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RESEARCH ARTICLE

Risk assessment of war wrecks – a comprehensive approach investigating four wrecks containing munitions in the German Bight/North Sea

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Abstract

Shipwrecks and dumped munition continue to be a major hazard, both in the North Sea but also on a global scale. Research within the EU Interreg project North Sea Wrecks (NSW), in cooperation with the German Aerospace Centre, Institute for the Protection of Maritime Infrastructures (DLR), is generating new insights into the status of wrecks, the potential leakage of pollutants from remaining munitions loads and the effects of contamination on exposed marine organisms in the North Sea environment. Further, historical documents are generated from archives to describe ship's history and sinking scenario. These historical findings were compared to models and images of the visual inspections of the wrecks. Further, samples of water, sediment and organisms are being analysed for traces of explosives. Combining the results of these different fields of research allows for a better understanding of the environmental risks deriving from these wrecks. This process is shown below by focusing on the wreck of the German light cruiser SMS MAINZ, which sank in 1914. Data were compared to three additional wrecks situated also within the southern German Bight. Available data about the wrecks were preliminary assessed using a wreck risk model. Finally, wrecks were ranked according to their potential environmental risk.

KEYWORDS

biological effects of explosives, chemical analysis, data fusion, historical documents, marine pollution, maritime risk assessment, shipwrecks, underwater inspection, underwater munition

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1 | INTRODUCTION

Millions of tons of munition were deliberately introduced into the European seas during and after the two world wars: Mine belts were laid to protect coasts and harbours from other war parties, naval battles were fought leading to unexploded munitions from warships, planes and artillery on the seafloor. Ordnances were also ditched by bombers returning to airports, and warships were scuttled to avoid enemy capture. Today, the amount of munitions derived from wartime activities is hard to estimate, but they are found in nearly all marine areas.

Most munitions, however, have entered the seas after the wars when Allies decided to disarm Germany by dumping the remaining munitions and chemical warfare material in both North and Baltic Sea [1].

From both world wars, 1.3 million metric tons of conventional munitions are estimated to lay in the North Sea along the German coast [2]. In addition, WWII was the largest loss of both military and commercial ships worldwide within a short period of time [3, 4]. It is estimated that over 7800 ships and vessels sunk during WWII [3, 4]. Around 3800 of them alone in the East Asian Pacific [3, 4]. But also the North Sea was a wet grave for many ships [5]. Data from the German Federal Maritime and Hydrographic Agency, Hamburg (BSH) and the German Maritime Museum – Leibniz Institute for Maritime History (DSM), Bremerhaven record at least 120 military ship and aircraft wrecks dating mainly from WW I and II within the German Territorial Waters and the German Exclusive Economic Zone (EEZ) in the North Sea. Many of these ships carried considerable amounts of munitions at the time of sinking, since they were war ships or transporters. Others were sunk for example outside German Waters, e.g., in the Skagerrak, deliberately together with redundant munitions or chemical warfare agents during dumping activities after the war. Altogether, the munition remains at wrecks is contributing significantly to the total amount of marine munition still being at our seas [3, 6]. Shipwrecks still containing fuel, dangerous cargo or munition may pose severe risks to the aquatic environment. Hence, shipwrecks are of particular importance for environmental risk assessments. There is a need develop methods to determine the relative risk posed by the wrecks and to collect the necessary data to validate that risk. To validate the risk sound data basis are needed to catalogue all the available information to wracks or other submerged threads as proposed back in 2009 by Overfield and Symons [7].

1.1 | Conceptual frame of “marine slow disasters”

For a long time, the ocean was regarded as a vast repository that could absorb endless quantities of waste, including radioactive substances or heavy metals – out of sight, out of mind. Because incineration of munitions on land has caused palpable environmental harm, disposal at sea, was considered as a safe long-term solution [8]. In addition, there were safety concerns and sea disposal following the war was used to rapidly disarm the Axis forces and place the munitions out of reach. Sea disposal offered for the Allies a way to remove large quantities of munitions in an efficient fashion. However, unexploded ordnance (UXO), no matter how old, may blow up. And even if they do not explode, environmental pollutants and toxic chemicals may be released as the metal shells corrode. Today, many of the munition remains at sea severely corroded and risk leaking contaminants.

In contrast to the obvious dangers of munition such as its explosion hazard, which is still a life-threatening risk for fishermen or offshore workers, the initially invisible and slower impacts of munitions at sea on the marine ecosystem have received little attention. The special temporality of these particular cases of environmental pollution – still causing problems more than 100 years after WWI and more than 75 years after WWII – leads us to question, whether too little attention has been paid to the other hazards below the risk of explosion. In the social science literature, the more gradual dangers have also come into focus, and this particularity is addressed with the term “slow disasters” [9, 10].

This term was developed in Science and Technology Studies (STS) and characterizes these phenomena as often having consequences years or decades later. Therefore, they risk effecting future generations of various species including humans either directly or via the food web [11]. In the marine environment, the mobility, sedimentation, and accumulation of anthropogenic substances, such as toxic chemicals, is very difficult to track and detect – impacts of these events on the environment and species including humans that may only occur in the future demonstrate the speculative and indeterminate nature of this field of research [12, 13]. Even if a toxic substance such as TNT can be detected in certain locations, the effects may remain unpredictable because, for example, studies of accumulation in marine food chains are not yet available.

The end of a war means the end of direct combat, but it often says nothing about the long-term impact on the environment and people, the “toxic legacies of war” as we have called them for the exhibition of the project “North Sea Wrecks” (NSW). The long-term repercussions of catastrophic wars and industrial accidents of the 20th century are examples of slow disasters that both affected the past and might affect the future [14, 15]. Wars thus leave behind complex “post-conflict landscapes” that still bear fast and slow disasters as shown by shipwrecks in the North Sea discussed in this article [16]. The risks they pose range from explosive potentials to the long-term and often unpredictable environmental pollution and intoxication for living species that is in the focus of our research. Therefore, the NSW project poses the question: Are war wrecks in the North Sea a source of marine pollution that has so far received little attention? And how can we determine which wrecks may pose a potential higher risk?

1.2 | Aim of the present study

For this study we collected all available information of the histories of the investigated ships, tried to estimate remaining munition on board at the time of sinking, by assessing archive information for both technical data about the armament and the usage of munition during war actions shortly before sinking. This information, together with distance and depth indications were used to select the wrecks for the German pilot studies. Like this, four wrecks were selected in German territorial and EEZ waters as pilots for this study (Table 1). Once a wreck was selected a comprehensive sampling campaign was conducted at the wreck site, ranging from physical inspection applying scanning techniques for visualisation, to analytical assessment of surrounding water, sediments and biota, up to biological investigations regarding health impairments of organisms living on or around the wrecks and as such being exposed to potential leakage of corroded munition. The results were fed to database connected with risk assessment models calculation the individual environmental risk for each wreck. In a last step, wrecks were ranked according to the information available at the time of writing this study.

2 | EXPERIMENTAL SECTION

2.1 | Selection of survey locations

As German pilots, four different wrecks are selected as case studies, on which standardised sampling and analysis methods are carried out. These wrecks are former naval ships, civilian ships converted for military purposes and decommissioned civilian ships or demilitarised naval ships. The latter were for example used for munition dumping actions in the years directly after the end of the Second World War [17]. The wrecks selected for the project date from the First and Second World Wars and cover a relatively wide range of different ship types (e.g., light cruisers, submarines, barrier breakers, torpedo boats, outpost boats, destroyers and Liberty ships). Within the project the focus is on identified wrecks allowing a compilation of the ship’s history and an estimation of the munition still on board at the time of the sinking. Partners from nine institutions of five countries (Norway, Denmark, Germany, Netherlands and Belgium) have selected suitable pilots within their territorial waters and/or EEZs.

For the German pilot investigations we focus on the wrecks of the SMS MAINZ, the SMS ARIADNE, the SMS HELA and the Barrier Breaker Nr. 163 FRIESLAND. All wrecks are located today in suitable distances west or south of the island of Heligoland (Figure 1).

2.2 | Historical research

In the following, the historical background of the investigated wrecks within the German waters, is presented in a condensed form. Therefore, these facts are summarised according to the topic of the article. The information

TABLE 1 Wreck specific and Site-specific indicators and activities as used for the VRAKA calculation of probability of release for the Wrecks SMS HELA, SMS MAINZ, Barrier Breaker FRIESLAND and SMS ARIADNE. For each parameter, lowest and highest reasonable values were given.

Wreck name	–	SMS HELA		SMS MAINZ		FRIESLAND		SMS ARIADNE	
Indicators	**Units**	**Lowest**	**Highest**	**Lowest**	**Highest**	**Lowest**	**Highest**	**Lowest**	**Highest**
Average sea-floor oxygen concentration	mg/l	0	10	0	10	0	10	0	10
Average sea-floor salinity	PSU	33.05	34.34	33.30	34.56	29.76	32.83	32.90	34.49
Average sea-floor temperature	°C	0	20	0	20	0	20	0	20
Average sea-floor current speed	m/s	0.26	0.55	0.24	0.55	0.38	0.66	0.31	0.53
Material	–	Steel		Steel		Steel		Steel	
Average hull thickness	mm	13.00	40.00	13.00	80.00	13.00	14.00	13.00	50.00
Seabed character	–	Erosional Seabed		Erosional Seabed		Erosional Seabed		Stable Seabed	
Wreck position on the seabed	–	Tilting on its side		Upright Position		Upright position		Upside down	
Depth	m	30.16	30.16	32	32	24.81	24.81	36.08	36.80
Time since sinking	years	108	108	108	108	79	79	108	108
Activities									
Construction	1/year	0.10	0.90	0.10	0.90	0.10	0.90	0.10	0.90
Diving	1/year	0.00	0.00	25.00	25.00	0.00	0.00	25.00	25.00
Military activity	1/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shipping traffic	1/year	173	173	155	155	7299	7299	89	87
Illegal salvaging	1/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storms	1/year	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Trawling	1/year	0.00	0.00	0.14	0.14	0.52	0.52	1.95	1.95
Substances									
Estimated UXO related TNT and propulsion charges	kg	1940	2926	1445	3373	1632	1933	1023	1172

presented about the quantities of remaining munitions and the explosives contained therein are estimates. An example for this imprecise variable is the often ambiguous character of the actual munition budget of the researched ships. Furthermore, are the combat situations not always traceable meticulously and thus, the consumption of munition cannot always be clearly determined. The actual rates of fire of the guns, their supply with munition or the failure of the same in a combat situation is often difficult to reconstruct.

The data about the standard armament of the ships, as mentioned in this article, is based on specialist secondary literature and original documents from military and other archives. However, the named variables partly lead to a certain generalisation of the information on the armament of the ships as well as the ratios of e.g. explosive charge and propellant within the projectiles. In order to make this transparent and comprehensible, the bases of the estimates are clearly marked in each case.

