Environmental effects of UXO-clearances

The exploration of the effects of unexploded ordnances for offshore windfarms
Rijkswaterstaat

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1 Introduction

Offshore wind development is an important industry to help the Netherlands meet its European Union CO2 reduction targets and become climate neutral by 2050. Offshore wind energy is expected to achieve a 55% reduction in CO2 emissions by 2030. The 2013 Dutch National Energy Agreement actioned the development of the first offshore wind energy areas in Borssele, Hollandse Kust South and Hollandse Kust North. The Offshore Wind Energy Roadmap released in 2018 further outlines the government's plans for 2024 to 2030 development. Figure 1 presents the roadmap for offshore wind farms areas until 2030 and further development beyond 2030 is required to meet increasing Dutch energy demands.

With the further expansion of offshore wind energy on the Dutch Continental Shelf (DCS), an increase in Unexploded Ordnance (UXO) clearances is expected. UXOs still pose a risk of detonation, even if they were fired or dropped over a century ago. In 2005, several Dutch fishermen lost their lives when a bomb exploded on deck when hauling in their nets (ANP, 2005) and in 2020 a British crabbing vessel was partly destroyed by a bomb on the seabed that was disturbed by their crabbing gear. Therefore, UXOs are considered a significant risk to health and safety on the North Sea. Apart from fishing, this also applies to other commercial activities like dredging and sediment extraction, cable laying, wind farm construction and oil & gas exploration. Hence, it is common practice to conduct an UXO Risk Assessment for sites where industrial development on the North Sea is planned. While the risks that UXO encounters and clearances poses on humans and the offshore industry are well understood. There is a need for thorough exploration to understand the effects of UXO clearances on local wildlife.

Extensive cumulative effect assessments (KEC 4.0) were conducted to evaluate the effects of offshore wind farm construction with regard to pile driving and geophysical surveys (Heinis et al., 2022). The following ecological threshold is set by the Ministry of Agriculture, Nature and Food Quality:

"With the construction of offshore wind farms, the populations of harbour porpoises (*Phocoena phocoena*) on the DCS must be maintained at a minimum of 95% of the present level with a high degree of certainty (>95%) (in other words, the probability of a population reduction of more than 5% may not exceed 5%)."

As the KEC 4.0 is focused on the effects of pile driving and geophysical surveys, the ecological effects of unexploded ordnance (UXO) clearances have not yet been considered. The distribution, extent, and effects of removing the UXOs to allow safe offshore wind development is not well understood. The offshore wind ecological programme (Wozep[1]) requested the support of Arcadis to provide insights into UXO effects in the following ways:

1. Estimate the expected number of UXO's within the borders of future offshore windfarms included in the North sea programme 2022 - 2027, that need to be cleared for the construction of offshore windfarms.
2. Summarize the current procedures and mitigation measures used to clear UXOs.
3. Estimate the sound and environmental effects of clearing UXOs in various conditions.
4. Estimate the ecological effects on the harbour porpoise population in the Dutch North Sea based on the outcome of questions 1 to 3, and express the effects in harbour porpoise disturbance.

Figure 1 shows the designated Wind Farm Zones as presented in the North Sea Programme 2022 – 2027 (Rijkswaterstaat, 2022). Data on UXO clearances is available for the Wind Farm Zones Borssele, Hollandse Kust Zuid, and Gemini (blue areas, Figure 1). Data from these Wind Farm Zones is used in this report to make estimations on UXO presence in Hollandse Kust Noord, Hollandse Kust West, IJmuiden ver, Nederwiek, Doordewind, Lagelander en Ten noorden van de Waddeneilanden. The areas of Hollandse Kust Noord, Hollandse Kust West and part of IJmuiden ver have been subdivided into sites and UXO presence will be estimated for site area only. Hollandse Kust Noord has already been cleared at the time this report was written but no data on the amount of UXOs is available yet so this Wind Farm Zone is included in the estimations. Part of IJmuiden ver, Nederwiek, Doordewind, Lagelander, and Ten noorden van de Waddeneilanden have not been subdiveded in sites yet. Usually the search area (green areas, Figure 1) is vastly bigger than the combination of sites within the search area. Estimations of UXO presence have been adjusted to an expected site surface area within these Wind Farm Zones. An overview of the modelled Wind Farm Zones and corresponding surface area is displayed in Table 1. Offshore Windpark Egmond aan Zee is not regarded in this report.

[1] https://www.noordzeeloket.nl/functies-gebruik/windenergie/ecologie/wind-zee-ecologisch-programma-wozep/

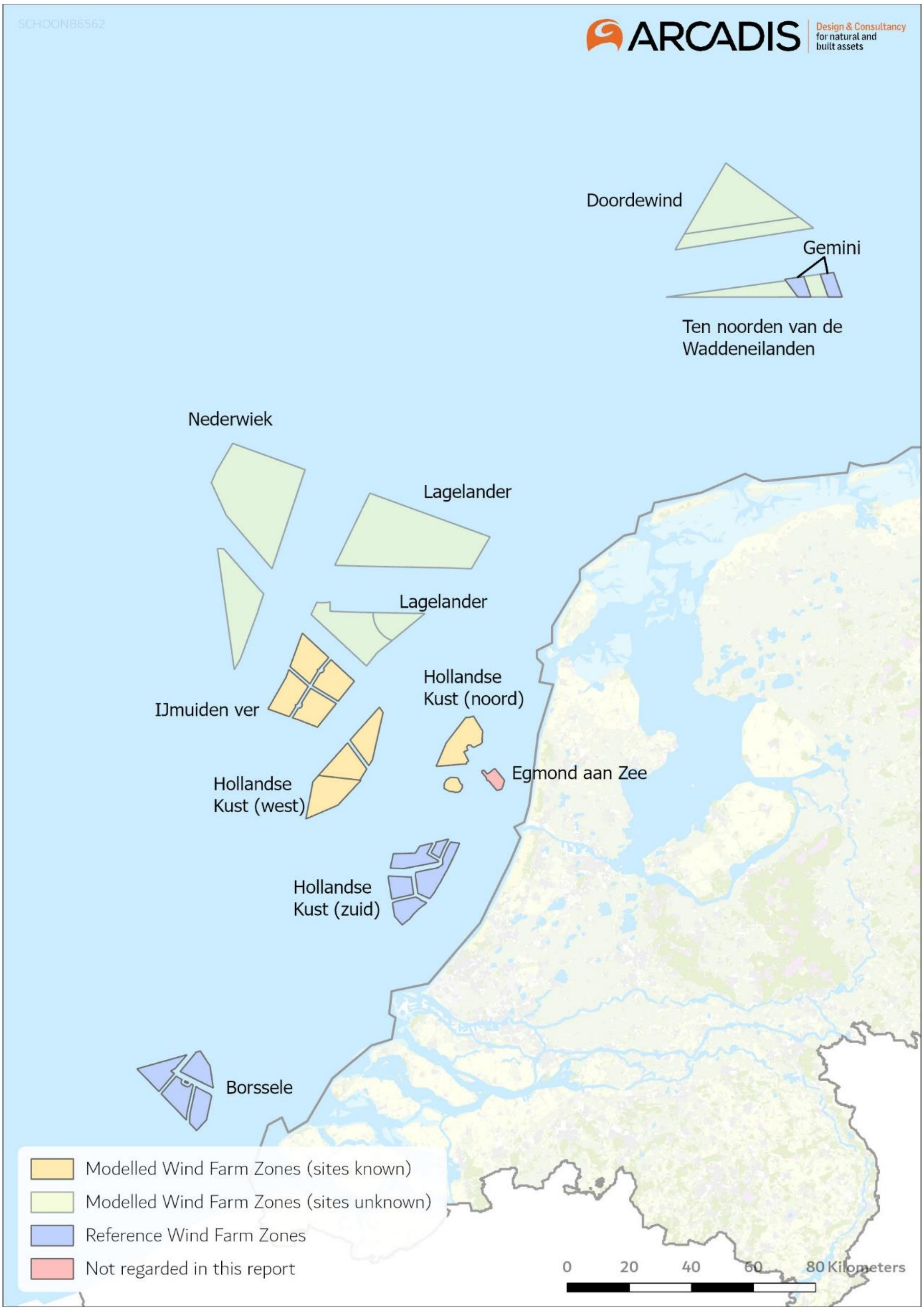

Figure 1: Designated Wind Farm Zones as presented in the North Sea Programme 2022 – 2027 (Rijkswaterstaat, 2022).

