international instruments is reflected in the Belgian procedures for encounters with ammunition at sea, diving and findings at sea as set out in *Berichten aan Zeevarenden* (www.vlaamsehydrografie.be).

7.5.1. Encounters with ammunition

In the procedure for encounters with explosives as set out in *Berichten aan Zeevarenden 2020- 1/14* a distinction is made between the situation in which an explosive is already on board a (fishing or dredging) vessel and the situation in which an explosive is still outside the vessel. If a suspicious explosive is detected in a trawl still outboard, it should not be hoisted on board. Cutting the trawl is always the safest measure.

In the event that the suspected explosive gear is only discovered after the contents of the trawl are on deck, the gear should be protected against impact by heat, vibration, and air. The explosive shall never be sunk in water deeper than the site it was found.
The position of the sunken explosive or of the trawl (marked or unmarked) must always be reported to the Maritime Rescue and Coordination Centre (MRCC) in Ostend), which in turn will inform Maritime Information Crossroads (MIK). The vessel will subsequently be given instructions with regard to entrance to port. A vessel which has an explosive on board or in its trawls or which has cut its trawl including an explosive, will inform nearby vessels accordingly.

7.5.2. Diving

The procedures for diving at sea as set out in Berichten aan Zeevarenden 2020- 1/73, apply to all non-military vessels in Belgian internal and territorial waters and the Belgian EEZ. Before leaving the port or entering Belgian waters, the vessel must report to the MRCC: the name of the vessel; the fact that it sets sail or sails with divers on board; the number of divers on board and the diving site. After arriving at the diving site, the vessel should inform the MRCC the vessel has arrived, the number of divers going into the water and the anticipated length of time that each diver will remain in the water. After concluding the diving activities, the vessel will inform the MRCC that all divers are back on board.

For diving activities planned in demarcated shipping lanes and anchorages, permission must be requested at least three weeks in advance from the MRCC. According to the regulatory measures for the protection of underwater cultural heritage, every dive to a historic wreck must be reported to the FPS Mobility and Transport at least 4 hours in advance.

7.5.3. Finds

According to *Berichten aan Zeevarenden 2020- 1/74*, finds at sea must be reported to the governor of West Flanders via governor@west-vlaanderen.be or via the website www.vondsteninzee.be. This applies to all discoveries which can be suspected to be underwater cultural heritage. This applies to all finds, regardless of age, in the Belgian territorial sea and all finds that have been under water for more than 100 years on the Belgian Continental Shelf and in the Belgian Exclusive Economic Zone.

8. Current state of Knowledge

8.1. Effects of *TNT*

We have discussed the effects and behaviour of *TNT* – a nitroaromatic explosive compound, including its possible hazards on human health and the environment. *TNT* is toxic to all organisms, with acute and chronic effects on marine species such as fish, copepods, corals, amphipods, and bivalves. *TNT* does not occur in the marine environment by natural sources; instead, it results from human activities. Transformation processes of the munition's residues include *photolysis*, *hydrolysis*, *oxidation*, *reduction*, and biological transformation. In general, *TNT* degradation in some coastal waters, especially fresh-saline mixing zones, may occur on the order of days to weeks. Bacteria are able to perform the complete degradation of ring-structured chemicals like steroids and polycyclic aromatic *hydrocarbons* (PAH), and several bacterial species can metabolize *TNT*. We concluded that although *TNT* has a low melting point and is thermally and chemically stable, it poses significant risks to human health and the environment. Further research on *TNT* biodegradation by bacteria is necessary to mitigate the risks associated with *TNT* contamination.

8.2. Techniques and Methods

We discussed the methods and techniques for dealing with underwater unexploded ordnance (*UXO*) in the North Sea region. An overview is presented in which the definition, advantages and disadvantages of discussed methods and techniques are shown in table 1. The currently favoured method is a controlled Blast-in-Place (BiP) procedure that uses high-order detonations. This technique creates shock and noise pollution which results in permanent damage to the health of marine mammals and could also damage the wreck near which the *UXO* was found. After the detonation of an *UXO*, residues remain on the seabed or are distributed in the water column.

A better method to reduce the impact of sound and shock waves on marine wildlife is the use of bubble curtains. These bubble curtains are reusable and can reduce the danger zone for porpoises, fish or birds by up to 99%.

This article also mentions the new techniques of using low-order/d*eflagration* techniques and magnetic methods. Low-order detonations burn faster and more violently and do not create as much noise pollution as high-order detonations. Magnetic methods use magnetic signatures of *UXO* to locate and remove them without detonation. Further research and development is needed for new techniques to make the process of underwater *UXO* removal more environmentally friendly and less harmful to marine life.