As standard explosive, the German Navy used from 1906 until approx. mid of WWI the so-called “Füllpulver – Fp/02” based on Trinitrotoluene (TNT). Later also mixtures of explosives and additives occurred. In addition, propellants such as nitrocellulose, cordit and others, with different chemical compositions were used [18–20]. The estimates presented here distinguish between explosives and propellants in general, but do not differ between different types of explosives or explosive mixtures. However, since SMS MAINZ, SMS ARIADNE and SMS HELA sunk already in the first year of WWI, we expect the ships to have only TNT as explosive on board.

2.2.1 | SMS MAINZ

By conducting research in the Federal Archive, Military Archive Freiburg im Breisgau (BArch-MA) and other scientific literature a detailed ship biography was compiled for the SMS MAINZ (Figure 2). The ship, a light cruiser of the Kolberg-class, was assigned to the IV. Torpedo Boat Flotilla on August 1914 and was part of the

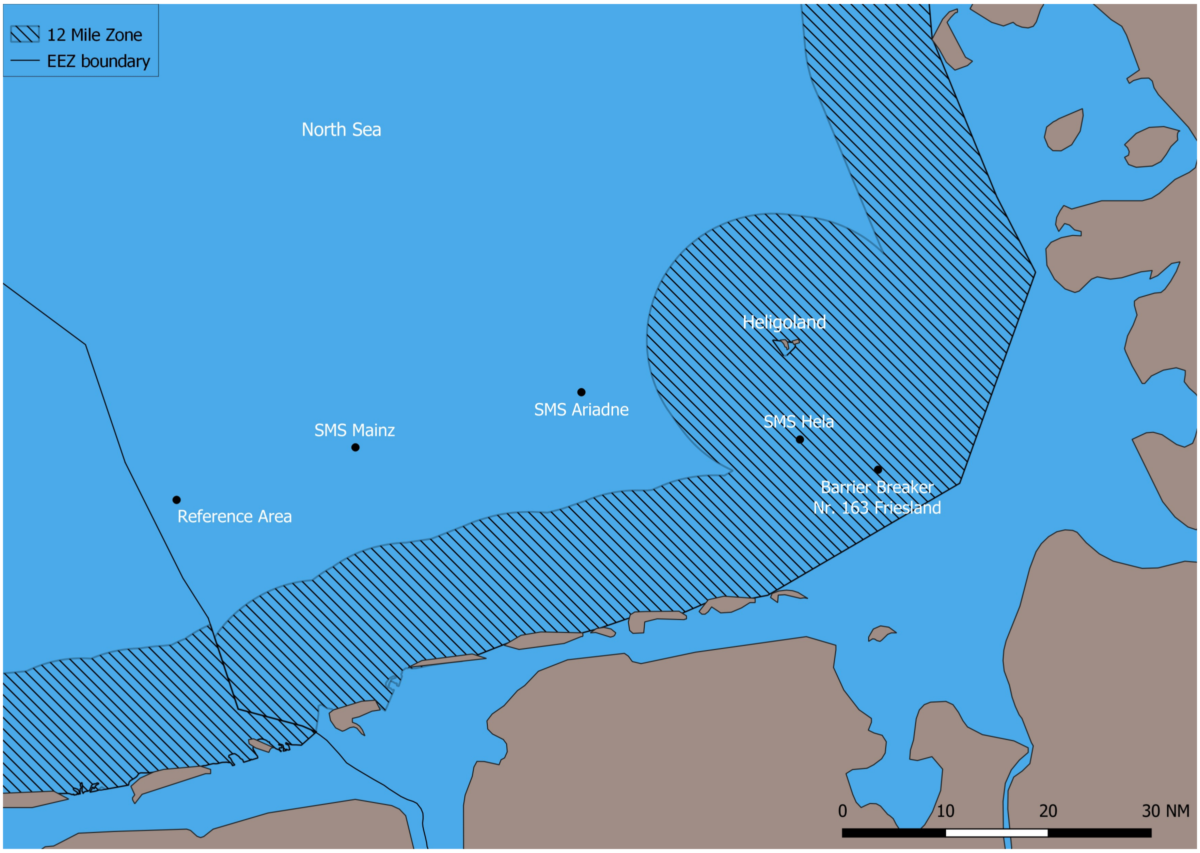

FIGURE 1 Map of the German Bight including the positions of the researched wrecks and reference area. Data Source: BSH, Natural Earth, Flanders Marine Institute (2019). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11 and Maritime Boundaries Geodatabase: Territorial Seas (12NM), version 3. Available online at http://www.marineregions.org/. https://doi.org/10.14284/386 and https://doi.org/10.14284/387.

protection forces of the German Bight in the first weeks of the First World War [21].

The SMS MAINZ had a displacement of 4.889 tonnes, an overall length of 130.55 m, a breadth of 14 m and a maximum side-height of 8.1 m [22]. The ship had a maximum speed of ≈26 knots and was able to carry max. 970 t of coal to fire 15 water-tube boilers. The crew of the SMS MAINZ consisted of 383 people including 18 officers.

The armament of the MAINZ consisted of twelve Quick-Loading (QL) guns, six on the portside and six on the starboard side, with a calibre (cal.) of 10.5 cm. Furthermore, the ship was equipped with two torpedo tubes cal. 45 cm in the fore ship, including five torpedoes (type C/06) and two machine guns cal. 8 mm with ≈6.200[1] to 10.000 rounds each [22, 23]. The munition budget for the QL guns cal. 10.5 cm consisted of ≈2.000 rounds.[2]

The SMS MAINZ took part at the Battle of Heligoland Bight and stood in a single fight southwest from the main fighting area with British light cruisers and destroyers on August 28th 1914 from 12:30 p.m. until ≈1:35 p.m. Thereby the ship received many heavy artillery hits as well as at least one torpedo hit at midship portside. The damages were as hard, that the order was given to abandon the ship as well as to open the sea valves. After the fighting stopped the British ships saved many German sailors. Especially the Destroyer HMS LURCHER is to be mentioned here, as this ship moored beside the stern of the sinking MAINZ and saved many crewmembers. At 02:10 p.m. the MAINZ sank over portside; 89 men of the 383-man crew died. The SMS MAINZ was sunk along with the German light cruisers SMS ARIADNE, SMS COELN and Torpedo Boat

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[1] According to a source about the munition budget from April 22nd 1913 »Nachweisung zur Abänderung des Munitions-Etats«, available in BArch-MA signature RM 92/2994, in total 12.400 rounds of cal. 8 mm munition for both guns were available on board.

[2] Relating to explosive grenades. The sources and literature differ in a precise quantity; values range from ca. 1.800 to ca. 2.200. The number 2.000 is therefore assumed as average, see: [22–24] and source about munition budget from April 22nd 1913 »Nachweisung zur Abänderung des Munitions-Etats«, available in BArch-MA signature RM 92/2994.

FIGURE 2 Photo of the SMS MAINZ from portside abeam, dating from the year 1912 (Photo archive German Maritime Museum).

V187 during the Battle of Heligoland Bight. This battle was the first direct confrontation between the British Royal Navy and the German Imperial Navy during the First World War [25].

At the time of the ship's sinking 300–720 rounds for the QL guns cal. 10.5 cm, two Torpedoes and an unknown amount of cal. 8 mm munition may have remained onboard. In addition, the estimate of rounds is based on an average rate of fire for the cal. 10.5 QL guns of 6–8 rounds per minute. Therefore, the remaining munition could include ≈1.5–3.4 t of explosives and propellant charges. The quantity of explosives and propellant charges within the munition for guns cal. 10.5 cm (refer to QL gun L/45 C/06 and C/11) was ≈4.0–4.34 kg per single round and for the torpedoes of type C/06 it was 122.6 kg per torpedo warhead [26]. The cal. 8 mm munition is excluded from the estimate due to the very small amount of propellant charges contained. The ship was also capable of carrying and laying mines, although these weapons were most likely not part of the standard armament and probably not on board during the time of sinking.

The extensive archive material and literature on the fate of the SMS MAINZ allows some rough estimations regarding the preserved amount of munition on the wreck. However, the mentioned assumption of the preserved munition is only valid if the ship participated in the battle with an assumed maximum number of, according to the traceable fighting situation, usable guns. This assumption is of course idealised as we do not know exactly how many of the guns fired, when exactly, with which frequency, when did they failed etc. Therefore, the real consumption of munition during the fight will be very likely less than the mentioned amount of preserved munition suggests, but this is not provable due to the lack of sources.

The Battle of Heligoland Bight as well as the individual fights between the ships during that day are described in detail in the first volume of the series "Der Krieg zur See. 1914–1918", which was published by the German Naval Archive in 1920 [27]. Further sources on this battle, such as the war diary, battle reports and eyewitness reports but also construction plans as well as reports about shipyard repairs etc. are available at the BArch-MA.

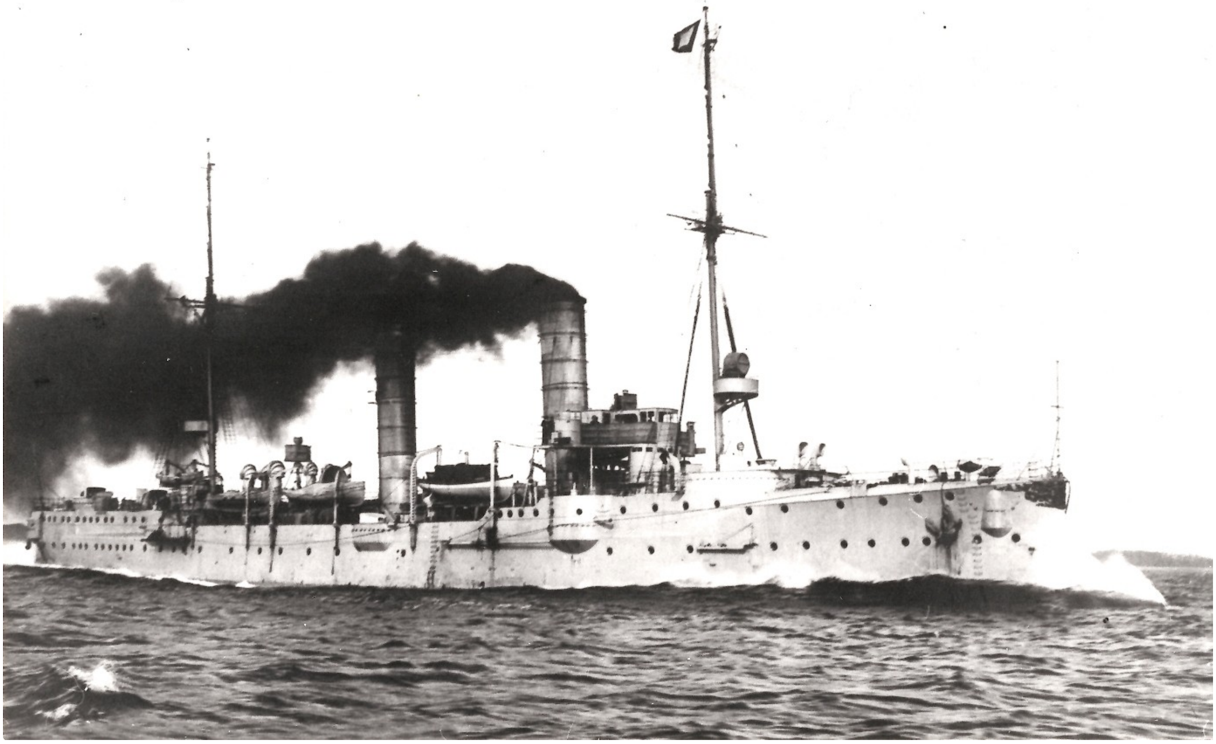

FIGURE 3 Photo of the SMS ARIADNE starboard forward, dating from the year 1905 (Photo archive German Maritime Museum).

