MMinE-SwEEPER

Deliverable Report

Deliverable No. 8.1: Environmental Risk Review

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Executive Summary

Work Package (WP) 8 aims to assess the security and environmental-related risks associated with chemical releases from munitions and clearance operations. As part of **Task (T)** 8.1, **Deliverable (D) 8.1** provides a synthesis of the most up-to-date measurements of chemical warfare agents (CWAs) and munition-related compounds (MCs) in European coastal seas, as well as their documented toxic effects on marine invertebrates and fish. The report combines data sourced from peer-reviewed scientific literature, technical reports and unpublished data from project partners. Findings from D8.1 indicated that the Baltic Sea is the most extensively studied European coastal region, whereas data from other European regions remain limited, with the few existing studies conducted decades ago. CWAs were mainly measured in surface sediment, while MCs were analyzed in both the water and surface sediments. To date, toxicity studies on CWAs have been restricted to freshwater invertebrates and fish. The dataset presented in D8.1 will help identify critical knowledge and data gaps, informing ongoing and planned studies within the MMinE-SwEEPER project and related EU co-funded projects, MUNIMAP, MUNI-RISK and REMARCO. Synthesizing data from these projects will further support the development of robust environmental risk assessment in support of future remediation strategies.

1. Introduction

The overarching objective of **Work Package (WP) 8** is to assess the security and environmental-related risks of chemical release from munitions and clearance operations. Within this framework, **Task (T) 8.1** aims to evaluate the environmental risk of marine munitions by compiling and synthesising current data on chemicals from chemical warfare agents (CWAs) and munition-related compounds (MCs), including their metabolites, in European (EU) coastal waters. Specifically, T8.1 focuses on environmental exposure levels in the water column and sediments, as well as on their toxicity effects on invertebrates and fish. T8.1 builds on the stakeholder dialogues conducted in WP1 and WP2, which emphasised the need for comprehensive background data on these chemicals in EU waters, to support decision-making before, during and after munition clearance.

In accordance with the WP8 objective "Compile and extend data on munition compound levels and their risk in EU coastal waters", the current report, Deliverable (D) 8.1, aims to provide a synthesis of the types, concentrations, and spatial distribution of CWAs and MCs along with their metabolites and associated impacts on aquatic biota. To provide an up-to-date overview of these compounds in EU coastal waters, D8.1 compiled data through an extensive literature review, which builds on a comprehensive review by Fauser et al. (2023). While research on CWAs has been ongoing for several decades, resulting in relatively accessible data on their environmental concentrations and spatial distribution, data on MCs remain limited largely due to the high cost of sampling and complexity (Beck et al., 2025; Lotufo, Chappell, Price, Ballentine, Fuentes, Bridges, George, Glisch, & Carton, 2017). To address the scarcity of open-access data on MCs, we sourced unpublished data or grey literature from project partners Aaron J. Beck (GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel) and Arnt Johnsen (Norwegian Defence Research Establishment, FFI), who are actively engaged in MC research in European coastal waters for several decades.

By compiling the existing data, D8.1 constitutes a critical step towards identifying key knowledge and data gaps necessary for a robust environmental risk assessment in support of remediation efforts.

The results generated in D8.1, along with the results from other tasks within WP8, will feed directly into WP9, which will use the compiled data to assess the risks associated with the different remediation strategies.

2. Materials and Methods

2.1 MCs

The data on environmental occurrence of MCs were sourced from project partners Aaron J. Beck (GEOMAR) and Arnt Johnsen (FFI), who have been working on munition-related research for several decades. Prior to obtaining this data, the MMine-SwEEPER consortium defined the scope of MCs relevant for D8.1 and identified specific compounds of interest (see Table 1 for selected compounds). Occurrence data for these MCs in EU coastal waters were then compiled with the support of the project partners. Toxicity data for MCs were obtained from Lotufo et al. (2017), who compiled existing toxicity data to derive interim water quality criteria (WQC) and protective values based on species sensitivity distributions. WQC are scientifically derived thresholds—such as chemical concentrations—established to restore and maintain the chemical, physical, and biological integrity of waterbodies, while protecting designated uses (US Environmental Protection Agency, 2017). Exceeding these criteria may indicate potential human health or ecological risks, requiring protective or remedial measures. In addition to the WQC, we obtained environmental quality standard (EQS) data from the Federal Environment Agency (Umweltbundesamt, UBA) of Germany (Personal communication, 2025).

2.2 CWAs

The dataset for CWAs was sourced from an extensive literature review of the entire EU coastal waters, building on studies by Fauser et al. (2023). Fauser et al. (2023) compiled data on CWAs and their degradation products along with associated risk assessment for invertebrates and fish in the Baltic Sea, covering the period from 2005 to April 2023. The dataset by Fauser et al. (2023) was compiled from peer-reviewed publications from 2005 to April 2023 and several EU projects, including

- **MERCW** (Modelling of Ecological Risks Related to Sea-Dumped Chemical Weapons; 2006-20010)
- **Nord Stream** (2008-2019),
- **CHEMSEA** (Chemical Munition, Search and Assessment; 2011-2014),
- **MODUM** (Towards the Monitoring of Dumped Munitions threat; 2013-2015),
- **DAIMON I & II** (Decision Aid for Marine Munitions; 2016-2021)

Deliverable 8.1 expands on the geographical and temporal scope of the studies by Fauser et al. (2023). We integrate all existing peer-reviewed literature and reports through August 2025, covering studies available for all European coastal waters, including the Atlantic and Arctic Ocean marginal Seas, the Mediterranean Seas and sub-seas, and the Black Sea region.

2.2.1 Literature Search - CWAs

A systematic literature search was conducted using selected academic databases and platforms, including Web of Science, Google Scholar, SciFinder, and Publish or Perish, covering all available literature until August 2025. These sources were prioritised for their extensive collection of credible peer-reviewed literature, advanced citation tracking capabilities and access to bibliometric data. The search terms used included: "chemical warfare agents (CWAs)", "mustard gas", "organoarsenicals", "Adamsite", "Lewisite", "Clark I and II", "degradation products", "metabolites", "measurements", "concentration", "toxicity", "threshold", "effects", "acute toxicity", "chronic toxicity", "sediment", "water", "invertebrate", "zooplankton", "copepod", "Daphnia" and "fish", "European seas", "Baltic Sea", "North Sea", "Irish Sea", "Celtic Sea", "English channel", "Bay of Biscay", "Barents sea", "Norwegian Sea", "Skagerrak strait", "Beaufort dyke", "Little Belt", "White Sea", "Mediterranean Sea", " Alboran sea", "Balearic Sea", "Ligurian Sea", "Tyrrhenian Sea", "Ionian Sea", "Adriatic Sea", "Aegan Sea", "Sea of Crete", "Myrtoan Sea", "Thracia Sea", "Levantine Sea", "Black Sea", "Sea of Azov". These keywords were combined in various configurations using Boolean operators (AND/OR/NOT) to efficiently retrieve relevant literature. To account for grey literature, we sourced relevant unpublished data directly from project partners.