Table 1 Overview of the offshore windfarms, lots and surface areas used in this study (M. Graafland (RWS), personal communication, 22-01-2024).

Offshore windfarm	Lot	Area (km^2)	Total area(km^2)	Year of commissioning
HKN	Hollandse Kust (noord) V	93,72	93,72	2023
HKW-Noord	Hollandse Kust (west) VI	93	177	2026
	Hollandse Kust (west) VII	84		2026
HKW-Zuid	Hollandse Kust West VIII	80	80	2023
IJmuiden Ver	IJmuiden Ver Alpha	230	690	2029
	IJmuiden Ver Beta	230		2029
	IJmuiden Ver Gamma	230		2029
Nederwiek	Nederwiek I	230	690	2030
	Nederwiek II	230		2030
	Nederwiek III	230		2031
Doordewind	Doordewind I	230	460	2031
	Doordewind West	230		2032
Lagelander	Lagelander	230	230	2036
Ten noorden van de Waddeneilanden	Ten noorden van de Waddeneilanden	63,36	63,36	2031

2 Estimation of expected UXOs

The Dutch Exclusive Economic Zone (EEZ) of the North Sea was one of the many military theatres of the First and Second World Wars. The North Sea during both wars was subject to naval warfare between warships, submarines, and airplanes. In both wars, large naval minefields were laid to disturb merchant shipping. During the Second World War, the military theatre in the air above the North Sea was significantly enlarged by a constant stream of allied and German bombers which had to pass over the North Sea in order to conduct airstrikes on Nazi occupied Europe or Great Britain. These aircrafts often dumped their unused ammunition above the North Sea on the way back from their target (Port of Rotterdam et al., 2019). As a result of these armed conflicts, a lot of ordnance was dropped, fired, and laid into the North Sea. Not all ordnance exploded during these wars and as a consequence, the seabed is still scattered with Unexploded Ordnances (UXOs).

In this chapter, we explore which Wind Farm Zones in the Dutch EEZ are at higher risk of UXOs and what types are expected. Also, we give an estimation of the total amount of expected UXOs in the different Wind Farm Zones in a worst-case and a most-likely scenario. These estimations will give input for the calculations of several levels of harbour porpoise disturbance in chapter 5.

2.1 UXO types

In Dutch legislation on UXOs (De Staatssecretaris van Sociale Zaken en Werkgelegenheid, 2020), there are 16 main groups or types of UXO. Ïn this report, we distinguish between types that have been used in combat situations on the North Sea, aerial ammunition types that have been dumped by bombers and land-based types that can be found in maritime ammunition dumpsites. Ammunition dumpsites are locations where decommissioned military ammunition is disposed. We also distinguish subcategories of underwater munitions since this main group is not specific enough for our analysis. Our UXO types of the main group 'underwater munitions' correspond with the terminology used in UXO desk studies, data on offshore UXO clearance and the Dutch Marine Explosive Ordnance Disposal (EOD). The following table shows the used subdivision of UXO types.

Table 2 Subdivision of UXO types.

UXO type	Naval combat ammunition	Aerial ammunition	Dumpsite ammunition	Relevant subcategories
Small Arms Ammunition	No	No	Yes	-
Artillery Shells	Yes	No	Yes	-
Hand Grenades	No	No	Yes	-
Rifle Grenades	No	No	Yes	-
Ammunition for Grenade Launchers	No	No	Yes	-
Rocket Projectiles	Yes	Yes	Yes	-
Aerial Bombs	Yes	Yes	Yes	-
Submunitions	No	No	Yes	-
Underwater Munitions	Yes	No	Yes	Naval Mines, Torpedoes, Depth charges
Land Mines	No	No	Yes	-
Booby Traps	No	No	Yes	-
Explosive material	No	No	Yes	-

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UXO type	Naval combat ammunition	Aerial ammunition	Dumpsite ammunition	Relevant subcategories
Fireworks	No	No	Yes	-
Demolition Charges	No	No	Yes	-
Detonators	No	No	Yes	-
Ammunition Accessories	No	No	Yes	-

Since none of the future Wind Farm Zones are projected to be located within known ammunition dump sites (Figure 2), the focus of our estimation of expected UXOs during UXO surveys concentrates on the naval combat ammunition and aerial ammunition that are located in Wind Farm Zones. Disposed ammunition in ammunition dump sites will not be cleared (detonated) and are not situated within offshore Wind Farm Zones and will therefore not be part of this study. Paragraphs 2.1.1 to 2.1.6 will give a short descriptions of every UXO type deemed relevant for this study, corresponding to the categories mentioned in Table 2 Subdivision of UXO types.