2.2.2 | SMS ARIADNE

SMS ARIADNE was a light cruiser of the Gazelle-class, built in 1899/1900 at "A.G. Weser" in Bremen (Figure 3). The ship had a displacement of 3.006 t, a length of 105 m, a width of 12.20 m, a height of 07.12–07.50 m and a max. draught of 05.50 m; it could carry ≈560 t of coal as fuel. The armament of the ship consisted of ten QL guns, five on the portside and five on the starboard side, with a cal. of 10.5 cm. Furthermore, the ship had two torpedo tubes cal. 45 cm in the fore ship, including five torpedoes (type C/03 or C/06) and two machine guns cal. 8 mm with ≈10.000 rounds each.[3] The munition budget of the QL guns cal. 10.5 cm consisted of ≈1.000 rounds [28, 24].

The ship was badly damaged in the Battle of Heligoland Bight on August 28th 1914 by British battle cruisers and could not be saved. After the fighting stopped the light cruiser SMS DANZIG started, around 03:00 p.m., to take over crewmembers from the ARIADNE. At 04:25 p.m., during a towing attempt, the ARIADNE started to overlay and finally sank keel up; 64 men of the 279-man crew died. The SMS ARIADNE seems to stand in battle from ≈02:00 p.m. to 02:30 p.m.

At the time of the ship's sinking and based on an average rate of fire for the cal. 10.5 QL guns of 6 rounds per minute, up to 100 rounds for the QL guns cal. 10.5 cm, five Torpedoes and an unknown amount of cal. 8 mm amunition seems to be remained. Therefore, this munition could include ≈1.0–1.2 t of explosives and propellant charges. The quantity of explosives and propellant charges within the munition for guns cal. 10.5 cm (refer to QL gun L/40 C/97) was ≈4.1 kg per single round, another source mention ≈4.34 kg, and for the torpedoes of type C/03 or C/06 it was 122.6 kg or 147.5 kg per torpedo warhead [26]. The cal. 8 mm munition is excluded from the estimations due to the very small amount of propellant charges contained.

The Battle of Heligoland Bight as well as the individual fights between the ships during that day are described in detail in Marinearchiv 1920 [27]. Further sources on this battle, such as the war diary, battle reports and also construction plans etc. are available at the BArch-MA. The extensive archive material and literature

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[3] For more information's about German torpedoes during that time, see [29].

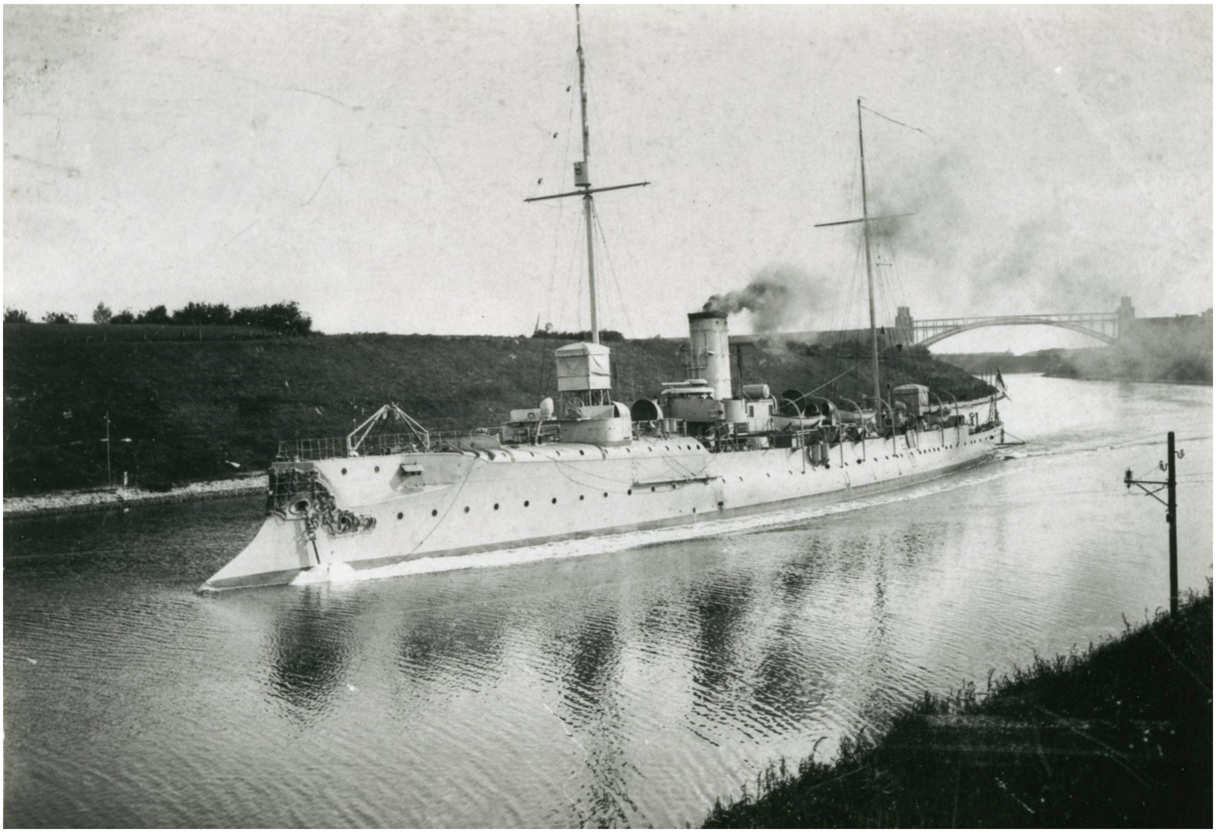

FIGURE 4 Photo of the SMS HELA starboard forward before final conversion (Photo archive German Maritime Museum).

on the fate of the SMS ARIANDE allows some rough estimations regarding the preserved amount of munition on the wreck. Like for the SMS MAINZ this assumption is of course idealised as we do not know exactly how many of the guns fired, when exactly, with which frequency, when did they failed etc. Therefore, the real consumption of munition during the fight will be very likely less than the mentioned amount of preserved munition suggests, but this is not provable using the described sources.

2.2.3 | SMS HELA

SMS HELA was an AVISO, built in 1893/94 at "A.G. Weser" in Bremen (Figure 4). After several conversions, the ship had its final conversion in 1914 and was used as a light cruiser. The ship had a displacement of ≈2.017–2.082 t, a length of 105 m, a width of 11 m, a height of 06.40 m and a draught of 04.64 m; it could carry ≈412 t of coal as fuel. The armament consisted of three QL guns cal. 8.8 cm, two at the fore deck and one in the aft, and four QL guns cal. 5 cm, two in the bow area and two midship. Originally, four QL guns cal. 8.8 cm and six QL guns cal. 5 cm were installed but during the conversions until 1910 two QL guns cal. 8.8 cm were removed [21, 30] only to reinstall a third QL gun cal. 8.8 cm again in August 1914 in the aft. Interestingly some original construction plans (youngest dates to July 1914) show four to five QL guns cal. 5 cm instead of six.[4] Furthermore, a contemporary drawing also shows only four of these guns [30]. For this reason, only four guns of this type are listed here. Additionally, the ship possessed three torpedo tubes cal. 45 cm, two in fore ship and one in the bow, including eight torpedoes (type C/03 or C/06) as well as two machine guns cal. 8 mm with ≈10.000 rounds each. The munition budget for three QL guns cal. 8.8 cm was ≈468 rounds and for the four QL guns cal. 5 cm was ≈524–1.000 rounds [30, 24].

The SMS HELA was on alert and at September 13th 1914 on the way to "Schillig Reede" north off Wilhelmshaven to be relieved by SMS FRAUENLOB. However, the HELA sank that day south off Heligoland after a Torpedo attack from the British submarine HMS E 9. During this event two men of the 195-man crew died.

As no target-orientated fire at the British submarine nor backfire from the HELA in general is mentioned, it

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[4] Construction plans available in BArch-MA signature RM 3/12382, RM 3/12377 and RM 3/12380.

seems that at the time of the ship's sinking approx. all munition was still on board. Therefore, this munition could include ≈1.9–2.9 t of explosives and propellant charges. The quantity of explosives and propellant charges within the munition for guns cal. 8.8 cm (refer to Torpedo boat Canon L/30 C/08) was ≈1.57 kg, another source mention ≈2.81 kg, and for guns cal. 5 cm (refer to QL gun L/40) ≈0.43 kg per single round. For the torpedoes of type C/03 or C/06 it was 122.6 kg or 147.5 kg per torpedo warhead [26]. The cal. 8 mm munition is excluded from the estimate due to the very small amount propellant charges contained. Further sources about the ship such as the war diary, the sinking report and construction plans etc. are available at the BArch-MA. This extensive archive material and literature on the fate of the SMS HELA allows some rough estimations regarding the preserved amount of munition on the wreck.