2.2.2 Inclusion and Exclusion Criteria-CWAs

Publications were included if they reported (1) measured concentrations of CWAs or their degradation products in water and sediments of European coastal seas, or (2) experimental or field-based toxicity data for aquatic organisms, including fish and invertebrates such as plankton. Studies focusing exclusively on modelling of CWAs, or mammalian (human and rodent) toxicity, were excluded.

2.2.3 Selection and Quality Assessment

A total of 154 full-text articles and reports were assessed for eligibility, this article broadly covered environmental concentrations and toxicity of the chemical warfare agents. Out of the initial 154 studies retrieved, 148 were excluded because they either lacked retrievable information, contained confidential data or had already been reviewed by (Fauser et al., 2023). Ultimately, the search provided six additional studies, with three focused on toxicological effects and three on the environmental concentrations, which were added to the database from Fauser et al. (2023).

2.2.4 Extraction and Harmonisation

From each eligible publication, the following data were extracted:

1. Type of chemical or degradation compound
2. Spatial location
3. Test species
4. Biomarkers
5. Toxicological endpoints (EC, NOEC)

All extracted data were then synthesized with the data in Fauser et al. 2023 and presented in the results sections.

3. Results

This section details the types, concentrations, sample counts and geographical distribution of CWAs and MCs measured in EU coastal waters. A summary of the chemical types, their degradation or derivative compounds, the detection frequencies and environmental matrices is provided in Table 1. MCs were detected in both the pelagic water column and the surface sediment, whereas CWAs were only measured in the surface sediment.

Within the MCs, 2,4-DNT was detected in the dissolved fraction of all three water samples analyzed. 2-ADNT was detected in 94.8% of the water samples (dissolved) and 95.1% of the surface sediment samples analysed, with no measurable concentration in particulate form. Among the CWAs, DM had the highest detection frequency (48%), while L1 [ox] had the lowest (0.7%).

Table 1. Types of MCs and CWAs detected in EU coastal waters. Number of samples (n) and detection frequency in percentages for each environmental matrix (water-particulate and dissolved, surface sediment). Not measured (n.m.). Not available (n.a.).

Type	Acronym	Chemical name	CAS number	Number of samples and detection frequency (n, %)			Detects without coordinates
				Water (dissolved)	Water (particulate)	Surface sediment	
MC	HMX	1,3,5,7-Tetranitro-1,3,5,7-tetrazocane	2691-41-0	1185 (34.8%)	n.m.	128 (17.2%)	0
MC	RDX	1,3,5-Trinitro-1,3,5-triazinane	121-82-4	1850 (51.7%)	665 (10.4%)	306 (7.8%)	0
MC	DNB	1,3-Dinitrobenzene	99-65-0	1853 (47.7%)	665 (10.2%)	306 (35.3%)	0
MC	TNT	2,4,6-Trinitrotoluene	118-96-7	1853 (80.0%)	665 (35.3%)	317 (42%)	0
MC	2,4-DANT	2,4-Diamino-6-nitrotoluene	6629-29-4	383 (1.0%)	n.m.	92 (100%)	0
MC	2,4 DNT	2,4-dinitrotoluene	121-14-2	3 (100%)	n.m.	n.m	0
MC	2,6-DANT	2,6-Diamino-4-nitrotoluene	59229-75-3	383 (2.4%)	n.m.	92 (15.2%)	0
MC	2-ADNT	2-Amino-4,6-dinitrotoluene / 2-aminodinitrotoluene	35572-78-2	1188 (94.8%)	n.m.	101 (95.1%)	0
MC	4-ADNT	4-Amino-2,6-dinitrotoluene / 4-aminodinitrotoluene	19406-51-0	1188 (90.9%)	n.m.	102 (89.2%)	0
MC	sumDANT	The sum of 2,4-diamino-6-nitrotoluene and 2,6-diamino-4-nitrotoluene	59229-75-3 and 6629-29-4	n.m.	n.m.	214 (51.9%)	0
MC	sumADNT	The sum of 2-Amino-4,6-dinitrotoluene and 4-Amino-2,6-dinitrotoluene	19406-51-0 and 35572-78-2	976 (98.9%)	665 (7.5%)	214 (84.6%)	0
CWA	1,2,5-TTP	1,2,5-Trithiepane	6576-93-8	n.m.	n.m.	516 (25.2%)	0
CWA	1,4-DT	1,4-Dithiane	505-29-3	n.m.	n.m.	499 (16.03%)	0
CWA	1,4-OT	1,4-Oxathiane	15980-15-1	n.m.	n.m.	278 (5.0%)	0

CWA	n.a.	1,4-thioxane	15980-15-5	n.m.	n.m.	64 (4.69%)	0
CWA	1,4,5-ODT	1-oxa-4,5-dithiepane	3886-40-6	n.m.	n.m.	466 (24.7 %)	1
CWA	L1[ox]	2-Chlorovinylarsonic acid (L1ox)	64038-44-4	n.m.	n.m.	465 (0.7%)	0
CWA	DM[ox]	5,10-Dihydropheno-arsazin-10-ol 10-oxide (DM[OX])	4733-19-1	n.m.	n.m.	683 (16.7%)	7
CWA	DM	Adamsite (DM)	578-94-9	n.m.	n.m.	126 (48.4%)	0
CWA	L2[deriv]	Bis(2-chlorovinyl) propylthioarsine	677355-04-3	n.m.	n.m.	61 (3.3%)	0
CWA	L2[ox]	Bis(2-chlorovinyl)arsinic acid (L2_ox)	157184-21-9	n.m.	n.m.	487 (1.0%)	0
CWA	BDPAO	Bis(diphenylarsine) oxide	2215-16-9	n.m.	n.m.	62 (8.1%)	0
CWA	CB	Chlorobenzene	108-90-7	n.m.	n.m.	66 (18.2%)	0
CWA	DA	Clark I (DA)	712-48-1	n.m.	n.m.	483 (10.4%)	0
CWA	DA[ox]	Diphenylarsenic acid (DA[ox])	4656-80-8	n.m.	n.m.	713 (20.2%)	37
CWA	Clark[deriv]	Diphenylpropylthioarsine (DPTA)	17544-92-2	n.m.	n.m.	377 (20.7%)	0
CWA	PDCA[deriv]	Dipropyl phenylarsonodithioite	1776-69-8	n.m.	n.m.	435 (32.41%)	0
CWA	PDCA[ox]	Phenylarsonic acid (pdca_ox)	98-05-5	n.m.	n.m.	743 (22.8%)	41
CWA	HD	Sulfur mustard	505-60-20	n.m.	n.m.	718 (3.62%)	8
CWA	TDG[ox]	Thiodiglycol sulfoxide	3085-45-8	n.m.	n.m.	531 (0.9%)	0
CWA	TDGA	Thiodiglycolic acid	123-93-2	n.m.	n.m.	171 (1.2%)	0
CWA	TCA[deriv]	Trichloroarsine (TCA) deriv.	7784-34-1	n.m.	n.m.	463 (1.5%)	0
CWA	TPA	Triphenyl arsine (TPA)	603-32-7	n.m.	n.m.	787 (14.2%)	7
CWA	TPAO	Triphenyl arsine oxide	1153-05-5	n.m.	n.m.	316 (16.1%)	0
CWA	CAP	α-Chloroacetophenone (CN)	532-27-4	n.m.	n.m.	711 (5.3%)	1