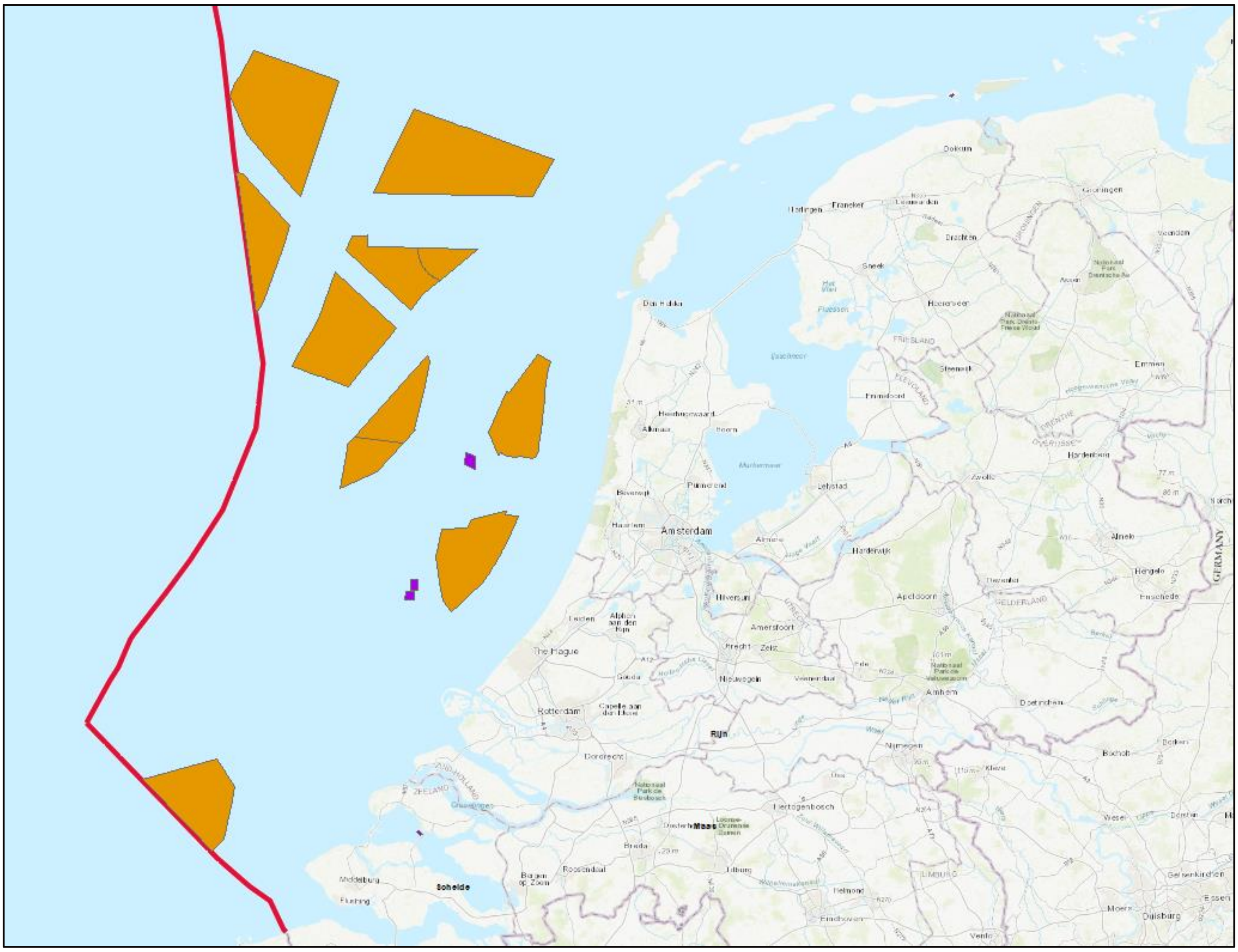

Figure 2: Ammunition dump sites (purple) in relation to the Offshore Wind Farm Zones (orange) within the Dutch EEZ (red line; Noordzeeloket). Offshore wind farm areas 'Doordewind' and 'Ten noorden van de Wadden' have been left out of this map, as there are no ammunition dump sites near these areas and increasing the scale further would impair the visibility of the dumpsites near Ameland and in the Eastern Schelde. Source: (Noordzeeloket, n.d.).

2.1.1 Artillery Shells

Artillery shells are projectiles with a payload of explosive, incendiary or other chemical filling. They are fired by artillery, guns, warships, and autocannons. In the naval theater, artillery shells were deployed by aircraft (20 mm cannon), coastal guns, naval vessels, and submarines. The main sub-types of artillery shells are high-explosive, phosphorous and pyrotechnical. The Net Explosive Quantity (NEQ) of artillery shells vary widely, from 7.7 gram (20 mm ordnance) to 7 kg (17 cm ordnance of German coastal artillery) (Army Air Forces Washington Dc, 1953).

2.1.2 Rocket Projectiles

Rocket projectiles were deployed by allied aircraft and launched from rails underneath the wings of these aircraft. The Royal Air Force (RAF) Coastal Command and the Royal Navy used 3-inch rockets with a 60 lb. warhead against German shipping and submarine targets. The warheads typically consisted of three main types: a solid steal warhead (no explosive charge), a high-explosive warhead and a semi-armor piercing warhead. The greatest NEQ of a 60 lb. warhead consisted of 6 kg of TNT or Amatol (Department of the army, 1952).

2.1.3 Aerial Bombs

An aerial bomb is an explosive or incendiary weapon intended to travel through air on a predictable trajectory. Aerial bombs are usually dropped from aircraft. Like artillery shells, there is a vast range of bombs designed during the wars and explosive charges differ greatly. In the naval theater, aerial bombs were deployed by aircraft against naval vessels and submarines. In addition to these aerial attacks on shipping, German and Allied aircraft conducted bombing campaigns against their respective territories, targeting industrial and civilian areas. Depending on the target, bombers flew various routes over the North Sea to Germany or Great Britain. To avoid the risk of crash landing with bombs on board, bombers often jettisoned their bomb load in the North Sea when they could not reach their target or when facing mechanical problems or damage from enemy fire. The NEQ of aerial bombs vary widely from 16,4 kg (German SD 50 bomb) to 1.102 kg (British blockbuster 4.000 lb. bomb). Most used were the 250, 500 and 1.000 lb. General Purpose bombs (Department of the Army, 1952).

2.1.4 Naval mines

Naval mines are explosive devices that are placed into the water to damage or destroy surface ships or submarines. Unlike depth charges, naval mines are deposited and left to wait until they are triggered by the approach or contact with a vessel. Therefore, a common method to differentiate naval mines is to look at the trigger needed for detonation: contact, influence (instead of direct contact), or remotely controlled. Most naval mines in the North Sea are made up of contact and influence mines. Remotely controlled naval mines were only used in harbours and are therefore not relevant for this study.

2.1.4.1 Contact mines

The contact mine is the most used naval mine. They need to be touched by the target before they detonate. The detonators of a contact mine are based in its horns, which uses electrical or chemical components to ignite the main charge. Contact mines are mostly moored with a steel cable to an anchor on the seabed to prevent it from drifting away. The naval mine itself is floating just below the surface or a few meters deeper. Moored contact mines typically were laid in minefields, with nearby sweep obstructors (non-explosive or explosive) to make clearing of the field more difficult. The NEQ of most used contact mines range between 80 and 227 kg (U.S. Navy Bomb Disposal School, 1945).

2.1.4.2 Influence mines

Influence mines are triggered by the influence of a ship or submarine, rather than direct contact. Most influence mines have fuses that make use of sensors that detect a magnetic, passive acoustic or water pressure displacement caused by the proximity of a vessel. Some influence mines had a ‘ship counter’ function, which means that the mine could ignore a certain number of ships passing over it before igniting. Influence mines were mostly dropped or laid at the seabed and are therefore also known as ground mines. NEQ of most used influence mines range between 300 and 680 kg (U.S. Navy Bomb Disposal School, 1945).

2.1.5 Torpedoes

Torpedoes are self-propelled underwater weapons that are launched above or below the water surface towards a naval target. These weapons are used by torpedo boats, submarines, and aircraft. Ignition of the explosive warhead can be caused by contact or magnetic influence. If a torpedo misses their target, the torpedo will eventually lose propulsion and sink to the seabed. The NEQ of torpedoes ranges between 280 and 303 kg ((U.S. Navy Bomb Disposal School, 1945).

2.1.6 Depth Charges

Depth charges are anti-submarine weapons, which are dropped into the water with the intend to detonate nearby a target, subjecting the target to a destructive hydraulic shock. Most depth charges are dropped by aircraft or naval vessels. The depth charge consists of a fuze set to detonate the charge at a specific depth. If detonation fails, the depth charge will sink to the seabed. The NEQ of depth charges used by the allied forces was 130 kg (U.S. Navy Bomb Disposal School, 1945)

2.2 Sources

In this paragraph, we will examine the main sources for this chapter. Per source, we will summarize the outcome with regards to UXO risk areas, which UXO types can be expected, and the amount of encountered UXOs in the past.

2.2.1 UXO Desk Studies

For the future development of Wind Farm Zones within the Dutch EEZ, it’s important to know if, and how many UXOs are present within these areas. It is common for the Rijksdienst voor Ondernemend Nederland (RvO; or Netherlands Enterprise Agency) to commission UXO Desk Studies to get insights in the risk of encountering UXOs within Wind Farm Zones. Typically, a UXO Desk Study is structured into two phases: historical research (phase I) and an UXO risk assessment (phase II). Primarily the historical research gives answer to the question if UXOs can be expected and if so, where and which type. The historical research itself is based on a broad array of sources, including:

- Archival sources (Dutch, German and English)
- Internet Databases
- Interviews
- Literature
- Maps
- Reports of the Dutch Coast Guard
- Reports of Royal Netherlands Navy

The UXO Desk Studies for the Dutch Wind Farm Zones are all conducted by the company REASeuro. Over the period 2014-2023, they have conducted UXO Desk Studies for the Wind Farm Zones of Borssele (2014), Hollandse Kust (Zuid (2016), Noord (2017) and West (2018)), Ten Noorden van de Wadden (2019), IJmuiden Ver (2020), and Nederwiek (2023) . Logically, the outcomes of finished UXO Desk Studies that were conducted for planned and/or realized Wind Farm Zones form the primary source of our analysis. The outcomes of these studies give a reasonable insight into what kind of UXOs can be expected in the unresearched future-projected Wind Farm Zones of Doordewind and Lagelander.