2.2.4 | Barrier breaker Nr. 163 FRIESLAND

The Barrier Breaker Nr. 163 FRIESLAND was originally built as SS WELLPARK at "George Brown & Co." in Greenock (Scotland) in 1904. It had a displacement of 1.029 gross registered tons (GRT), a length of ≈70 m, a width of 09.49 m, a height of 04.72 m and a draught of 04.65 m; the ship used coal as fuel. It served until 1941 as cargo ship for various owners and was renamed several times; after 1929 as FRIESLAND [32]. In 1941, the FRIESLAND was accused of carrying so-called banned ware ("Bannware") and was taken over by the German Navy ("Kriegsmarine"). Afterwards the ship was modified as barrier breaker and commissioned as Nr. 163 FRIESLAND to the 1st Barrier Breaker Flotilla on September 25th 1941. The armament of the ship consisted of one QL gun cal. 7.5 or 8.8 cm, including 260 rounds.[5] The number of rounds for QL guns cal. 8.8 cm refers to the standard armament of small barrier breakers (500–900 GRT) during the Second World War [31]. Furthermore, one QL gun cal. 3.7 cm, including 2.000 rounds and two anti-aircraft guns (FLAK), including ≈2.000 rounds each, were installed. The ship was also equipped with a "VES-System" ("Vorwärts-Eigenschutz-Anlage" = forward self-protection system) consisting of magnetic coils in the fore ship to clear up magnetic mines. Additionally, an "Otter-System", a "Detonation device" (KKG = "Knallkörpergerät") and a "Sound Buoy Turbine" (GBT = "Geräuschboje Turbine") were probably part of the mine clearing equipment [31, 32]. The Otter System and the KKG usually worked with small charges. Since no further information is available on this for now, these charges are not included in the estimate.

On March 19th 1944 the ship was part of a mine clearing operation together with barrier breaker Nr. 176 VALERIA and Nr. 167 MALMEDY as well as "Flakjäger" Nr. 22. At 08:05 p.m. a mine hit the FRIESLAND. Several towing attempts conducted by the other ships failed because of the bad weather conditions. In the night between 00:20 and 00:40 a.m. the ship finally sank and 44 men of the ≈80-man crew died.

The use of the armament is not mentioned in the contemporary sources, neither the salvage of munition during the sinking. Therefore, it seems that at the time of the ship's sinking approx. all munition was still on board. Therefore, this munition could include ≈1.6–1.9 t of explosives and propellant charges. Due to the unknown number of rounds for the possible 7.5 cm QL gun, this munition will be excluded here. The quantity of explosives and propellant charges within the munition for guns cal. 8.8 cm (refer to QL gun C/30) is ≈2.54–3.62 kg per single round. For guns cal. 3.7 cm (refer to QL gun C/30) it is 0.391–0.395 kg per single round and for FLAK cal. 2 cm (refer to Flak/38) it is 0.0472–0.0505 kg per single round [33]. Further sources about the ship such as the war diary and the sinking report are available at the BArch-MA. This archive material and literature on the fate of the FRIESLAND allows some rough estimations regarding the preserved amount of munition on the wreck.

2.3 | Wreck descriptions

As the NSW project is a pioneer project for its topic and not a monitoring project to search for new nor to identify previously unknown military wrecks, we had to focus on already identified wrecks for the researches. The four examples presented here have already been identified and could therefore be sampled within the project. Descriptions about former researches and evaluations of the wrecks can be found for example in wreck reports compiled by the BSH. These reports form an important basis of the wreck biographies as well as for the planning for the investigations carried out in the project. In the following, the wreck sites are briefly described on the basis of the BSH-data and the data obtained during the research cruises in the project by using e.g., an autonomous underwater vehicle (AUV) and a remotely operated vehicle (ROV).

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[5] Contemporary sinking report speak of a cal. 8.8 cm gun on the foredeck. See "Bericht über Untergang von Sperrbrecher 163 am 20.03.1944." in „Kriegstagebuch der 1. Sperrbrecherflottille. 16.-31. März 1944", available in BArch-MA signature RM 71/74.

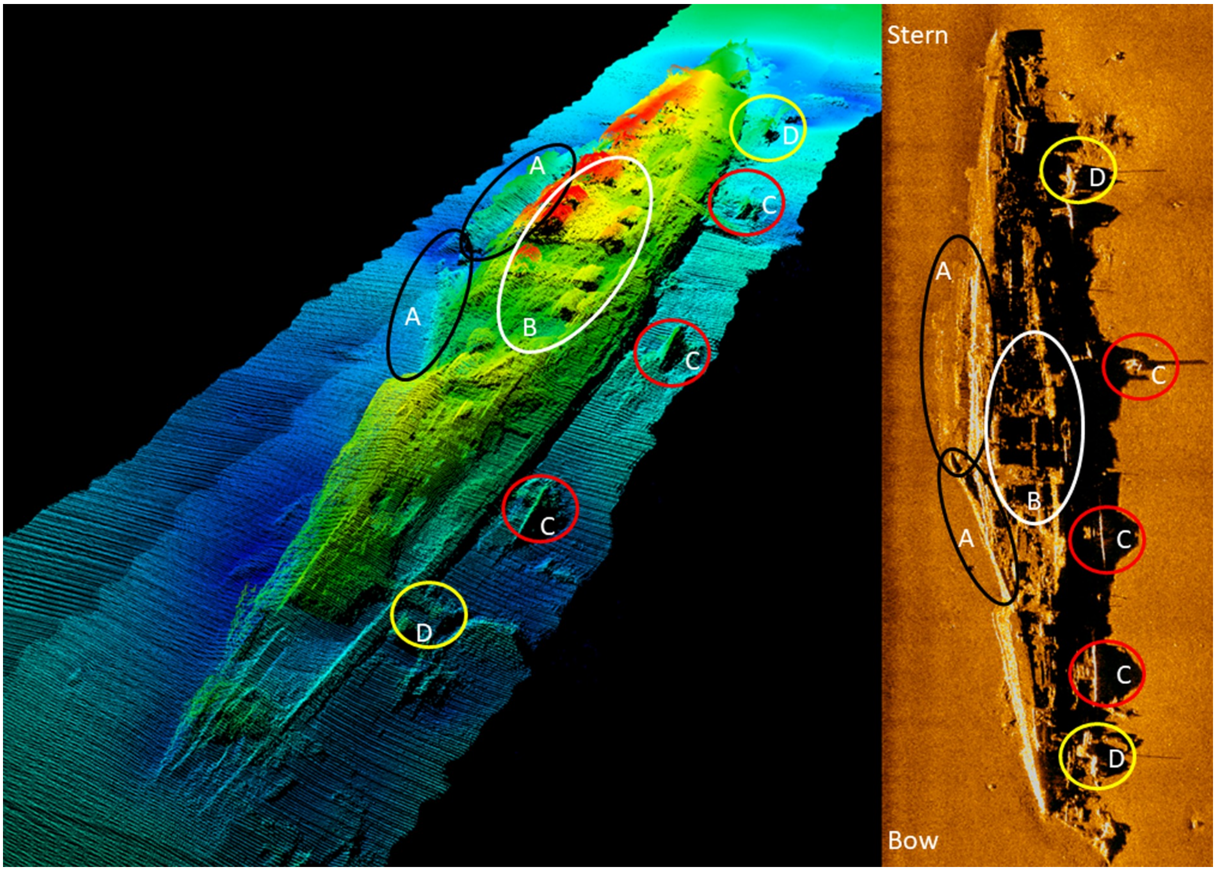

FIGURE 5 3D animation of AUV multibeam echosounder (left), and 2D animation of AUV side scan sonar (right), from the wreck site of the SMS MAINZ. Black circle (A) = collapsed hull areas starboard, white circle (B) = boiler room area with steam collectors, red circle (C) = remains of QL guns, yellow circle (D) = unidentified objects (probably QL gun remains). (Scans provided by DLR).

2.3.1 | Wreck of SMS MAINZ

The wreck is situated ≈25 nautical miles (nm) north off the island of Borkum and ≈40 nm west-southwest off Heligoland in nearly 30 m depth. (see Figure 1) It lies on keel, is slightly inclined to the portside and, with the exception of some smaller protruding parts, preserved up to the level of the former armoured deck. The wreck is preserved over a length of about 114 m. However, the entire bow area is badly damaged and only preserved up to the level of the front chain locker. Therefore, ≈16 m of the total length of ≈130 m are missing in the bow area. The width of the wreck is 14 m and it protrudes from the surrounding sediment to a height of ≈5 m.

Some massive objects lie in the immediate vicinity on portside (Figure 5). The bow is completely damaged, whereas the stern is well preserved. On the starboard side of the ship, a huge part of the preserved hull has collapsed over a large area. In the central area, with the former boiler rooms, some steam collectors of the former boilers are preserved. Furthermore, many small parts such as pipes, sleeves, hand wheels and cables can be found here. A similar situation is observable in the area of the former engine rooms. Many arm-thick pipes with flanges and sockets are preserved here, as well as some larger parts that may belong to the former turbines or condensers. The massive objects on portside are some of the QL guns cal. 10.5 cm that have fallen off or broken out from the wreck. Remains of the former munition hoists in the fore ship and aft are clearly visible in the ROV data. Blasting or salvage actions on the wreck are not assignable in the wreck biography so far. The munition chambers and the torpedo room seem to be preserved beneath the partly collapsed armoured deck.

Unfortunately, it was not possible to carry out a detailed inspection of these areas and the probably preserved munition using the ROV.

2.3.2 | The wreck of SMS ARIADNE

The wreck is situated ≈23 nm north-northeast off the island of Norderney and ≈20 nm west-southwest off Heligoland in nearly 37 m depth (see Figure 1). It lies keel