3.1 Study Areas and Sample Counts

The Baltic Sea is the most extensively studied marine area in Europe for exposure concentrations of CWAs and MCs. Other studied marine areas include the Adriatic Sea (Mediterranean), the Skagerrak Strait (connecting the North Sea and Kattegat) and the Belgian coast of the North Sea (Figure 1).

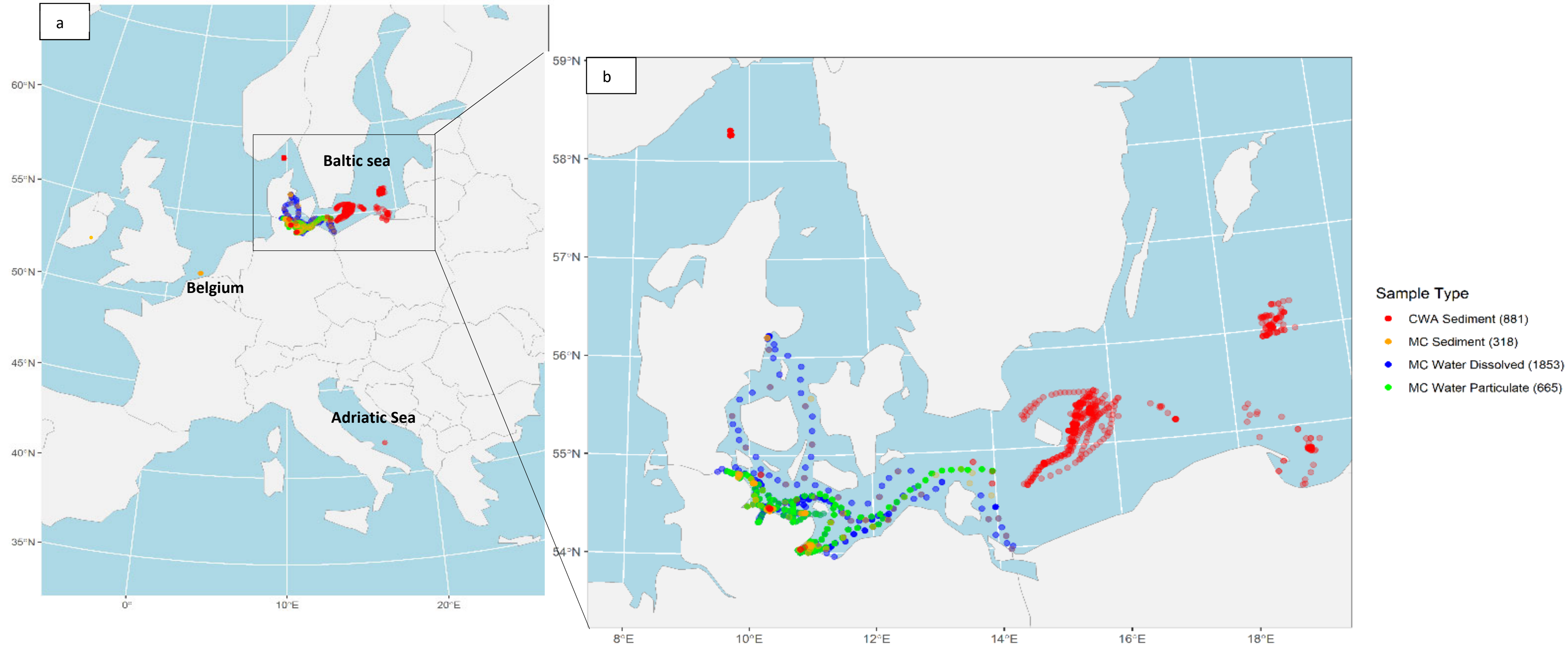
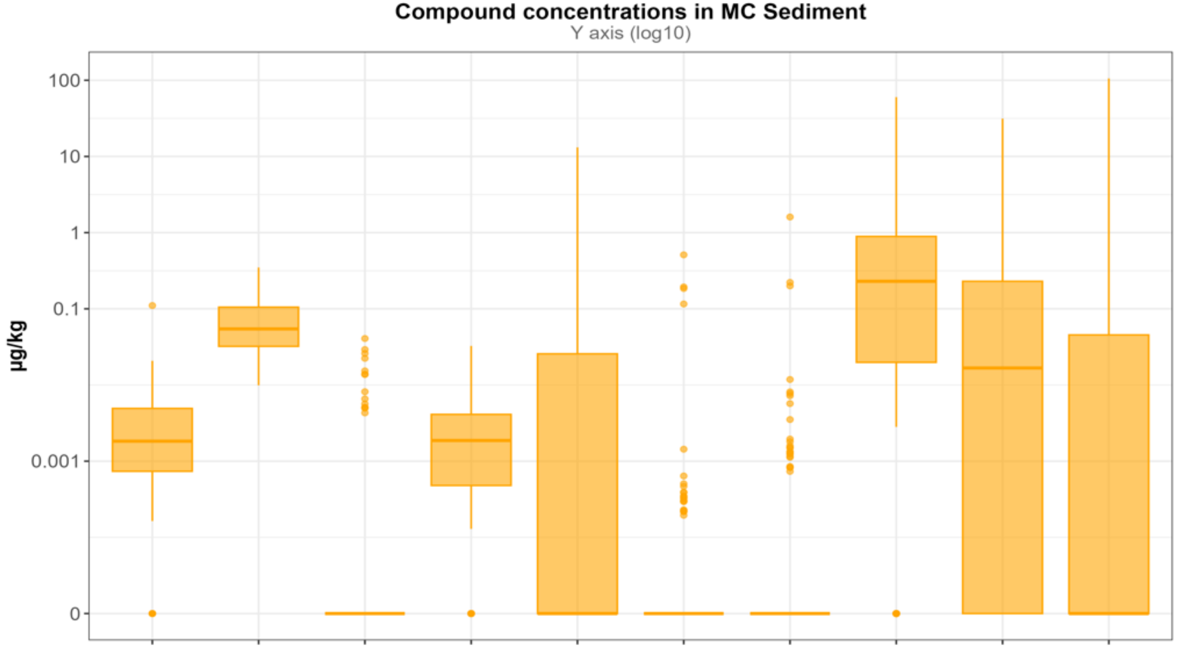


Figure 1. Locations and number of samples analysed for CWAs and MCs in European seas (a) and for the Baltic region (b).