8.3. Laws and regulation

The conclusions from the IDUM report on the Legal Aspects of Marine Munitions Management: Decision Making in de the Face of Uncertainty and Risk are relevant and valid in the North Sea Region. The various national, regional, and international laws on underwater munitions and wreck management in the North Sea Region are fragmented. The applicable international and EU agreements and national laws touch on certain aspects of the issues (environmental protection, hazardous materials and/or explosives handling), none address wrecks and munition in a holistic manner nor provide mechanisms for international cooperation, the potential to learn from each other's experience or enforcement. Notably the existing EU food safety rules concerning chemical risks and contaminants do not cover *TNT* and its *metabolites*. In conclusion, there is need for a comprehensive international agreement for underwater munitions and wreck management with special attention to food safety regulation.

Table 1: Overview of the studies techniques listing their definitions, advantages and disadvantages.

Technique	definition	Advantages	Disadvantages
High order detonation, Blast-in-Place	BiP involves placing a contact donor charge on the targeted UXO, which is then ignited or detonated through electrical or mechanical means.	1. Effective detonation	1. High Environmental impact (noise, damage/injuries)
		2. Control over detonation	2. Left over residue and contamination
		3. Relatively common technique (is not really an advantage in our eyes)	3. Risk of damaging, e.g. cultural heritages such as ship wrecks
Bubble curtain	The bubble curtain acts as a barrier, reducing the impact of sound and shock waves generated during blasting.	1. Wildlife protection	1. High Effort, time, and cost
		2. Reusability and ease of deployment	2. Depth limited around 40 to 50 meters
			3. Left over residue and contamination (of the blasted UXO)
Low-order / deflagration techniques	used to clear or make UXOs transportable without causing a high-order detonation.	1. Reduced noise and disturbance	1. Left over residue and contamination
		2. Transportable after detonation possible (depends on the used technique)	2. Chance of unintended High-order detonations
		3. Controlled and precise	3. Limited effectiveness
Recovery techniques	These involve the direct retrieval and removal of UXOs from the marine environment using various equipment and methods.	1. Minimized environmental impact	1. Multiple safety considerations
		2. Precise and targeted operations	2. High complexity and cost (dependent on the UXO to be clearded)
		3. Enhanced capabilities	3. Limited information on post-recovery processing methods

9. Advise

Based on the results of this desk study, it is advised to:

1. Given the significant risks that *TNT* poses to human health and the environment, it should be considered to invest in further research on *TNT* biodegradation by bacteria to mitigate the risks associated with *TNT* contamination.
2. If deciding to use high-order detonations for the removal underwater unexploded ordnance (*UXO*), it should be considered to use bubble curtains to reduce the impact of sound and shock waves on marine wildlife. Additionally, it should be considered to invest in the research and development of new techniques to make the process of underwater *UXO* removal more environmentally friendly and less harmful to marine life.
3. It should be considered to develop a comprehensive international agreement for underwater munitions and wreck management with special attention to food safety regulation. This agreement should address the fragmented nature of the various national, regional, and international laws on underwater munitions and wreck management in the North Sea Region and provide mechanisms for international cooperation and enforcement.

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Glossary

Word	Definition
(e)DNA metabarcoding	A method used to identify and analyse DNA sequences from multiple organisms present in an environmental sample, often used to study biodiversity.
1,3,5-trinitrobenzen (1,3,5-TNB)	A highly explosive compound commonly used in the production of explosives and propellants.
2,4,6-Trinitrotoluene (TNT)	A powerful explosive that is commonly used in military applications.
2,4-amino-6-nitroluene (2,4-DA-6-NT)	A chemical compound used in the production of dyes and pigments, as well as in the synthesis of explosives.
2-amino-4,6-dinitrotoluene (2-ADNT)	A chemical compound that can be found as a metabolite of *TNT* in organisms and the environment.
4-amino-2,6-dinitrotoluene (4-ADNT)	A chemical compound that can be found as a metabolite of *TNT* in organisms and the environment.
aerobic	In the presence of oxygen, usually referring to processes or organisms that require oxygen to function.
amino derivatives	Chemical compounds that are derived from or contain amino groups.
anaerobic	Organisms acting or living without free oxygen
anoxic	Without oxygen, usually referring to an environment or condition where oxygen is absent.
aoxic	A term that may refer to an environment or condition where oxygen is extremely limited or absent.
aromatic structure	A molecular structure characterized by a ring of atoms, often containing alternating single and double bonds, such as benzene.
axis gradiometer	A type of instrument used to measure the strength and direction of magnetic fields, often used in detecting buried metallic objects like unexploded ordnance.
binary mixtures	Mixtures composed of two different substances or components.
biogenic amines	Organic compounds that are produced by living organisms and contain an amine group, often found in foods, and involved in physiological processes.
bioremediation	The use of biological processes or organisms to eliminate or reduce harmful effects of pollutants in the environment.
carbonyl	A functional group characterized by an oxygen atom double-bonded to a carbon atom.
carbonyl reductase	An enzyme that catalyses the *reduction* of *carbonyl* compounds to their corresponding alcohols.
carcinogenic	Having the potential to cause cancer in living organisms.
carcinoma	A type of cancer that originates from epithelial cells.
chromosomal aberrations	Structural abnormalities or rearrangements in the structure of chromosomes, often associated with genetic disorders or cancer.
cis-dihydrodiol	A chemical compound with two *hydroxyl* groups on adjacent carbon atoms in a cis configuration.
CS-OOO	An abbreviation for Certificatie Opsporen Ontplofbare Oorlogsresten.
CWA	Abbreviation for Chemical Warfare Agents