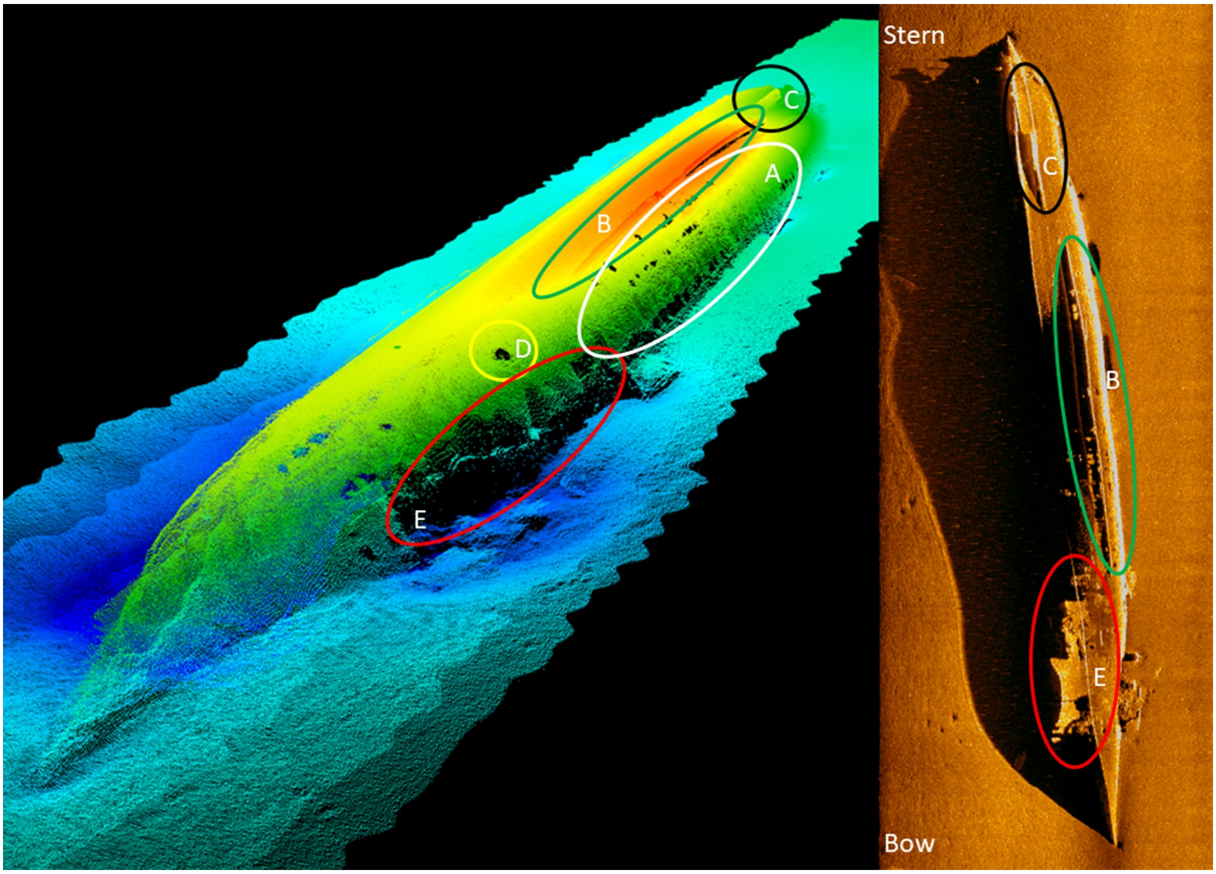

FIGURE 6 3D animation of AUV multibeam echosounder (left) and 2D animation of AUV side scan sonar (right) from the wreck site of the SMS ARIADNE. White circle (A) = perforated hull, green circle (B) = gulper keel on starboard, black circle (C) = propeller shaft, shaft block and shaft hose on starboard, yellow circle (D) = double tube with open hatch, red circle (E) = large hole in the hull (in Side Scan image the hole is visible in the scan shadow). (Scans provided by DLR).

up on the ground and is slightly inclined to portside. The wreck is preserved in total length of 105 m and a width of 12 m. It protrudes from the surrounding sediment to a height of about 4 m. The stern and the bow with the prow are clearly visible. The hull is well preserved, but perforated in some places. Whether this is natural rust or artificial intervention or both is not clear yet. Both the keel and the starboard gulper keel are completely visible. The propeller shaft, shaft block and shaft hose on starboard are preserved as well. The propeller shaft on portside is also visible but slightly snapped off. The shaft block and shaft hose on portside also seem to be preserved, but do not protrude as far as on starboard; both propellers are missing. In the fore ship area, a double tube with an open hatch can be seen on the starboard. This appears to be the open starboard torpedo tube. Furthermore, in the fore ship area on starboard, a large hole in the hull with a scour in front of it can be seen. The view through this hole shows various small parts, chains and not yet clearly identified objects. On the opposite side, there seems to be a smaller hole as well.

Remains of the superstructure and armament of the ship cannot be identified (Figure 6). However, this is not surprising, as the ship lies keel-up. Before the 1970s, blasting actions appears to have been carried out on the wreck. For example, the propellers were blown off.

So far, it can be said that the hull seems to be quite good preserved. That could mean on one side that the preserved munition inside could be relatively sealed off from outside influences. Although the big hole in the fore ship and the small holes in the hull may allow, on the other side, a good water flow through the whole wreck, which maybe affect the stability of the munition casings; further research is necessary here.

2.3.3 | The wreck of the SMS HELA

The wreck is situated ≈15 nm north off the island Wangerooge and ≈9 nm south-southeast off Heligoland in nearly 35 m depth (see Figure 1). It lies on keel and is slightly inclined to starboard. The wreck seems to be preserved in total length of 105 m and a width of 11 m. It

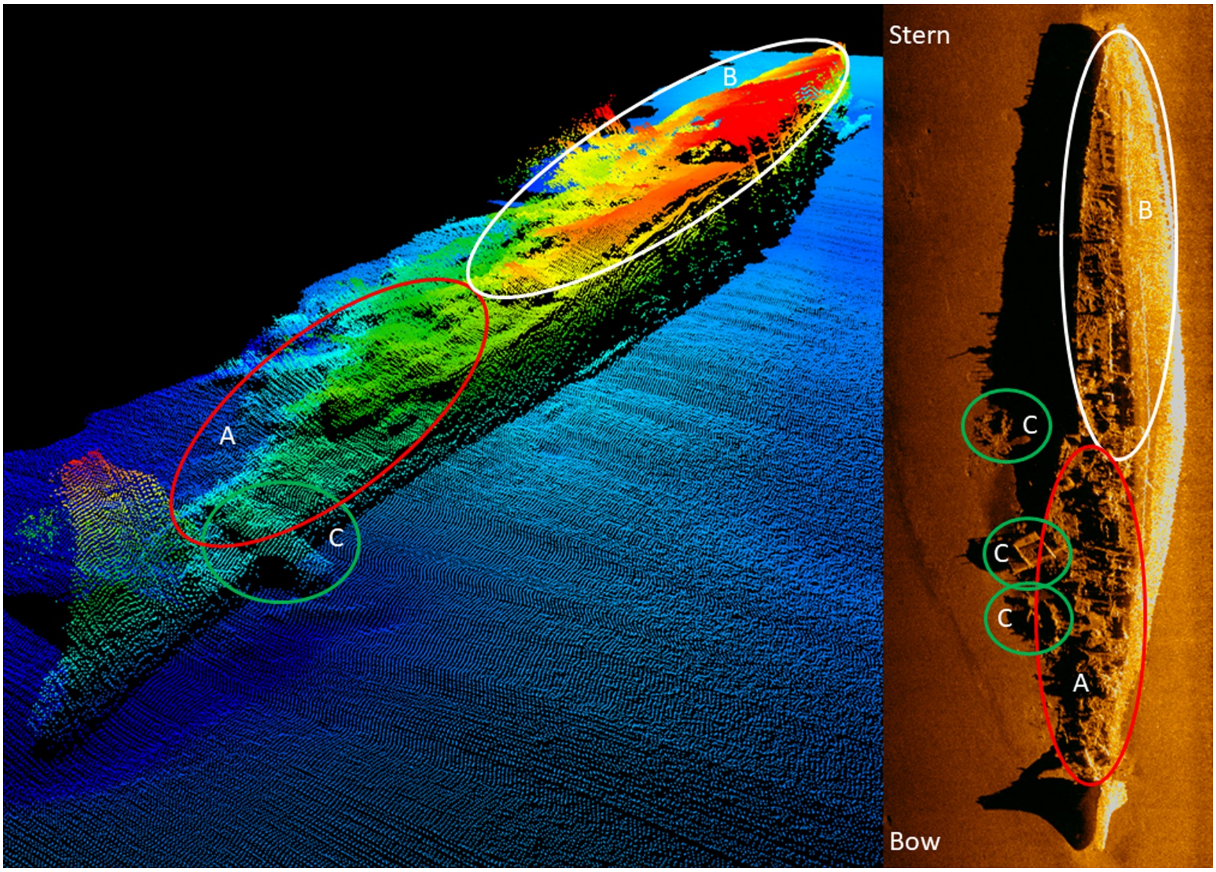

FIGURE 7 3D animation of AUV multibeam echosounder (left) and 2D animation of AUV side scan sonar (right) from the wreck site of the SMS HELA. Red circle (A) = damaged fore ship area, white circle (B) = well preserved midship area and aft, green circle (C) = unidentified objects. (Scans provided by DLR).

protrudes to a height of ≈7 m at the bow and ≈5 m in the aft from the surrounding sediment. Bow and prow are well preserved, but the fore ship is completely damaged. It seems that the entire fore ship area up to the level of the former waterline and up to the area of the former bridge is affected by this destruction. In this area the ship's front munition chamber was situated, as well as the torpedo rooms. The midship area, aft and stern are relatively well preserved. In the stern area, the wreck seems to be preserved possibly up to the level of the former upper deck. The stern itself seem also intact and raised slightly from the sea bottom. Because of this, the portside propeller shaft is visible. The state of preservation of the starboard propeller shaft is not clear. This also applies to the unclear presence of the propellers in general. In the destroyed fore ship area, many larger and smaller fallen objects, which are not identified yet, can be seen.

Regrettably, it was not possible to take underwater images with the ROV from the HELA, as the visibility at the wreck site was very poor. In addition, no clearly identifiable parts of the former armament are visible or be at least recognisable (Figure 7). Clearance or salvage actions on the wreck are not assignable in the wreck biography so far. However, as especially the fore ship area is conspicuously damaged, blasting actions were probably carried out here in the past. Eyewitnesses of the sinking on the other hand mentioned that it looks like the fore ship would break apart but then sunk very quickly while the aft section was already under water.[6] This could be also a reason for the destruction in the fore ship area. Although no evidences for a break can be seen in the scan-data so far.

Therefore, further investigations have to be carried out in that matter. No conclusions about possible preserved munition within the munition chamber and the torpedo rooms in the fore ship can be made for now. Since the extent of the damage in the fore ship is not completely comprehensible, the munition chamber and torpedo rooms could be either still partly intact or completely destroyed. In contrast, the munition chamber in

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[6] Sinking report available in BArch-MA signature RM 92/2640.