3.2 Measured Environmental Concentrations of MCs and CWAs

3.2.1 MC Concentration in Sediments

The highest concentration of MC detected in sediment was TNT (105.7 µg/kg), while the lowest concentration was for 4-ADNT (0.03 µg/kg), a degradation product of TNT (Figure 2). Other MCs detected, which are not associated with TNT, are HMX (highest conc. = 0.5 µg/kg) and RDX (highest conc. = 1.6 µg/kg).

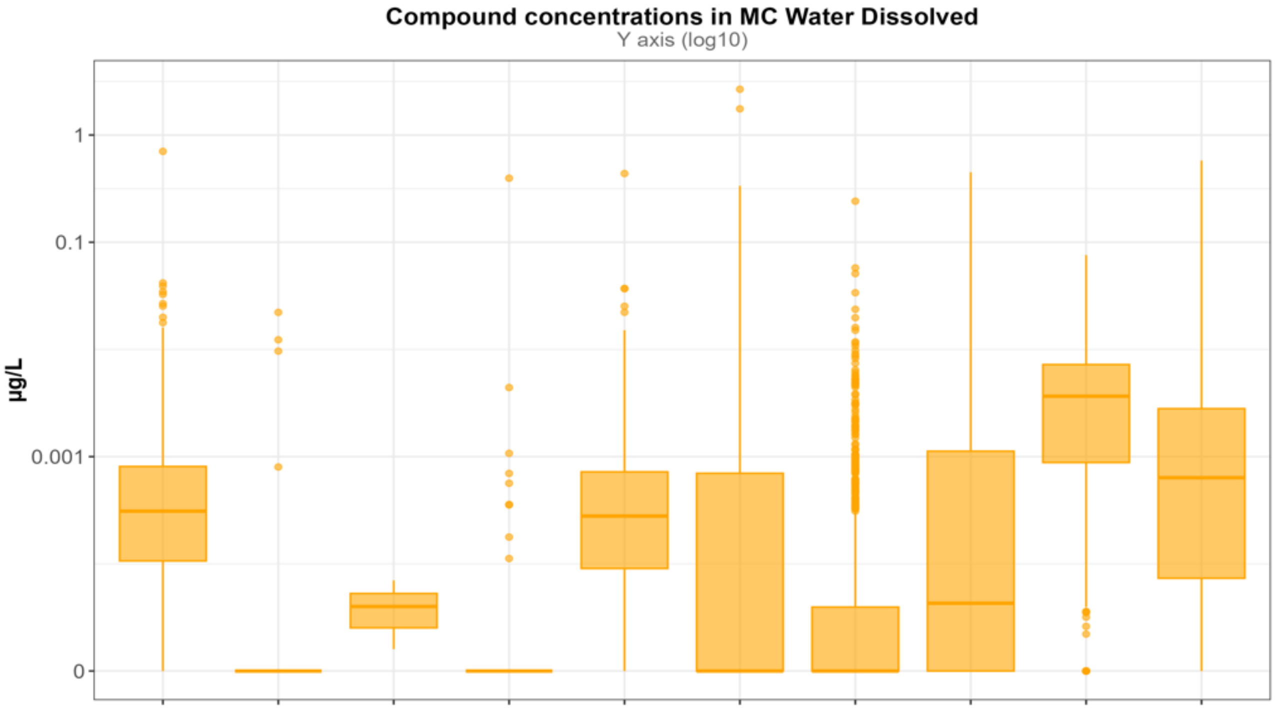


Statistics [µg/kg]	2-ADNT	2,4-DANT	2,6-DANT	4-ADNT	DNB	HMX	RDX	sumADNT	sumDANT	TNT
Median	0.00182	0.05448	0.00000	0.00186	0.00000	0.00000	0.00000	0.22995	0.01672	0.00000
Mean	0.00446	0.08571	0.00219	0.00317	0.06655	0.00792	0.00684	1.59395	0.99828	0.66878
SD	0.01137	0.07986	0.00671	0.00443	0.75361	0.05159	0.09318	5.37780	3.25371	6.40418
SE	0.00113	0.00833	0.00070	0.00044	0.04308	0.00456	0.00533	0.36762	0.22242	0.35969
Min	0.00000	0.00991	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Max	0.11038	0.34860	0.04076	0.03255	13.16501	0.51090	1.60400	60.12992	31.37792	105.69701
Range	0.11037	0.33868	0.04075	0.03254	13.16500	0.51089	1.60399	60.12991	31.37791	105.69700

Figure 2. Concentration of munition compounds (MCs) in sediments of European seas.

3.2.2 MC Concentrations in Water (Dissolved and Particulate)

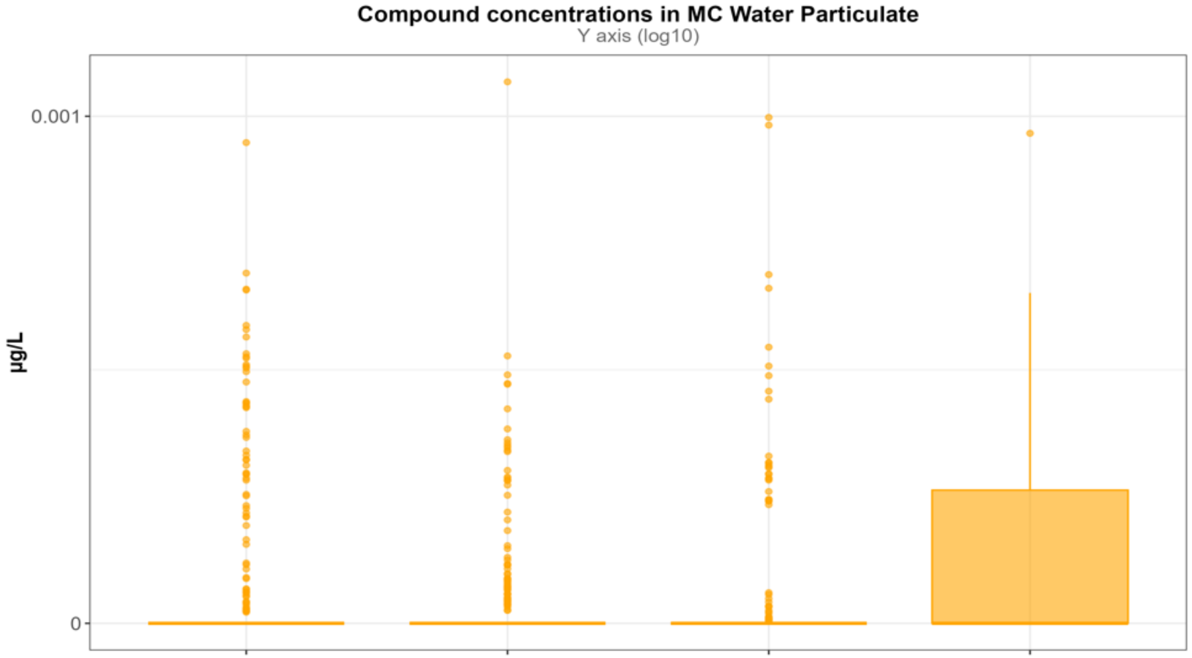
The highest concentration of dissolved MC in the water was observed for DNB (2.7 µg/L), and the lowest for 2,4-DNT (0.00007 µg/L). Similar to the sediment compounds, dissolved forms of HMX and RDX were detected in the water (Figure 3).