Table 3 desiplays the categories that REASeuro uses to differentiate in the likelihood of UXO presence.Table 3 Terminology for the likelihood of presence of UXO.

Presence term	Meaning
Negligible	No evidence pointing to the presence of this type of UXO within an area, but it cannot be discounted completely
Remote	Some evidence of this type of UXO in the wider region but it would be unusual for it to be present within the area of study
Feasible	Evidence suggests that this type of UXO could be present within the area

Presence term	Meaning
Probable	Strong evidence that this type of UXO is likely to be present within the area
Certain	Indisputable evidence that this type of UXO is present within the area

The results of all completed UXO Desk Studies for the Dutch Wind Farm Zones are summarized in Table 4. UXO Desk Studies for Wind Farm Zones Lagelander and Doordewind have not been conducted yet and are therefore not displayed in Table 4.

Table 4 Summary of the completed UXO desk studies for Dutch Wind Farm Zones.

Offshore wind farm	Type of UXO expected	Likelihood of presence	Remarks
Borssele	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Certain Certain Certain Certain Certain	REASeuro (2014) made no subdivisions in the likelihood of presence.
Hollandse Kust Noord	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Certain Certain – remote Feasible Probable Remote	Artillery shells are certain for the post-WWII shooting range of the Dutch army and remote for WWI and WWII munitions.
Hollandse Kust West	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Certain Remote – negligible Feasible Probable Remote	The wind farm zone lies outside the range of coastal artillery positions; therefore the likelihood of presence is considered remote-negligible for artillery shells.
Hollandse Kust Zuid	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Certain Certain Certain Certain Certain	
Ten Noorden van de Wadden	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Probable Feasible Negligible Certain Negligible	German ships have fired incidentally on allied aircraft with anti-aircraft guns in this area; therefore REASeuro considers the likelihood of presence feasible for artillery shells.
IJmuiden Ver	Aerial bombs Artillery shells Depth charges Naval mines Torpedoes	Probable Feasible Negligible Probable Feasible	German ships have fired incidentally on allied aircraft with anti-aircraft guns in this area; therefore REASeuro considers the likelihood of presence feasible for artillery shells.
Nederwiek	Aerial bombs Artillery shells	Probable Remote	

Offshore wind farm	Type of UXO expected	Likelihood of presence	Remarks
	Depth charges Naval mines Torpedoes	Remote Probable Feasible	

2.2.2 Data on naval mines

Most North Sea minefields of the First and Second World War were registered during both wars on maps and in minelaying documents. These documents formed the basis for post-war minesweeping operations. These operations by the North Sea nations were critical for post-war revival of commercial shipping. It is important to note that minesweeping was not synonymous to mine clearance. The objective of the operations was to clear the shipping lanes for navigation. This was performed with sweeping gear that cut the wires or cables of moored contact mines, which caused the mines to float to the surface and made it easy to shoot at them with cannon or rifle fire. Shooting the contact mines caused them to sink or to detonate. That is the reason why quite some unexploded naval mines are sunken moored contact mines. Other kinds of mines, like (acoustic) ground mines, could disarm themselves after a certain time period or run out of batteries. These kind of ground mines were not actively sought and lay most of the time still on the sea bottom.

Minefield maps and documents form important documents for UXO Desk Studies and risk assessments. The collected information on minefields (WWI or WWII) by (Ordtek, 2023), REASeuro (L. J. J. Arlar, 2019; L. Arlar & van den Berg BSc, 2018; Dekker & Moonen Bsc, 2023; Schuddink & van den Berg BSc, 2017; van den Berg BSc, 2014, 2016; van Wijk et al., 2020) and UXOIntelligence (2022) that show an overlap with the Wind Farm Zones are summarized in Table 5. The likelihood of presence is taken from the UXO Desk Studies conducted by REASeuro. In contrast to REASeuro, Ordtek and UXOIntelligence provide data for Wind Farm Zones Doordewind and Lagelander which could therefore be included in Table 5.

Table 5 Summary of the collected information on minefields (WWI or WWII) by Ordtek, REASeuro and UXOIntelligence that show an overlap with the Wind Farm Zones.

Offshore wind farm	Minefields	Type of mines expected	Likelihood of presence
Borssele	WWI British WWII German WWII British	ECII Net mine LMB mine Mk 9 en Mk 14	Certain Certain Certain
Hollandse Kust Noord	WWII German WWII German WWII British WWII British	German EMC Static cutter sweep obstructers British Mk 14 British Mk 17	Probable Probable Probable Probable
Hollandse Kust West	WWI German WWII German WWII British WWII British WWII German WWII German	E-Mine EMC-mine Mk 14 Mk 17 LMA (ground mine) LMB (ground mine)	Probable Probable Remote Remote Remote Remote
Hollandse Kust Zuid	WWI German WWI British WWII British WWII German 	UE/150 (120 NEQ) Vickers Elia Mk II Mk 20 Mk 14 Mk 17 EMD EMC Sprengboje	Certain Certain Certain Certain Certain Certain Certain Certain Certain

Offshore wind farm	Minefields	Type of mines expected	Likelihood of presence
		Static cutters	Certain
Ten Noorden van de Wadden	WWI British	Mk I (contact mine)	Certain
		Mk II (contact mine)	Certain
		Mk III (contact mine)	Certain
	WWII British	Mk I-IV (ground mine)	Certain
		Mk V (ground mine)	Certain
	WWII German	EMD (contact mine)	Certain
		EMC (contact mine)	Certain
IJmuiden Ver	WWI British	Type H Mk II	Feasible
	WWI British	Vickers Elia	Feasible
	WWII German	EMD	Probable
		EMC	Probable
Nederwiek	WWI German	E-mine type IV	Probable
	WWI British	Vickers Elia	Probable
		Mk II	Probable
	WWII British	Mk 20	Probable
		Mk 14	Probable
		Mk 17	Probable
	WWII German	EMD	Probable
		EMC	Probable
		Sprengboje	Probable
		Static cutters	Probable
Doordewind	WWI British	Mk I (contact mine)	Certain
		Mk II (contact mine)	Certain
		Mk III (contact mine)	Certain
	WWII British	Mk I-IV (ground mine)	Certain
		Mk V (ground mine)	Certain
	WWII German	EMD (contact mine)	Certain
		EMC (contact mine)	Certain
Lagelander	WWI German	E-mine (probably 150 NEQ)	Probable
	WWII British	A Mk (groundmine 500 NEQ)	Probable
	WWII German	EMC (150 NEQ)	Probable
	WWII German	EMD (150 NEQ)	Probable
		Static cutter sweep obstructers (1 NEQ)	Probable

2.2.3 Data on aerial bombs

During the Allied bombing campaign against Nazi Germany, a total of around 1.8 million tonnages of bombs were dropped by the RAF Bomber Command and US 8th Air Force (Noble Frankland et al., 1951). This is equal to over 3.5 million bombs of a 1.000 lb. caliber. It is generally accepted that of all dropped aerial bombs during the war, about 15% failed to explode. This failure or dud rate of 15% means that hundreds of thousands of aerial bombs are UXOs (Port of Rotterdam et al., 2019) and many ended up in the North Sea (as explained in paragraph 2.1.3).

Primary targets of the bombing campaign were German or German-controlled industry in occupied Europe and residential areas in Nazi Germany. As seen in Figure 3, a lot of aerial bombs were dropped at harbours stretching the

English Channel, German industry in the Ruhr area, industrial cities in southern Germany, the capital Berlin, and major ports like Bremen, Emden, Hamburg, and Kiel.