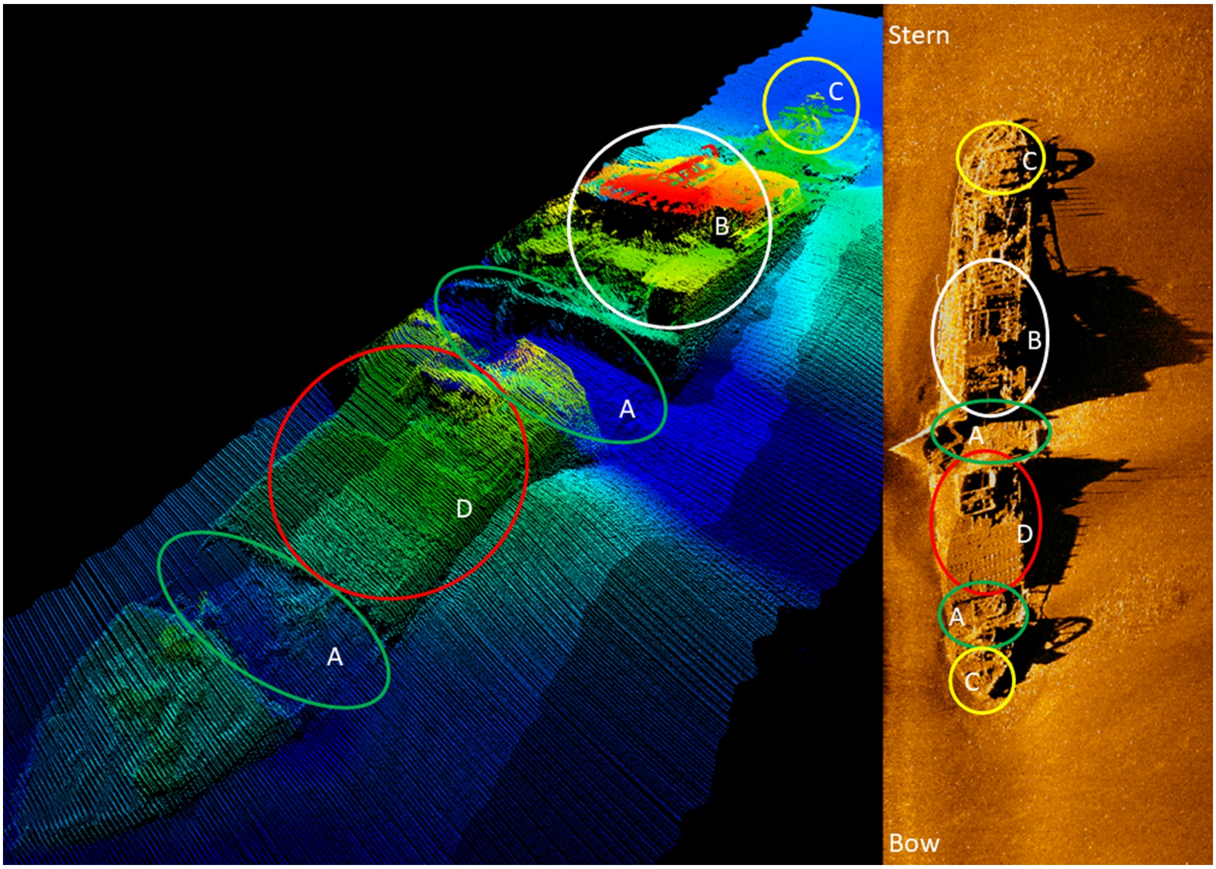

FIGURE 8 3D animation of AUV multibeam echosounder (left) and 2D animation of AUV side scan sonar (right) from the wreck site of the FRIESLAND. Green circle (A) = gaps near forecastle and before bridge area, white circle (B) = protruding bridge area midship, yellow circle (C) = gun platforms bow and stern, red circle (D) = large cargo hatch and remains of "VES System". (Scans provided by DLR).

the aft is probably intact as the wreck is quite well preserved in that area.

2.3.4 | The wreck of the Barrier Breaker Nr. 163 FRIESLAND

The wreck is situated ≈11 nm west-northwest off the island of Scharhoern and ≈14 nm southeast off Heligoland in nearly 25 m depth (see Figure 1). It lies on keel and has a large gap in front of the area of the former bridge (Figure 8). Still the wreck is preserved almost in total length of 70 m and a width of 9 m. It protrudes from the surrounding sediment to a height of about 5 m, mainly in the former bridge area. A slightly smaller gap can be seen in the fore ship area directly in front of the former forecastle. In general, the fore ship, including the bow, and the aft, including the stern, are in good condition. The area of the former bridge is clearly visible with the deck superstructures and protrudes the furthest. In the bow area, the remains of a gun platform are clearly visible.

The same applies to the gun platform in the stern area. In the fore ship, directly in front of what could be a large cargo hatch, the construction remains of the "VES System" are visible. Larger sedimentations can only be seen on the portside area of the wreck next to the fore ship and the aft. Regrettably, due to time reasons and bad visibility, it was not possible to take underwater images with the ROV from the FRIESLAND.

In the 1970s, some blasting actions appears to have been carried out on the wreck. For example, a third gun platform in the midship area was blasted off as it protrudes too much from the wreck. The large central gap could be a result due to this blasting actions. However, this is not clear from the former wreck reports. Furthermore, the gun platforms in the bow and stern area are still visible but it is not clear if the guns are also preserved. Although the wreck is generally quite intact it shows large destruction evidences (two gaps) and further damages at the deck as well as in the bridge area and at the gun platforms. However, munition could be still preserved near or beneath the gun platforms and/or below the remaining parts of the deck. Furthermore, remaining mines, which caused the loss of the FRIESLAND could also be preserved in the area.

2.4 | Wreck investigations

2.4.1 | Sampling campaign

As explained above the estimation of remaining munition amounts on the wrecks based on historical data and/or visible inspections are not easy to conduct and remain often inaccurate. As an indirect measure and a proof for the existence of munition on the wreck, water, sediments and biota living on or around can be analysed for the presence of explosives. If munition is still present on the wreck and corroded, so that leakage takes place, traces of munition compounds will most probably be measurable in the surrounding waters or sediments of the wreck. In contrast, if no traces of explosives are found, munition remains on the wreck are either low or still encapsulated by intact shells. All these results are incorporated in the subsequent risk analysis.

To trace explosives, water samples are collected in lee of the current, at stern, midships and bow. Water samples are taken at seafloor level, as well as at 5 and 10 m above ground using a water sampling rosette equipped with hydrographic sensors. Per depth 2 times one litre of sampled water is extracted over solid phase extraction (SPE) columns immediately after collection.

Subsequently sediment samples are taken on both sides of the wreck at bow, midship and stern using a standard Van-Veen grabber. From each grabber two sediment samples are taken one from the sediment surface and one from ≈5 cm below. Further, also organisms living on and in the sediment are collected for chemical analysis. Samples and water extracts for chemical analysis are stored at −20 °C until being processed in the laboratory.

Furthermore, non-migrating flatfish (dab, *Limanda limanda*) are fished as close as possible to the wreck sites. Fish of a minimum size of 25 cm are visually inspected regarding the liver colour and dissected for samples of liver and kidney for biomarker assessments. Further, gill, blood, filet and bile samples for chemical analysis are taken directly thereafter. Finally, also otoliths for age determination are sampled and stored separately.

Blue mussels (*Mytilus edulis*) deriving from the island of Sylt, an area free of dumped munition, are transferred and exposed for several weeks in steel cages mounted on remotely operated tripods placed close to the wrecks at bow, midship and stern using the ship's crane. In addition to mussels, also steel cages with passive sampling devices, are mounted at the tripods able to trap chemicals, including dissolved explosives, from the water column via their silicon membrane. During the pilot assessment at the SMS MAINZ, no current meter was added to passive sampler. The passive samplers are only used to accumulate even lowest concentrations, potentially not detectable in pure water samples.

After retrieval, mussels are dissected and samples of the digestive gland, mantle and gills are taken for further chemical and biomarker analysis. Mussel and fish tissue samples for biological analysis are shock frozen in liquid nitrogen and stored at in a dewer containing nitrogen vapour until further processing. Tumours found in fish liver tissue are separated and fixated in a formalin solution for further microscopic analysis.

2.4.2 | Physical inspection

In order to gain an understanding of the current state of the wreck and confirm the historical-archaeological assessment, an autonomous underwater vehicle (AUV) and a remotely operated underwater vehicle (ROV) are used to map, scan and visually inspect the wreck and the surrounding area. The AUV offers the possibility to fly previously planned missions largely autonomously. It is used to obtain sonar data in 2D with a side scan sonar and in 3D with a multibeam echosounder.

Reports from previous investigations of the wreck site, by BSH are examined in order to determine position and orientation of the wreck as exactly as possible. Information on minimum altitude, obstacles protruding from the wreck and overall state are considered when planning AUV missions. Additionally, historic documents about the type of armament and about the sinking process of the ship are taken into account for determining the area of interest.

In order to validate the reports and gain real time situational awareness, first an overview mission for the AUV in a safe depth is planned and executed. The data are processed and analysed on the spot to plan a more detailed while still safe and economical mission to obtain optimum multibeam data resolution. The wreck is scanned in a pattern of perpendicular lines. Their spacing is set according to the desired resolution, opening angle of the multibeam sonar and safe distance to the wreck. For optimum data quality, flying in a constant depth is usually preferred following the sea floor at a fixed altitude.

The data from the AUV's sensors are processed immediately after resurfacing and used as a detailed map for navigation and targeted inspection with a ROV. The ROV is steered via cable. It is carrying a forward-looking imaging sonar (FLS) and a low light camera. The live feed from the FLS is compared to the sonar data from the previous AUV missions for navigation. With its better manoeuvrability compared to the AUV, the ROV allows close inspection of the wrecks via a live video feed and is used to confirm the presence of munition shells on and around the wreck.

2.4.3 | Chemical analysis

Sediment and water samples, membranes of passive sampling devices, as well as tissues of organisms living on or around the wrecks are screened for traces of dissolved explosives and their metabolites.

Sediment and water samples were collected around the wrecks. For sediment samples Van Veen grab sampling was performed. Once on board, the sediments were mixed by hand, stored in a one-litre polyethylene bottle, and frozen at −20 °C. Water samples were collected using a CTD device with water rosette that was lowered as close as possible above the seabed around the wreck. The water was transferred into one-litre polyethylene bottles and frozen at −20 °C on board. All samples were sent to the Institute of Toxicology at Kiel University Medical School (Germany) for chemical analyses of dissolved explosives and their metabolites.

Water and sediment samples are treated according to the method published in Bünning et al. [34]. Mussels and fish filets are lyophilized and processed according to the solid phase extraction mussel method from Bünning et al. [34]. For bile, an adapted workup according to Ek et al. [35] is used, in which 100 mg of bile is incubated with 3600 µ glucuronidase in buffer (pH = 4.8) for 18 h at 37 °C, then extracted over 1 mL SPE columns and eluted with 250 µL acetonitrile.

All samples are analysed for the energetic compounds 1,3-dinitrobenzene (1,3-DNB), 2,4-dinitrotoluene (2,4-DNT), and 2,4,6-trinitrotoluene (TNT), as well as the TNT-metabolites 4-amino-2,6-dinitrotoluene (4-ADNT) and 2-amino-4,6-dinitrotoluene (2-ADNT) by GC-MS/MS in SRM mode. A Thermo Scientific TSQ8000 EVO triple quadrupole mass spectrometer coupled to a TRACE1310 gas chromatograph is used. Sample injection is done on a split/splitless injector for water and sediment samples, and by large volume injection on a PTV injector for biota samples, each on quartz wool liner. The separation is performed on Thermo Scientific TG-5MS amine columns (15 m×0.25 mm×0.25 µm). GC oven temperature programs, SRM transitions, and detection and quantification limits are described in Bünning et al. [34]. Quantification is performed using external calibration curves of the energetic compounds.

2.4.4 | Biological effects of exposed organisms

In the marine environment organisms are exposed to a range of substances, many of which can cause metabolic disorders, an increase in disease prevalence, and may affect even the population by changes in e.g., growth, reproduction, and survival. It is agreed that the effects of hazardous substances are assessed by both, chemical and biological measurements in an integrated manner [36]. Like this, the bioavailability of hazardous substances and their impact on marine organisms or processes can be correlated.