Statistics [µg/L]	2-ADNT	2,4-DANT	2,4 DNT	2,6-DANT	4-ADNT	DNB	HMX	RDX	sumADNT	TNT
Median	0.00030	0.00000	0.00003	0.00000	0.00027	0.00000	0.00000	0.00003	0.00365	0.00063
Mean	0.00164	0.00013	0.00004	0.00106	0.00123	0.00975	0.00064	0.00466	0.00538	0.00371
SD	0.02063	0.00138	0.00003	0.02023	0.01290	0.08115	0.00757	0.02182	0.00682	0.01856
SE	0.00060	0.00007	0.00002	0.00103	0.00037	0.00189	0.00022	0.00051	0.00022	0.00043
Min	0.00000	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Max	0.70465	0.02218	0.00007	0.39585	0.43753	2.67516	0.24164	0.45023	0.07591	0.57841
Range	0.70464	0.02217	0.00005	0.39584	0.43752	2.67515	0.24163	0.45022	0.07590	0.57840

Figure 3. Concentration of dissolved munition compounds (MCs) in the pelagic water column of European seas.

However, particulate HMX was not detected in any of the samples (Figure 4). The highest concentration of particulate MC in water was observed for RDX (0.01 µg/L). MCs occurred at higher concentrations in the dissolved than in the particulate form.

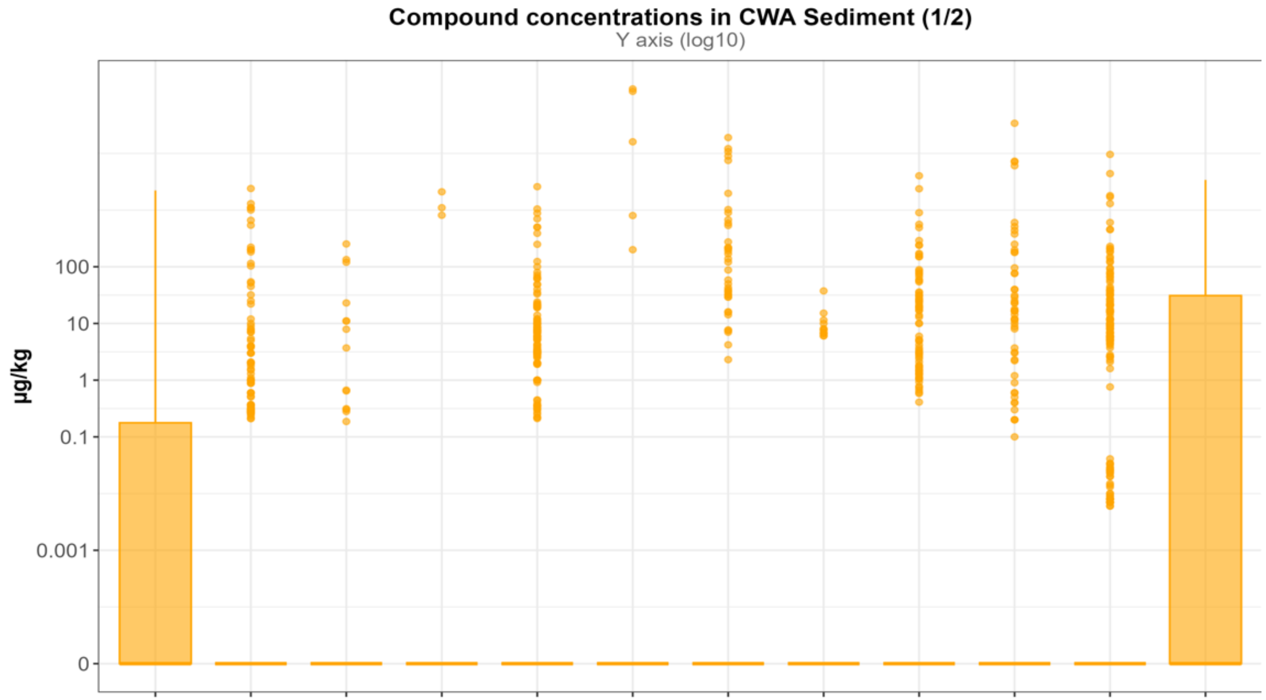


Statistics [µg/L]	DNB	RDX	sumADNT	TNT
Median	0.00000	0.00000	0.00000	0.00000
Mean	0.00002	0.00001	0.00001	0.00003
SD	0.00004	0.00005	0.00005	0.00005
SE	0.00000	0.00000	0.00000	0.00000
Min	0.00000	0.00000	0.00000	0.00000
Max	0.00079	0.00137	0.00099	0.00086
Range	0.00078	0.00136	0.00098	0.00085

Figure 4. Concentration of particulate munition compounds (MCs) in the pelagic water column of European seas.