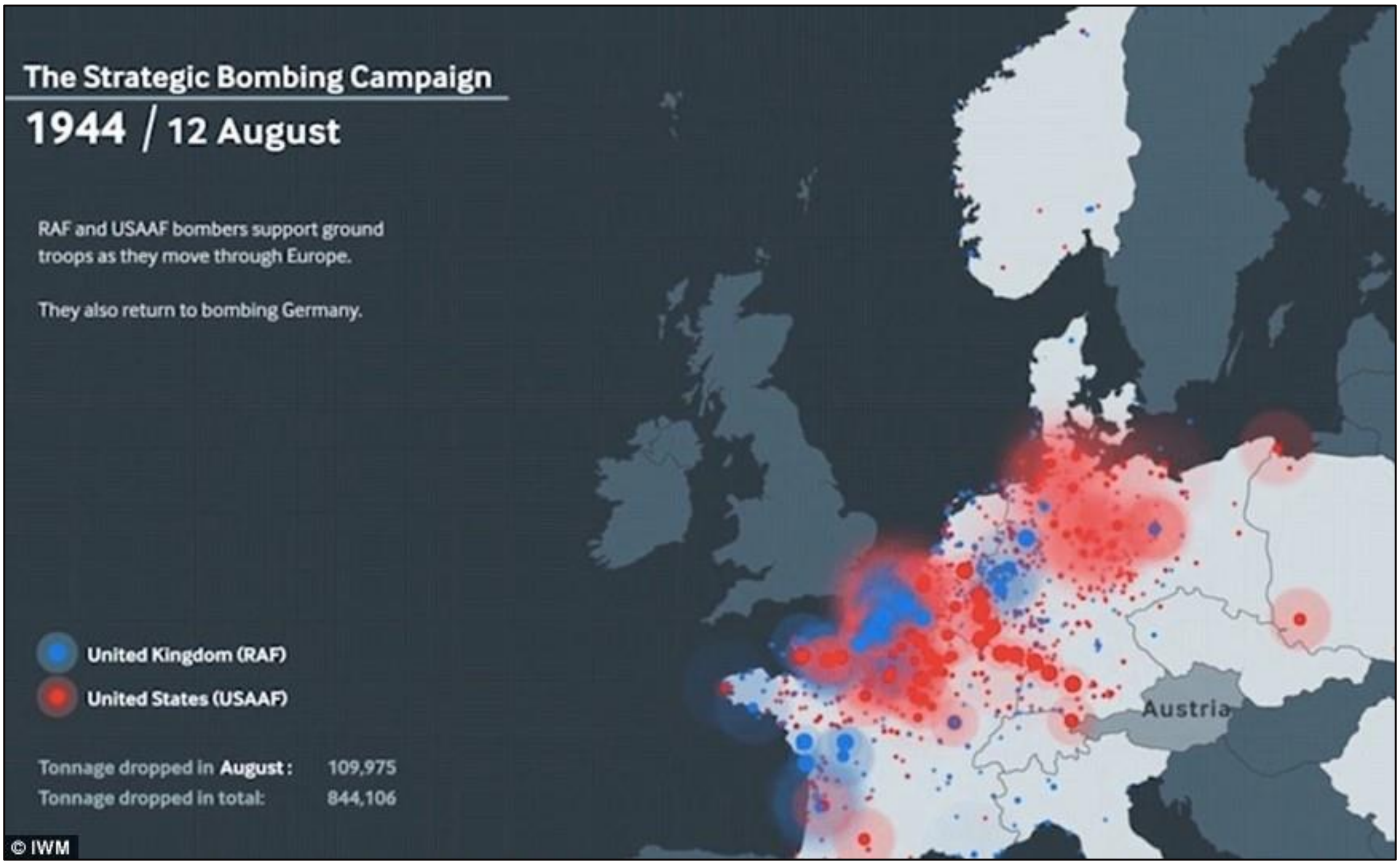

Figure 3: Map of bombing targets in Europe. The bigger circles are more often targeted (Imperial War Museum, 2016).

Data on the Allied bombing campaign were recorded in Operations Record Books (ORBs) which usually give per date the primary target, bomb load per aircraft, time of take-off and landing, and information on the flight paths. Many flight paths towards targets and back to base in the United Kingdom ran across the North Sea. An example of such flight paths is given in figure 4. As described in 2.1.3, aircraft that could not reach their target or when faced with mechanical problems or damage by enemy fire decided to jettison their bomb load along their flight path above the North Sea. That is the prime reasons why many UXOs that are found in the North Sea are aerial bombs.

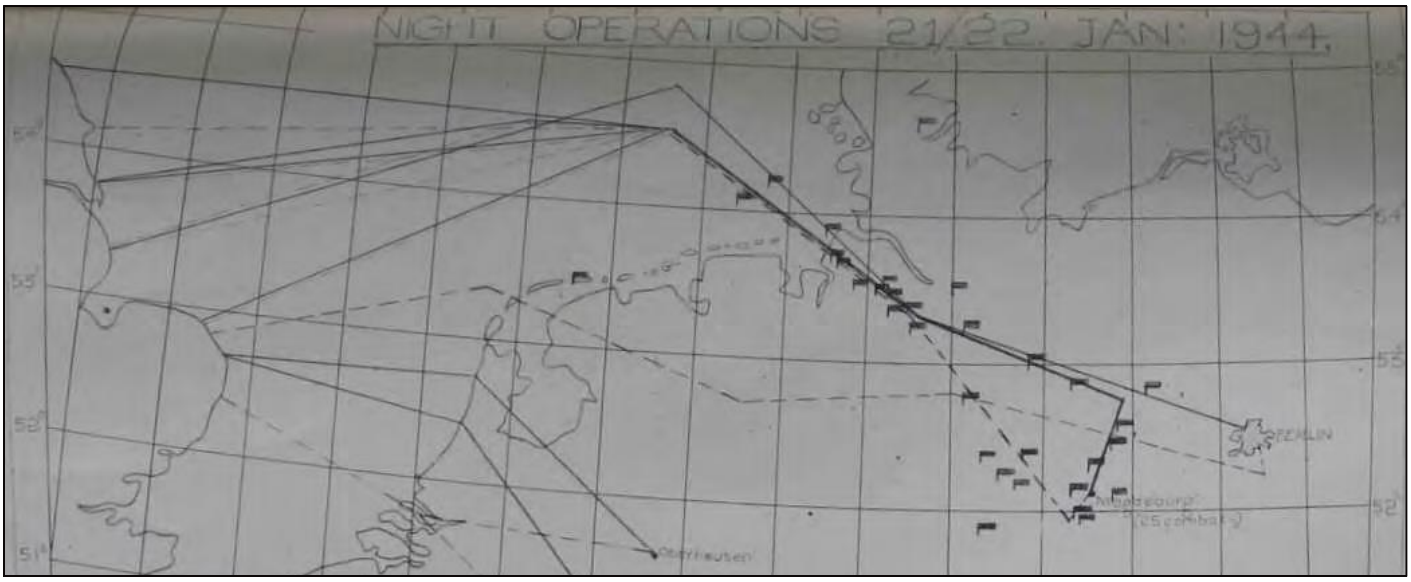

Figure 4: Flight path of several night bombing operations on 21/22 January 1944 (Dekker & Moonen Bsc, 2023).