Wrecks and their remaining munition are subject to corrosion over the decades. In case munition remains are not silted up, but are in contact with the surrounding water, it is most likely that shells are not fully intact anymore and that leakage of toxic munition compounds takes place. Like these wrecks may become a significant point source for dissolved explosives. From field investigations and lab experiments it is known that exposed organisms take up explosives from the surrounding water [37, 38]. At the SMS MAINZ the concentrations of explosives and their metabolites were measured in water, passive sampler, sediment and the tissues of fish and mussels. Samples of mussels and fish are analysed for biological effects on different organismal levels using a multi-biomarker approach. Measured effects are correlated with the detected level of explosives in the respective tissue. Furthermore, chemical and biological data from the wreck sites are compared to samples taken at the reference area in order to eliminate local effects unrelated to the wrecks. The reference area is part of natural reserve of Borkum Riffgrund (Figure 1) in the vicinity to the Dutch sea border. Here, no munition dump sites are located and no larger wrecks are mapped. In addition, the site is comparable to the investigated wrecks site in concerning depth and principle hydrographic parameters.

2.4.5 | Data fusion, risk assessment and wreck periodisation

Given the large number of wrecks within a given EEZ, there is a need to perform environmental risk assessments and prioritize them to determine the focus for decision makers. To perform environmental risk assessments, we considered wreck- and site-specific parameters regarding integrity, hydrography and human activities and their interactions to calculate the probability that the wreck would start leaking. In addition, probabilities of leakage were weighed with the potential amount of fuel and/or UXO related harmful substances on board which could be discharged from the wreck.

To make wreck comparable, we consider an idealized and simplified wrecks for which we described the most important parameters that are most likely to induce changes to the wreck integrity. These parameters were subdivided indicators and activities. The indicators constitute: oxygen concentration, salinity, temperature, current velocities, material, hull thickness, seabed character, wreck position on the seabed, water depth and time since sinking. The most important activities around a wreck were identified to be construction, diving, military activity, shipping traffic, illegal salvaging, storms and trawling. All activities are expressed as a frequency per year. Also note that these activities include storm events. Deterioration is also classified as an activity, since its process is affected by the listed indicators.

With the listed indicators and activities, the VRAKA method [39] was used to calculate the probability of an opening in a wreck. In order to apply this method, expert elicitations were conducted with a focus on the North Sea region. The SHELF approach was used [40, 41] to formulate a general probability of our idealized wreck at which it would be damaged because of an activity. Similarly, the experts formulated the interaction between activities and indicators to determine the posterior probability from where Bayesian updating allows to update probability of release for each individual wreck with site specific conditions.

3 | RESULTS AND DISCUSSION

3.1 | Wreck analysis

By deploying an AUV at the four different wrecks, the existing reports of the BSH were confirmed showing intact wrecks, half buried in the sediments, in ≈25–40 m depth with remaining superstructures of several meter height. Overall, the wrecks seem to be in a stable position with no immediate risk of being dislocated or breaking into parts. In the scans produced at the wrecks many details such as bows or sterns, guns and gun towers, machinery fragments, etc. could be clearly identified. The following visual inspection by ROV remained difficult at some wrecks due to the bad visibilities. Only at SMS MAINZ and ARIADNE comparisons between scans, construction plans and ROV images was possible. At SMS HELA and at the Barrier Breaker FRIESLAND, only scans could be used for wrecks description

The analysis of water, sediment, passive sampler and biota samples confirmed the presence of dissolved explosives, in the vicinity of all wreck. Energetic compound concentrations in the sediments ranged from below the limit of detection until the single-digit ng/kg or low two-digit ng/kg range, while water concentrations were detected from below the limit of detection up to the one-digit ng/L range. Thus, making it most likely that the wrecks are the source of the measured dissolved explosives. Calculation about the remaining amount of munition onboard of the wrecks are, however, not possible using these results. Water and sediment concentrations are dependent on the hydrographical regime of the wreck site and sediment quality. Further, no flow measurements were conducted so that values measured in the passive samplers cannot be correlated to any volumes of waters.

In the present study mussel and fish species were investigated regarding their response to the exposure with explosives in the water and sediments. The investigations are still ongoing but macroscopic analysis of fish organs revealed higher numbers of liver diseases in fish caught directly at the wrecks of SMS MAINZ and SMS ARIADNE compared to species caught a reference area at Borkum Riffgrund free of munition remains.

3.2 | Wreck prioritisation

In the table below (Table 1), the indicators and activities for four wrecks, namely: the SMS HELA, the SMS MAINZ, the FRIESLAND and the SMS ARIADNE are given. The adopted ranges used for the wrecks were extracted from a variety of data-sources. The activities, describing the human and events that may affect a wrecks integrity were derived from the EMODNET human activities spatial datasets valid for the individual locations of the Wrecks [42], with exceptions of the activities related to diving and construction. These activities are based on assumptions to indication whether diving and construction takes place at the wreck sites. If this was the case, diving and construction were assigned assumed ranges of 25, and 0.1–0.9 respectively. In addition, a general assumption was made where a significant storm event occurs at a once per 100 years would occur.

Ranges related to the listed indicators were obtained from historical research (wreck properties), observations made by divers and of hydroacoustic imagery (seabed characteristics, wreck position) and statistical indications (5th and 95th percentile) for current speeds, and salinity obtained from numerical simulations provided by the Bundesanstalt für Wasserbau [43]. All wrecks are situated in German Territorial waters and EEZ.

Running the VRAKA simulations yielded probabilities of release of 0.32, 0.41, 0.25 and 0.27 for the SMS HELA, SMS MAINZ, Barrier Breaker FRIESLAND and

TABLE 2 Ranking list of selected wrecks. For each wreck results regarding the probability of release ($P_{release}$) presence of fuel and UXO and the total amount of estimated harmful substances.

–	Name	Prelease	Munition	Fuel coal	Total Substances	Indexed risk
1	SMS MAINZ	0.41	True	Unknown	2409 kg	100
2	SMS HELA	0.32	True	Unknown	2433 kg	79
3	SMS ARIADNE	0.27	True	Unknown	1097.5 kg	30
4	FRIESLAND	0.25	True	Unknown	1782.5 kg	45

SMS ARIADNE, respectively (Table 2). For the SMS HELA, deterioration was found to play a major role resulting in a relatively low probability of release (0.32), without little significant human activities. For the SMS MAINZ, diving and trawling activities play a more significant role (0.41). The Barrier Breaker FRIESLAND is subject to large frequencies of ship traffic and to a certain degree also trawling activities but resulted in a low probability of release (0.25). The SMS ARIADNE is subject to high frequency of possible trawling activities as well as diving activities, increasing the probability of release to around 0.27.

Apart from the probability of release, the amount of harmful substances, either fuel or UXO, would constitute the potential environmental risk. If no harmful substances would be present, no environmental risk would exist. Yet, with increasing quantities the potential release would constitute an elevated risk. The amount of harmful substances on board ranges from an estimated ≈1000–3400 kg. By multiplying the probability or release with the amount of substance allows us to rank the wrecks according to the risk they pose as indicated in Table 2. The Indexed risk is the product of the probability of release and the total amount of harmful substances sorted, relative to the highest value amongst the pool of wrecks. The results imply that the SMS Mainz and SMS HELA would be ranked to be prioritized for possible measures such as monitoring or affirmative actions like mitigation.

3.3 | Wreck exhibition

Another result of the NSW project is a travelling exhibition as a creative and accessible form of science communication. It is intended to raise public awareness of the still rather unknown environmental problem of underwater munitions. The exhibition, called "Toxic Legacies of War", can be seen at several stations since August 2021. It is conceived as a pop-up exhibition that can be shown both outdoors in public spaces and indoors, such as in museums or other institutions.

The exhibition tours all partner countries and aims to increase society's awareness of the problem and encourage a dialogue between stakeholders. The presentation of the content and the design have so far been perceived with interest by visitors, among whom there were many who previously knew little or nothing about the problem. The website of the German Maritime Museum features an online version of the exhibition, additional information and in-depth texts about the work in the project and the investigated wrecks [44] (link: www.nsw.dsm.museum).

3.4 | Wreck assessment

In most European countries wrecks are mapped and actively surveyed. In Germany, the BSH is responsible and conducts the monitoring of wrecks on different time scales according to their estimated risk towards shipping traffic. Other risks, such as environmental hazards posed by the wreck's remaining fuel, armament and/or other dangerous cargo are not recorded systematically.

For this study the research work started by investigating all available historic resources including military archives. However, a ship's biography based on archival sources and scientific literature can only be traced up to the sinking of the ship. Once the ship has become a wreck, its second biography begins. However, a detailed wreck biography is often more difficult to compile than a ship biography, due to often lacking data and information. In case of the SMS MAINZ the first comprehensive dataset of the wreck dates back to the year 1993 [45]. This dataset is presented in a report prepared by the BSH. However, these wreck reports are sometimes incomplete, since e.g. not all clearance or salvage operations are listed. Together, this may influence the amount of munition still preserved on the wreck. Due to these uncertainties, an estimate of the amount of preserved munition must always be accompanied by the phrase "at the time of ship's sinking".

Therefore, a combined consideration of both biographies is crucial. Historical sources like construction plans, contemporary fighting and sinking reports, dockyard reports, munition budgets and further ship biographical details can be found for example in the BArch-MA. Unfortunately, are wreck biographies usually much more incomplete than ship biographies. In order to obtain a maximum number for an estimate about the used munition on the ships – before their loss – it is assumed here that e.g. MAINZ and ARIADNE could participate at the combat situations during the Battle of Heligoland Bight with the maximum number of possible guns according to the battle situation. This assumption is of course idealised and provides therefore a maximum value. To obtain this maximum value the fighting reports of both ships, as described in Marinearchiv 1920 [27], were used. This is why the actual amount of preserved munition on both wrecks may well be higher but not determinable.

3.5 | Corrosion and leakage

Using historical research to gain information about potential munition load on a wreck is an appropriate method for first estimates. However, this method does not work for unidentified wrecks of which numerous examples are on the ground of the global seas. Further, corrosion rates depend on many factors and are hard to predict either. However, corrosion rates decide about the status of the remaining munition on board of a ship. Corrosion processes on munition items of the same type may vary considerably leading to full corrosion and even complete disintegration at one item whereas a comparable munition item at a different place at the wreck is maybe completely intact and still able to explode. In some cases, visual inspections of wrecks will help to determine amount and status of the remaining munitions, however, will also produce uncertainties and will be unusable in many other cases since munition is not visible.