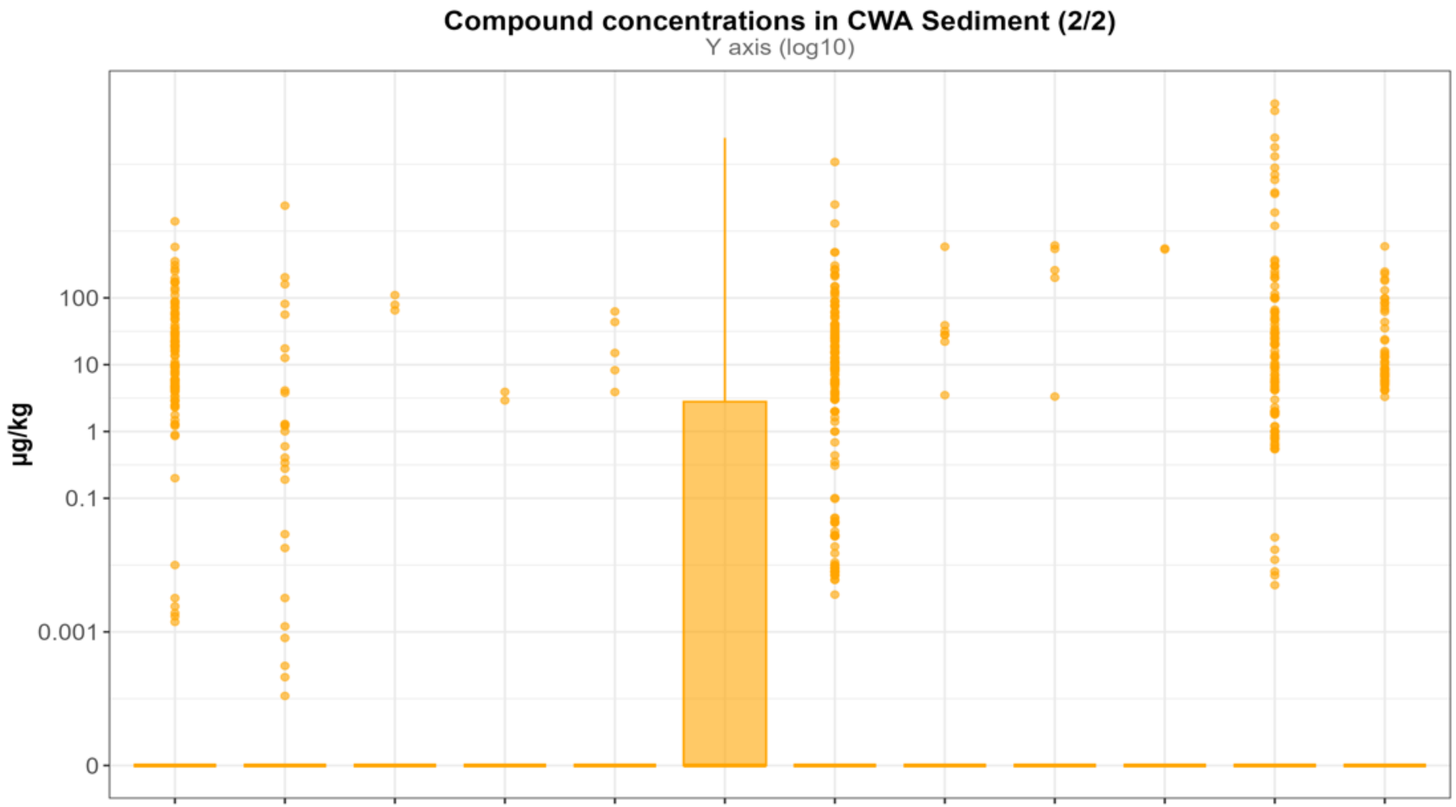
3.2.3 Measured CWA Concentrations in Sediments

The measured CWAs included mustard agents and degradation products (e.g., 1,2,5-TTP, 1,4-DT, 1,4-thioxane), organoarsenicals and derivatives (e.g., Clark(deriv), DA, DA[ox]), Lewisites & derivatives (e.g., L1[ox], L2[deriv], L2[ox]) and other CWAs/additives (CAP, CB, TCA[deriv], 2-chloro-1-phenyl-ethanone, BDPAO). Concentrations varied considerably across the different compounds (Figure 5). The highest was observed for BDPAO (137000 µg/kg), while the lowest was that of L2 [deriv] (3.9 µg/kg).



Statistics [µg/kg]	1,2,5-TTP	1,4-DT	1,4-OT	1,4-thioxane	1,4,5-ODT	BDPAO	CAP	CB	Clark[deriv]	DA	DA[ox]	DM
Median	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Mean	23.51507	18.99661	2.03424	62.65626	17.54235	4483.87098	92.99000	1.96971	28.83121	119.53602	33.10145	71.13160
SD	147.15620	152.71006	18.59643	309.24507	144.26656	23313.67145	1035.78523	5.55641	248.66900	1634.22076	409.46030	352.16055
SE	6.47819	6.83624	1.11534	38.65563	6.68302	2960.83924	38.84498	0.68395	12.80710	74.35962	15.33441	31.37296
Min	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Max	2216.83870	2400.00001	252.53209	2100.00001	2585.78709	137000.00001	19015.17516	37.50001	4026.27021	33958.33334	9583.33334	3400.00001
Range	2216.83869	2400.00000	252.53208	2100.00000	2585.78708	137000.00000	19015.17515	37.50000	4026.27020	33958.33333	9583.33333	3400.00000

Figure 5. Concentration of different chemical warfare agents (CWAs), their degradation products, and derivatives in European seas.



Statistics [µg/kg]	DM[ox]	HD	L1[ox]	L2[deriv]	L2[ox]	PDCA[deriv]	PDCA[ox]	TCA[deriv]	TDG[ox]	TDGA	TPA	TPAO
Median	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Mean	8.82857	4.10275	0.54625	0.11212	0.27367	118.68263	27.11870	1.58950	3.03830	6.31580	301.20936	8.01260
SD	64.69233	90.13570	6.95231	0.62075	3.53791	1324.06894	411.74533	27.27611	38.02703	58.23780	3877.24535	42.97796
SE	2.47538	3.36383	0.32241	0.07948	0.16032	63.48425	15.10547	1.26763	1.65023	4.45356	138.20887	2.41770
Min	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Max	1400.00001	2400.00001	110.00001	3.92095	62.60001	24867.67762	10833.33334	583.33334	610.00001	550.00001	81250.00001	590.00001
Range	1400.00000	2400.00000	110.00000	3.92094	62.60000	24867.67761	10833.33333	583.33333	610.00000	550.00000	81250.00000	590.00000

Figure 6. Concentration of different chemical warfare agents (CWAs), their degradation products, and derivatives in European seas.

3.3 Regulatory and Toxicity Values for MCs and CWAs

3.3.1 MC Regulatory Relevant values

The chronic WQC values for MCs (Table 2). Criteria specific to saltwater are provided, where available; otherwise, combined (freshwater + saltwater) or freshwater values are reported.

Table 2. Chronic water quality criteria (WQC; µg/L) for MCs. Saltwater values are only derived from saltwater data, combined values are derived from freshwater and saltwater data, and freshwater values are only derived from freshwater data.