To give an idea of the possible flight paths used by Allied bombers, we have made a map of every airbase used by the RAF and US Army Airforce (USAAF) in the United Kingdom (see Figure 5, blue aircrafts). Most bases were situated in the East of England, East Midlands, South East England and Yorkshire. As shown on a map in Figure 6 (Noble Frankland, 1951), these bases were ideally situated for most targets in Western Europe. The air bases in the East of England were heavily used for bombing raids on the Ruhr Area, which is probably the prime reason that many aerial bombs that are encountered in the North Sea lay in the area opposite to the East of England Figure 5, purple dots; Beneficial Cooperation data, 2005-2020). Another part of the explanation is the absence of activity. Less to no activity (fishing, survey, dredging etc.) means no encounters above the “Terschelling – German Bight” shipping lane. From the UXO data, it is clear that UXOs will be mainly found in areas with a lot of activities (Helsloot & Helsloot, 2023).

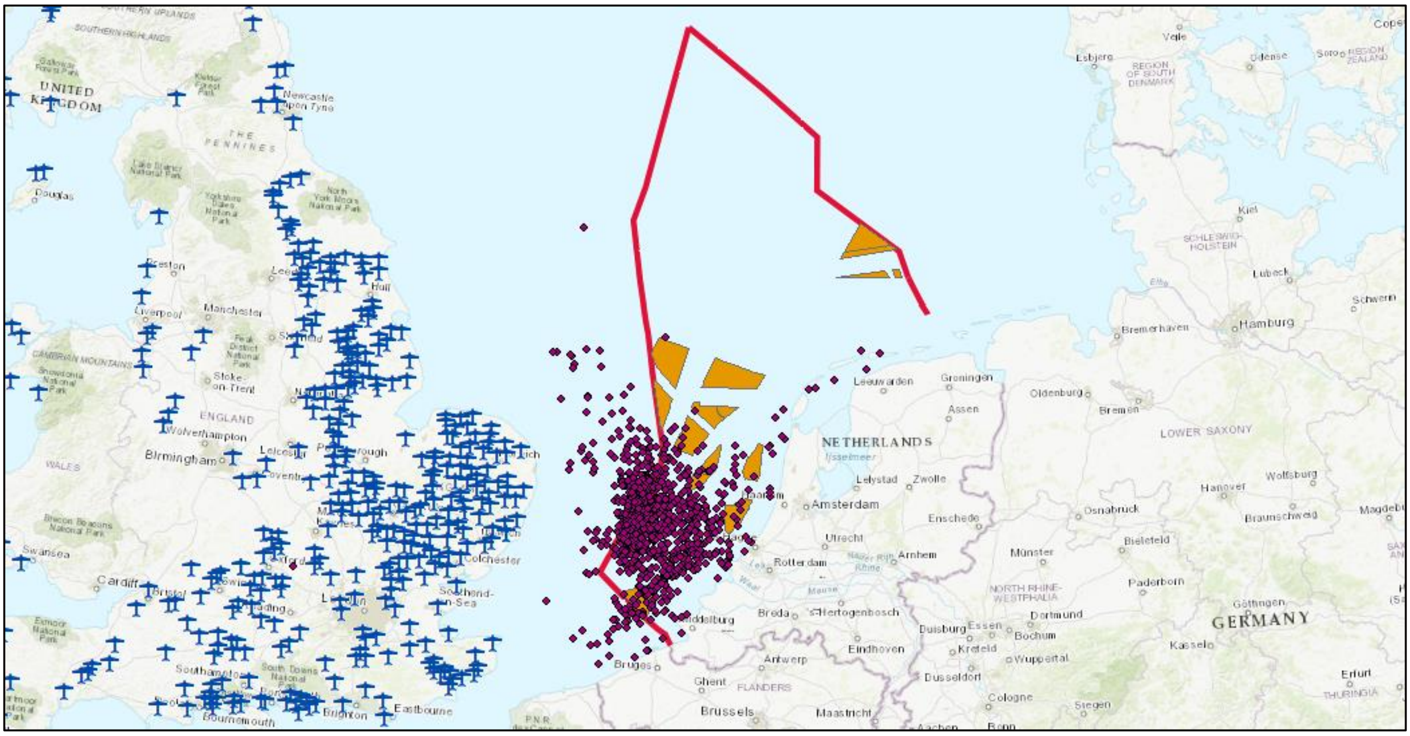

Figure 5 Wartime RAF airbases (blue aircraft) and encountered aerial bombs (purple dots; Beneficial Cooperation data, 2005-2020) in relation to the Offshore Wind Farm Zones (orange) within Dutch EEZ (red line; Noordzeeloket).

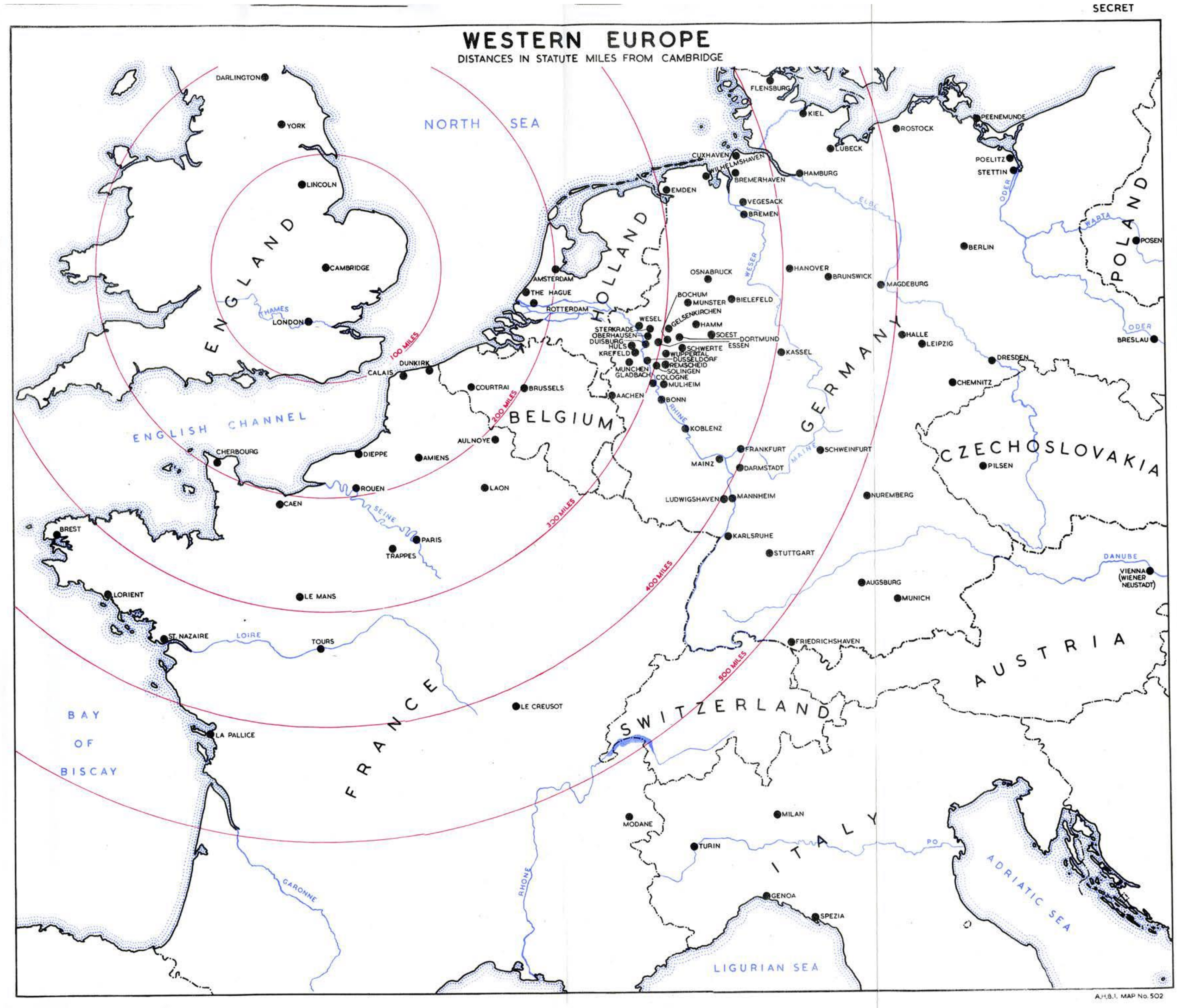

Figure 6: Range map of allied bomber aircraft, calculated from Cambridge (Noble Frankland et al., 1951).