Word	Definition
cyclotrons	Particle accelerators used to accelerate charged particles in a circular path for various purposes, including the production of radioactive isotopes.
deflagration	A rapid combustion process that propagates through a substance at subsonic speeds, typically associated with explosive materials.
dehydrogenase	An enzyme that catalyses the removal of hydrogen atoms from a molecule.
deoxygenation	The removal or *reduction* of oxygen from a substance or environment.
detoxify	To remove or neutralize toxic substances.
diol intermediates	Intermediate compounds that contain two *hydroxyl* groups.
dioxygenase enzymes	Enzymes that catalyse the incorporation of both atoms of molecular oxygen into organic compounds.
energetic compounds	Chemical substances that possess high energy content and can release energy rapidly.
Environmental DNA	Genetic material obtained from environmental samples (such as water, soil, or air), allowing the detection and identification of organisms without directly observing them.
exothermic	A process or reaction that releases heat or energy to its surroundings.
exudation	The process of releasing or secreting a substance, often referring to the release of fluids or compounds by living organisms.
gene amplicon sequencing	A technique used to determine the DNA sequence of a specific gene or DNA region by amplifying and sequencing targeted DNA fragments.
genotoxicity	The ability of a substance to damage DNA or cause genetic mutations, potentially leading to cancer or other diseases.
hepatic DNA	DNA present in liver cells.
hepatocellular neoplasms	Abnormal growths or tumours that originate from liver cells.
HMX	A powerful explosive compound used in military applications, also known as octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine.
hydride	A compound containing hydrogen in a negative *oxidation* state.
hydrocarbons	Organic compounds composed of hydrogen and carbon atoms.
hydrolysis	The chemical breakdown of a compound through a reaction with water.
hydroxyl	A functional group characterized by a hydrogen atom bonded to an oxygen atom.
hydroxylation	The addition of a *hydroxyl* group (-OH) to a molecule.
IARC	An abbreviation that typically refers to the International Agency for Research on Cancer, an agency that classifies carcinogens.
immunotoxicity	The ability of a substance to adversely affect the immune system and its functions.
ketones	Organic compounds characterized by the presence of a *carbonyl* group (C=O) bonded to two other carbon atoms.
lipid peroxidation	The oxidative degradation of lipids, resulting in the production of reactive compounds that can damage cells and tissues.
metabolites	Small molecules that are intermediates or end products of metabolic processes in living organisms.
metabolization	The process by which a substance is metabolized or transformed by biochemical reactions in the body.
mineralization	The conversion of organic compounds into inorganic substances through biological or chemical processes.

Word	Definition
multibeam echosounder	A type of sonar system used to create detailed maps of the seafloor and underwater structures.
NH3-moieties	Ammonia-containing groups or components.
nitrite	A compound containing the NO2- ion, often used as a food preservative and involved in various chemical reactions.
nitroso derivatives	Chemical compounds that contain the nitroso group (-NO) bonded to another atom or group.
octanol-water partition coefficient	A measure of the relative solubility of a chemical compound in octanol (an organic solvent) and water, often used to estimate its distribution in biological systems.
Octyls	Chemical compounds derived from the eight-carbon alcohol octanol.
oxidation	A chemical reaction in which a substance loses electrons, resulting in an increase in its *oxidation* state.
oxidative stress	Imbalance between the production of reactive oxygen species and the body's ability to neutralize them, leading to cellular damage.
photodegradation	The breakdown or degradation of a substance caused by exposure to light.
photolysis	The decomposition or breakdown of a compound by light energy.
Polycyclic aromatic hydrocarbons (PAHs)	Organic compounds composed of fused aromatic rings, often produced by incomplete combustion of organic materials, and considered pollutants.
prostaglandins	Hormone-like substances involved in various physiological processes and inflammation.
protocatechuate 3,4-dioxygenase	An enzyme involved in the degradation of aromatic compounds.
RDX	A powerful explosive compound commonly used in military applications, also known as cyclotrimethylenetrinitramine.
recombinant protein	A protein produced through genetic engineering techniques, involving the introduction of DNA encoding the protein into host organisms.
reduction	A chemical reaction in which a substance gains electrons, resulting in a decrease in its *oxidation* state.
ring cleavage	The breaking of a cyclic compound's ring structure, often occurring during the degradation of aromatic compounds.
total field magnetometer	An instrument used to measure the strength and direction of magnetic fields.
upregulated	Increased expression or activity of a gene or protein.
UXO	Abbreviation for Unexploded Ordnance, referring to explosive munitions that were deployed but did not detonate as intended.
xenobiotics	Chemical substances that are foreign to an organism's metabolism or natural environment, mostly referring to synthetic compounds.
β-ketoadipate pathway	A metabolic pathway involved in the degradation of aromatic compounds.

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