MC	Chronic WQC (µg/L)	Criterion data basis
2,4,6-TNT	**0.15**[a], 32.6[b]	Saltwater
2A-4,6DNT	342 [b]	Combined freshwater and saltwater
1,3,5-TNB	25 [b]	Combined freshwater and saltwater
1,3-DNB	76 [b]	Freshwater
2,4-DNT	900 [b]	combined freshwater and saltwater
RDX	859 [b]	Combined freshwater and saltwater
HMX	329 [b]	Freshwater
NG	7 [b]	Freshwater

[a] The environmental quality standard (EQS), value from UBA. They relied on the data provided by Stanley et al. (2015) specifically, the *Rana pipiens* 28-d NOEC (1.5 µg/L – see figure 7) *10 Assessment Factor (AF) = **0.15 µg/L**

[b]Lotufo, et al. (2017); USA and AA QS saltwater from UBA.

3.3.2 MC Toxicity Values

There are extensive studies, including Lotufo et al. (2017; Figure 7), assessing the LC50 for TNT and other munition-related compounds; however, the present report will provide only the hazardous concentration for 5% of species (HC5).

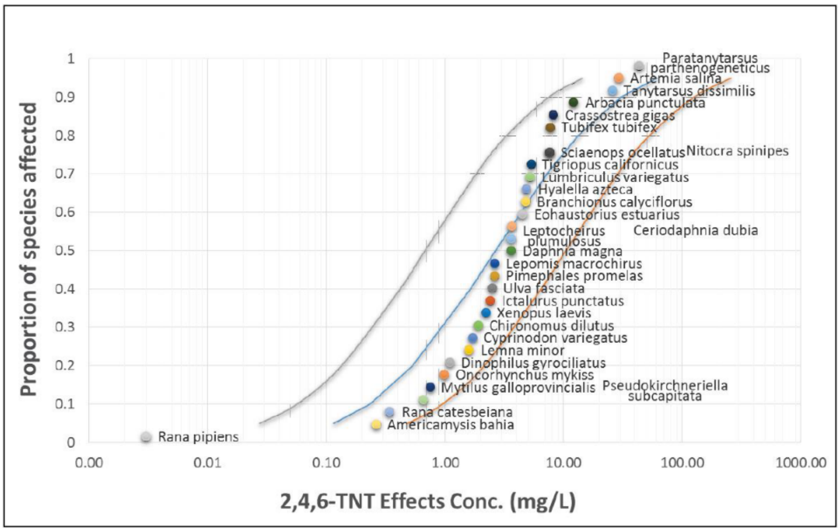


Figure 7. Species distribution for 2,4,6-TNT using no-effects data. The outer line represents 95% confidence intervals (Lotufo, et al., 2017).

The HC5 values (Table 3) were estimated from the SSD using the data by Lotufo, et al. (2017). The lowest HC5 values were observed for 2-ADNT (1.2 µg/L), whereas the highest was observed for TNT (116 µg/L).

Table 3. Hazardous concentration for 5% of species (HC5; µg/L). Values not calculated because data available for fewer than six species (N.C.).

MC	HC5 (µg/L)
TNT	116
2-ADNT	1.2
4-ADNT	2
TNB	114
1,3-DNB	274
2,4-DNT	615
2,6-DNT	710
RDX	2.1
HMX	N.C.
Picric Acid	24.5
Tetryl	N.C.
NG	88
NQ	N.C.

3.3.3 CWA Regulatory Relevant Values

The Predicted No Effects Concentration (PNEC) estimates for CWA by Fauser et al. (2023) are shown in Table 4 and the selected toxicological data for the main CWA groups are shown in Table 5. For invertebrates, the concentrations ranged from 0.00004 µg/L (PDCA[deriv]) to 10.9 µg/L (1,4-OT). For fish, the PNEC values ranged from 0.01 µg/L (CB) to 100 µg/L (CAP).

Table 4. Predicted No Effect Concentration (PNEC; µg/L) of CWA for *Daphnia magna* and fish (Fauser et al., 2023).

CWA	**PNEC [µg/L]**	
	Daphnia magna	**Fish**
HD	0.9	0.07
TDG[ox]	9.8	0.2
1,4-DT	2.9	0.2
1,4-OT	10.9	0.2
1,4,5-ODT	1.7	3.1
1,2,5-TTP	0.02	0.2
TDGA	10.7	0.2
DM	0.004	58
DM[ox]	9.9	58
DA	0.004	58
DA[ox]	9.9	58
Clark[deriv]	0.004	58
TPA	0.2	58
TPAO	10.2	58
PDCA[ox]	10.0	58
PDCA[deriv]	0.00004	58
L1[ox]	0.0003	58
L2[ox]	0.0003	58
L2[deriv]	0.0003	58
TCA[deriv]	1.1	58
CAP	0.05	100
CB	0.25	0.01

Table 5. Selected toxicological data for main CWA groups (Fauser et al., 2023).

Chemicals	**Selected toxicity values (µg/L)**
Organoarsenicals	290 (fish for inorganic As)
Mustard gas degradation products	1530 (fish – 14-day survival test for 1,4,5-oxadithiepane)
Other parent and degradation products	Use the lowest EC_{50}, LC_{50}, or NOEC from peer-reviewed literature

3.3.4 CWA Toxicity Values

Toxicity studies of CWAs have primarily been conducted using the freshwater invertebrate *Daphnia magna* and the zebrafish, *Danio rerio* (Table 6). A wide range of toxicity was observed among CWAs and their transformation products, with EC_{50} values for *D. magna* varying over five orders of magnitude. Compounds such as PDCA exhibited high acute toxicity, with an EC_{50} of 0.36 µg/L, whereas others, including oxidized derivatives, showed no observed effect concentrations (NOECs) as high as 108762 µg/L (Table 6).

Table 6. Toxicity of CWAs to invertebrates (*Daphnia magna*) and fish based on Effective Concentration for 50% of the test population (EC50), No Effect Concentration (NOEC) and Species Sensitive Distribution (SSD). Not measured (n.m.).