2.2.4 Data on artillery shells

The Dutch coastline was part of the German Atlantic Wall, an extensive system of coastal defences and fortifications along the coast of continental Europe and Scandinavia. The fortifications consisted of coastal guns, batteries, mortars and artillery situated in bunkers and casemates. The coastal guns had a significant shooting range against Allied war ships and landing craft. For coastal guns along the Dutch section of the Atlantic Wall, the shooting range was about 20 to 22 km (Port of Rotterdam et.al. 2019). Naval battles against German convoy shipping and Motor Gun Boats (MGB or *Schnellboot)* also mostly occurred in this area (Schuddink & van den Berg BSc, 2017).

In Figure 7, a 22km zone of the Dutch coast is given to illustrate the area in which most coastal artillery shells should be expected.

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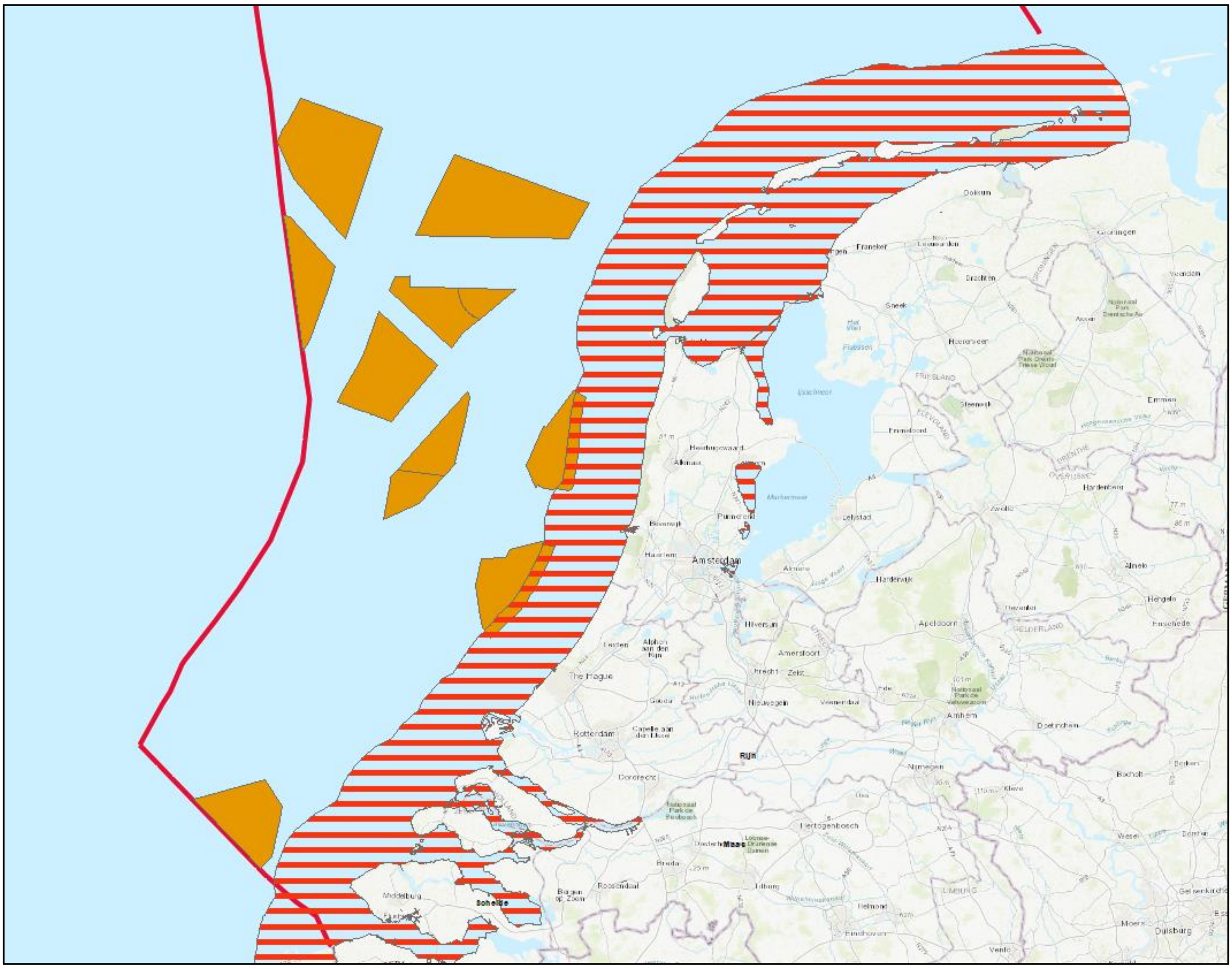

Figure 7 Maximum shooting range of German coastal guns (red; (REASeuro 2017) and Offshore Wind Farm Zones (orange) within the Dutch EEZ (red line; Noordzeeloket). The only overlap with Offshore Wind Farm Zones is with Hollandse Kust Noord and Hollandse Kust Zuid.

In the post-war era, the Dutch army operates several shooting ranges along the coastline of North Holland and at the Vlieland Wadden Island. Shooting practices are directed at sea and most artillery (practice) shells end up on the seabed. If we compare the post-war shooting ranges with the registered artillery shell encounters on the North Sea, a clear correlation between both appears (see Figure 8). Also notably is the fact that, as expected, almost all artillery shell encounters are within the previously mentioned 22 km zone.