It is therefore necessary to proof the existence of munition indirectly via the analysis of surrounding waters, sediment and organisms living on or nearby the wreck. Using this method at least corroded and leaking munition on board of a wreck can be detected. However, statements about the total amount or the amount of leaking munition are not possible, since measured concentrations of dissolved explosives in the surrounding water of a wreck is dependent on many factors such as distances to the wreck, current velocity, local current situation at the wreck, etc. However, the determination of dissolved explosives is crucial for the risk assessment, since a leaking wreck is of much higher environmental risk, than a non-leaking one. In the present study leakage of explosives was detected at all investigated wrecks. Since for a first risk assessment only a true or false information is needed, the individual concentrations are not marked here, but will be investigated in detail and published in a future publication.

3.6 | Effects on organisms

Former research projects show that organisms such as mussels and fish take up dissolved explosive chemicals and might therefore be a source of contamination for human seafood consumers [46–50]. Detailed studies regarding a potential transfer of energetic compounds into the food chain are urgently needed to ensure marine food safety. Further, the extent to which substances such as TNT significantly impact marine species and ecosystems is of great scientific interest. Despite increasing research, our knowledge about long-term effects of energetic compounds on the environment is still limited and more research is needed. Despite accidents, the effects of industrial and military loads of wrecks in the ocean are difficult to determine because they manifest slowly and often in unpredictable ways. Also, this study revealed correlations between concentrations of dissolved explosive measured in the vicinity of the wrecks to the health of fish caught directly at the wreck sites, compared to those from reference areas being unexposed to dissolved explosives. These findings were supported by the chemical analysis conducted in parallel to the fish sampling. At wreck sites dissolved explosives were detected in the surrounding sea water, in organisms living on the hull of the wrecks and in tissues of fish caught nearby. In contrast, at the reference areas these correlations were not found. Overall, there is evidence that dissolved TNT and metabolites are involved in the health impacts of fish investigated at the wreck sites. However, also these results need to be further elaborated. Once they are verified and published, they will be included in the presented risk model.

Over all, the information about the investigated wrecks is comprehensive and a sufficient basis for the individual risk evaluation of the wreck. In a final step data was fed into the project data base and used for the calculation of the overall risk assessment. Results were compared and finally ranked. The presented prioritization can be a valuable method to prioritize amongst many wrecks to concentrate and distribute the resources available to survey and mitigate these wrecks, when choices must be made. Given that the method is subject to simplifications and assumptions, it does not capture the full complexity of the environmental risk including the toxicity and mobility of individual substances. The risk is therefore to be interpreted as a probability that an estimated amount of potentially hazardous substances could impose a risk to its direct environment. It does however apply the same method to all wrecks and therefore makes them comparable and enables ranking. With a priority made, especially if the pool of wrecks is much larger, this type of ranking would allow a more adequate for decision makers. The method is being connected to wreck databases via the WRECKNS tool, making the available and scalable for practical application.

3.7 | Operational implications

Any consideration of the risks posed by wrecks in the North Sea must account for the limitations of the underlying dataset(s) which impact both the collective assessment of the inventory as well as that of individual wrecks. These are derived from the wreck databases compiled by various national bodies and which are used in the production of hydrographic charts. As such, they are invariably excellent for their primary purpose which is to ensure navigational safety. Individual wrecks, and particularly those in shallower waters are accurately positioned with a good level of detail on their condition, dimensions and orientation with many frequently updated via recurrent surveys. However, a proportion of wrecks are either marked as 'unknown' or have been misidentified and this problem becomes more pronounced where deeper, more remote and less frequently re-surveyed wrecks are concerned. The exact scale of this issue is difficult to quantify although the recent study by McCartney [51] has provided an insight to the significant effort involved in determining the identities of 273 wrecks in the Irish Sea via a process of survey and archival research. The implications for the many thousands of North Sea war wrecks are obvious as accurate identification is fundamental to the subsequent risk assessment process.

When considering war wrecks, it is also important to remember that the term encompasses both purpose-built warships, merchant ships requisitioned for military service and purely merchant wrecks. In the latter case many merchant ships were lost with part or full cargos of munition and so, in terms of quantity of explosives, may present a greater risk than their military counterparts (for example the wreck of the Second World War Liberty ship SS RICHARD MONTGOMERY in the Thames estuary). Even where this is not the case merchant ships during both World Wars were routinely provided with defensive armament with an appropriate, and sometimes significant allocation of munition. While details of the armament allocated to individual merchant ships can often be determined from archival research it is often difficult to ascertain the quantity of munition assigned to them and the details of the storage arrangements. Consequently, even when the identity of a wreck has been confirmed, significant effort may still be required to confirm where munition is likely to be present and in what amounts before sampling and risk assessment can take place.

A further challenge arises from the intermingling of wrecks reflecting the nature of the fighting in both World Wars. In each conflict the North Sea was an active battleground with the ship losses of the various participants widely dispersed without respect to current national boundaries. Consequently, active management of the risks posed by the inventory must take account of the differing positions of the countries bordering the North Sea with regards such fundamental issues as wreck ownership, willingness to share existing survey data, attitudes to war losses and the interplay between environmental/safety concerns and heritage management. In the case of heritage management several, though by no means all of the countries bordering the North Sea are signatories to the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage (Convention on the Protection of the Underwater Cultural Heritage – UNESCO Digital Library). Germany, for example, has not yet ratified the named Convention. Generally, further work on cultural heritage management, especially in Germany, is required as future remedial action to address the problems detailed in this paper might involve the removal of munition from wrecks with intrusive, and potentially destructive work (for example, via the cutting of sections of a wreck to allow access to internal magazines).

Indeed, this particular challenge highlights the shifting attitudes to wrecks and the interplay between different stakeholders. The heritage value of wrecks has long been recognised, encompassing their archaeological significance and in many cases their importance as the last resting place of the sailors lost in their sinking leading to them being afforded protection by a variety of means. Notably the UNESCO convention noted above as well as national measures enacted by individual countries, for example the UK's Protection of Military Remains Act 1986 (Protection of Military Remains Act 1986 (legislation.gov.uk)). Concerns over the environmental and safety risks posed by these self-same wrecks is a more recent phenomenon with initial work in this area focused on addressing the problems posed by the oil remaining on many legacy wrecks (see, for example, Landquist et al., [52]). Similarly, while the potential explosive risk posed by the munition remaining in such wrecks as the SS RICHARD MONTGOMERY has long been acknowledged, the impact of toxic substances leaking from munition contained within wrecks and entering the food chain is a new area of research. Thus, the work of the NSW project is contributing to the increasingly dynamic nature of wreck management and is further highlighting the need to work collaboratively with stakeholders across a range of disciplines to ensure that safety and environmental issues are addressed in a manner sympathetic to the heritage and emotive value of individual wrecks. It is likely that a pragmatic approach to dealing with environmental problems on protected wrecks can be found that minimises disturbance to them and key to this will be an open and honest dialogue between all interest groups to identify workable solutions.

4 | CONCLUSION

The concept elaborated by NSW and presented in this publication is intended to be transferable and as such not only applicable for WW wrecks in the North Sea. In contrast, the measurement and the subsequent risk assessment shall work also in completely different marine regions. Preliminary results of the project being available at the time of writing this publication were used to explain the general approach and to produce a first initial ranking of the four wrecks. However, other investigations, especially the comprehensive chemical analysis of many different matrices from ranging from water samples, over sediment samples up to the analysis of many different fish and mussel tissues are ongoing. Same is true for the biological effect assessment linking the chemical analysis to health impairments detectable in fish and mussels. In a future step these results will be included into the risk assessment may leading to a different ranking of the assessed wrecks. Overall, we believe to provide a valuable tool for research and administration to cope with the many wrecks on the grounds of our seas, since a ranking of wrecks according to its environmental risks clearly identifies starting point for any risk reducing actions.

AUTHOR CONTRIBUTIONS

All authors contributed substantially to the conception and design and to the analysis and interpretation of the presented concept and data. In addition, all authors were involved in drafting, revising and approving the article. Further, all authors agreed to the outcomes presented in the section discussion and outlook. In details the authors were responsible for following sections and paragraphs: S. Bergmann, is coordinator of the “North Sea Wrecks” project, wrote parts of the introduction and the section 1.1. Conceptual frame of “Marine Slow Disasters”. Further, he developed the concept of the travelling exhibition and for science communication via “scrollytelling”. M. Brenner, is coordinator of the research expeditions to the described wrecks, wrote parts of the introduction, section 2.4.1. Sampling campaign and section 2.4.4. Biological effects of exposed organisms. J. S. Strehse, did the coordination of the chemical analysis and is author of section 2.4.3. Chemical analysis. T. H. Bünning, assisted in the coordination and of chemical analysis and co-authored section 2.4.3. Chemical analysis. E. Maser is head of lab of chemical analysis and co-author section 2.4.3. Chemical analysis. P. Grassel is co-curator of the travelling exhibition and responsible for the historical and archive research. He is co-author of section 2.2 Historical research and wrote the section 2.3 Wreck descriptions. D. Heuskin is head of DLR team organising the physical investigations of the wrecks, programming and conducting AUV scans at the wreck site, co-authoring section 2.4.2 Physical inspection. D. Brandt is responsible for programming and the organisation of physical wreck investigations, the production of wreck scans and co-authored the section 2.4.2 Physical inspection. M. Berger is responsible for programming and organisation of physical wreck investigations, the production of wreck scans and he co-authored section 2.4.2 Physical inspection. S. Van der Wulp, is programming and organising the risk assessment, authored the section 2.4.5 Data fusion, risk assessment and wreck prioritisation. M. Skellhorn co-authored of the subsection Operational implications. P. Hill co-authored the subsection Operational implications. S. Van Haelst, is diving operator and diver for sampling at SMS Mainz. M. De Rijcke is diving operator for sampling at SMS Mainz. U. Wichert is responsible for historical and archive research and co-authored section 2.2 Historical research. All authors: section 3 Results and Discussion, and section 4. Conclusions.

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focussing on only one wreck without final ranking was presented in June 2022 at the European Workshop on Maritime Systems Resilience and Security (MARESEC 2022), organized by the German Aerospace Centre – Institute for the Protection of Maritime Infrastructures, at Forum Fischbahnhof, in Bremerhaven, Germany. Based on the presentation a conference proceeding entitled: North Sea Wrecks – An interdisciplinary approach towards understanding the risks posed by wrecks containing munitions in the North Sea was published at Zenodo (https://zenodo.org/record/7149216#.Y4oLE4SZO3A).
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CONFLICT OF INTEREST STATEMENT

I, as the corresponding author, declare on behalf of all the authors of the submission, that there is not any financial interest or personal relationship with other people or organizations that could inappropriately influence this work.

DATA AVAILABILITY STATEMENT

The study presented here is a conceptual work, based on archive information and secondary literature mainly. However, the authors declare that the data supporting the findings of this study are available within the paper or they are available from the corresponding author upon reasonable request.

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