CWA	Measured (µg/L)	
	***Daphnia magna* (EC50)**	**Fish (14d EC50 and SSD)**
HD	8916 [1]	690 (SSD)[2]
TDG[ox]	98392 (NOEC) [1]	n.m.
1,4-DT	28742 (NOEC) [1]	n.m.
1,4-OT	108762 (NOEC) [1]	n.m.
1,4,5-ODT	830 [2]	1530 (14d EC50)[2]
1,2,5-TTP	214.8 [1]	n.m.
TDGA	106657 (NOEC) [1]	n.m.
DM	44.4 [6]	n.m.
DM[ox]	99227 (NOEC) [6]	n.m.
DA	37.02 [6]	n.m.
DPA, DA[ox]	99.064 (NOEC) [6]	n.m.
DPTA, Clark[deriv]	37.02	n.m.
TPA	1992 [6]	n.m.
TPAO	101821 (NOEC) [6]	n.m.
PDCA	0.36 [6]	n.m.
PDCA[ox]	99547 (NOEC) [6]	n.m.
PDCA[deriv]	Same as PDCA	n.m.
Lewisite (L)	2.5 [6]	n.m.
L1[ox]	Same as L	n.m.
L2[ox]	Same as L	n.m.
L2[deriv]	Same as L	n.m.
TCA, AsCl3	10921 [6]	n.m.
TCA[deriv]	Same as TCA	n.m.
CAP	496 (QSAR LC50) [3]	500 (SSD)[5]
CB	2500 [4]	100 (SSD)[5]

1) Czub et al. (2020)
2) Sanderson & Fauser (2019)
3) QSAR, acute toxicity LC50
4) CEPA (1992)
5) Sanderson et al. (2008)
6) Czub et al. (2021)

4. Discussion

D8.1 synthesizes the most up-to-date data on environmental exposure and toxicity of munition-related compounds (MCs) and chemical warfare agents (CWAs) in European coastal waters. The review confirms a strong geographical imbalance in available data, with the Baltic Sea being by far the most intensively studied region. This focus reflects both historical factors, such as large-scale post-World War II dumping of munitions in areas like the Bornholm Basin and Gotland Deep, and the Baltic Sea's continued geopolitical, economic, and environmental relevance (Dahl, 2014; Greenberg et al., 2016; Slakaityte et al., 2022). Long-standing regional cooperation frameworks (e.g., HELCOM) have further facilitated coordinated monitoring and research efforts.

In contrast, several other European regions known or suspected to be hotspots for dumped munitions, including the Mediterranean Sea, North Sea, Barents Sea, and White Sea (Beck et al., 2022; Greenberg et al., 2016), remain poorly characterized. Existing studies from these regions are scarce and, in many cases, several decades old (Amato et al., 2006; Granbom, 1996; Tørnes et al., 2002). Given the progressive corrosion of munition casings and changing environmental conditions (HELCOM, 2024 and reference therein), these historical data may no longer be representative of current exposure scenarios. This creates substantial uncertainty for environmental risk assessment and for planning safe and effective remediation or clearance activities outside the Baltic Sea.

The compiled data shows that MCs, particularly TNT and its amino- and dinitro-degradation products, are frequently detected in both sediments and the water column. This pattern is consistent with the widespread historical use of TNT, its relatively high solubility compared to other explosives, and its slow degradation under marine conditions (Beck et al., 2019; Bünning et al., 2021). In contrast, CWAs and their degradation products are predominantly detected in sediments, with very limited evidence of their presence in the pelagic water column. This likely reflects their low water solubility, rapid hydrolysis, and strong association with particulate matter and sediment matrices (Bartelt-Hunt et al., 2008).

From a toxicological perspective, the review highlights a major limitation for environmental risk assessment: the lack of marine-specific chronic toxicity data, particularly for CWAs. Most available toxicity studies have been conducted with freshwater species such as *Daphnia magna* and zebrafish, which constrains the derivation of robust marine water quality criteria and species sensitivity distributions. While interim regulatory values and predicted no-effect concentrations (PNECs) exist for several MCs, comparable benchmarks for CWAs in marine systems are largely absent. As a result, current risk assessments rely on extrapolations that introduce additional uncertainty reflected in the associated assessment factors.

Overall, the review underscores that while significant progress has been made in characterizing environmental risks from marine munitions in certain areas of the Baltic Sea, substantial knowledge gaps persist at the European scale. Addressing these gaps is essential for supporting evidence-based decision-making before, during, and after munition remediation activities.

5. Conclusions

This Environmental Risk Review (D8.1) was developed within WP8 of the MMinE-SwEEPER project to support the assessment of security- and environment-related risks associated with marine munitions and their remediation. In line with the objective of WP8 "Compile and extend data on munition compound levels and their risk in EU coastal waters", D8.1 compiles and synthesizes existing knowledge on the occurrence, exposure levels, and ecological effects of munition-related compounds (MCs) and chemical warfare agents (CWAs) in European coastal waters. The deliverable establishes a common evidence base to support risk assessment before, during, and after clearance activities, clarifies current knowledge and uncertainties, and provides a foundation for subsequent modelling, monitoring, and scenario-based analyses within WP8, WP9, and the wider MMinE-SwEEPER project. Importantly, the synthesis highlights that substantial data gaps persist not only in European waters outside the Baltic Sea but also within the Baltic Sea itself, including several sub-regions where historical munition dumping has been reported (e.g., according to EMODNET), yet remain poorly characterized in terms of environmental exposure and risk.

Key conclusions:

- **Environmental occurrence has been well documented primarily in the Baltic Sea.** The Baltic Sea is the only European marine region with extensive, relatively recent data on MCs and CWAs, reflecting historical dumping practices and sustained regional monitoring efforts.

- **Large geographical data gaps persist outside the Baltic Sea.** Other European coastal regions identified as potential hotspots for dumped munitions remain poorly studied, with existing data often outdated. This limits the reliability of environmental risk assessments in these areas.

- **Munition-related compounds (MCs) are more widely detected in both water and sediments than CWAs.** MCs, especially TNT and its degradation products, are frequently found in sediments and the water column, whereas CWAs and their derivatives are mainly confined to sediments.

- **Toxicity data are insufficient for robust marine risk assessment, particularly for CWAs.** Most available toxicity information is based on freshwater species, and there is a lack of marine-specific chronic toxicity data needed to derive water quality criteria and species sensitivity distributions.

- **Some regulatory and risk assessment elements are partially in place, but important gaps remain.** Interim water quality criteria and toxicity thresholds exist for several MCs, while comparable regulatory benchmarks for CWAs in marine environments are largely lacking.

- **This deliverable contributes to a consolidated baseline across Europe.** By harmonizing published, grey, and partner-provided data, D8.1 contributes to a common reference point for identifying priority compounds, regions, and data gaps.

- **The results directly support future work within MMinE-SwEEPER and beyond.** The findings will assist targeted monitoring, marine ecotoxicological testing, and risk assessments in WP8 and WP9, and contribute to coordinated efforts with other EU-funded projects such as MUNI-RISK and MUNIMAP.

- **The compiled dataset directly enables risk-oriented spatial modelling to support decision-making.** The harmonized occurrence and toxicity data can be used to model concentrations and risks of CWAs and MCs in unexplored or poorly characterized areas of the Baltic Sea, particularly in focus regions, sensitive ecosystems, and areas of high human interest (e.g. fisheries, shipping lanes, offshore infrastructure). Such modelling is directly relevant for WP9, where scenario-based assessments of remediation, clearance, and disturbance activities require spatially resolved exposure estimates.

These conclusions provide a basis for prioritizing future monitoring and research, improving environmental risk assessments, and supporting informed decision-making on marine munition remediation strategies across European waters.

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