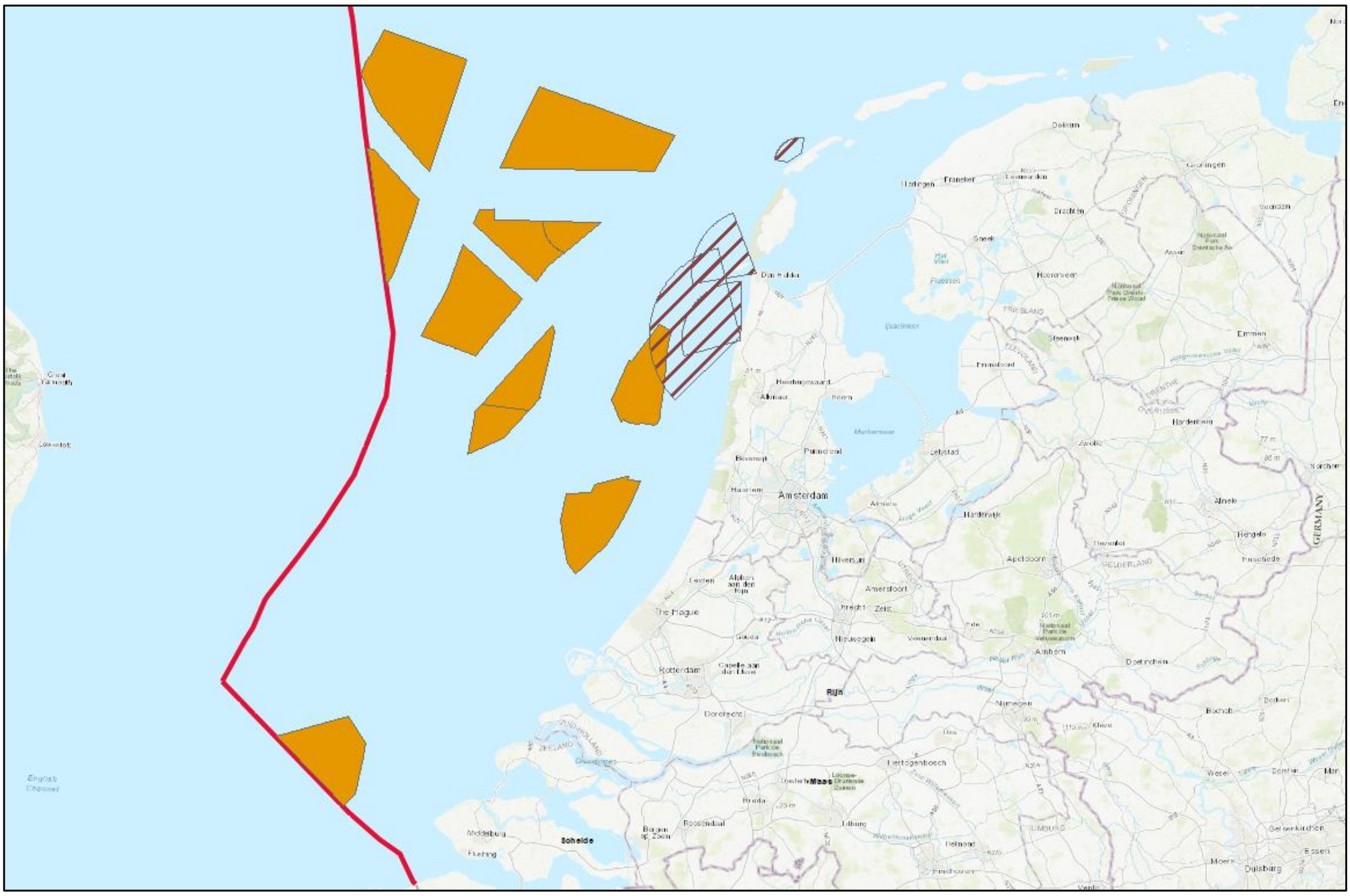

Figure 8 Post-war shooting ranges of the Dutch Army (bron; Noordzeeloket, n.d.) and Offshore Wind Farm Zones (orange) within the Dutch EEZ (red line; Noordzeeloket). The only overlap between one of the shooting ranges is with the Offshore Wind Farm Zone Hollandse Kust Noord. Since 2021, the orientation of this shooting range (Petten) has been tilted to the north to avoid Hollandse Kust Noord (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016).

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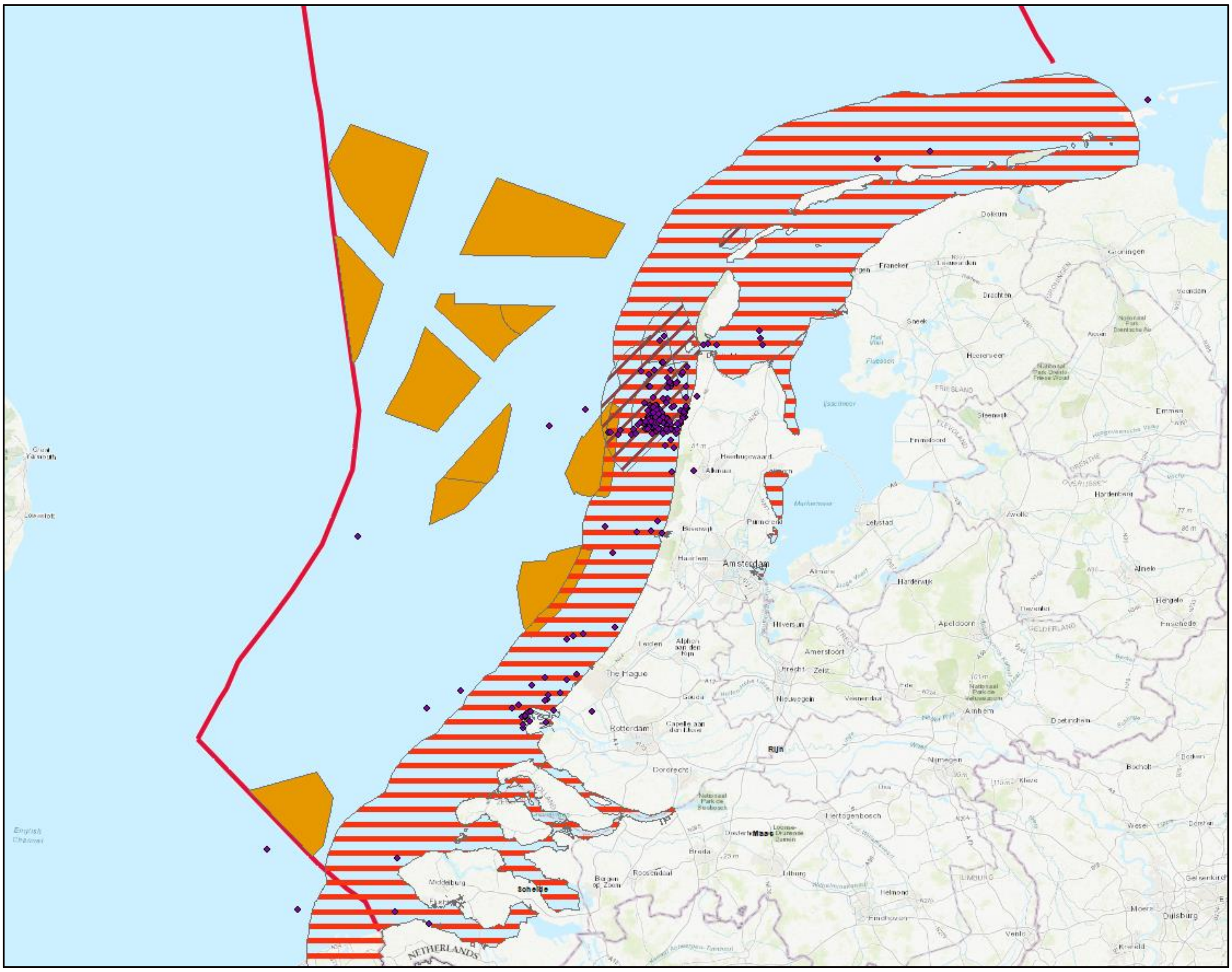

Figure 9: UXO encounters of artillery shells (purple dots; Beneficial Cooperation data, 2005-2020) compared to the shooting range of German coastal guns (red) and post-war shooting ranges of the Dutch Army (brown).

2.2.5 Data on offshore UXO clearance

Post-war UXO encounters and clearance in the Dutch EEZ of the North Sea are being registered into different databases: OSPAR, Beneficial Corporation and Mine Registration of the Dutch Coast Guard. The differences between these databases and their use for this study are discussed in the following paragraphs.

2.2.5.1 OSPAR (1999-2021)

The *Convention for the Protection of the Marine Environment of the North-East Atlantic* or OSPAR Convention was signed in 1992 by 15 nations bordering the North-East Atlantic and the European Union. The purpose of the convention is to regulate international cooperation on environmental protection in this part of the Atlantic Ocean. Since 1999, this convention has resulted in the annual recording of conventional and chemical munitions encounters in the North-East Atlantic. The data includes the location of UXO encounters, nature of the encounter, type of munition (chemical or conventional), action taken, and the country involved. UXO types (aerial bombs, naval mines, etc.) are not given.

The majority of UXO encounters in OSPAR are registered within the Dutch EEZ of the North Sea (Figure 10). This prevalence of encounters in the Dutch EEZ of the North Sea are likely a result of war activities and current country-based bias. The increased war activities included regular crossing of this area for the Allied Bombing Campaign on

Nazi Germany and the extensive use of naval minefields in the Dutch EEZ. The Netherlands increased their reporting following a deadly accident in 2005 (Port of Rotterdam et.al. 2019).

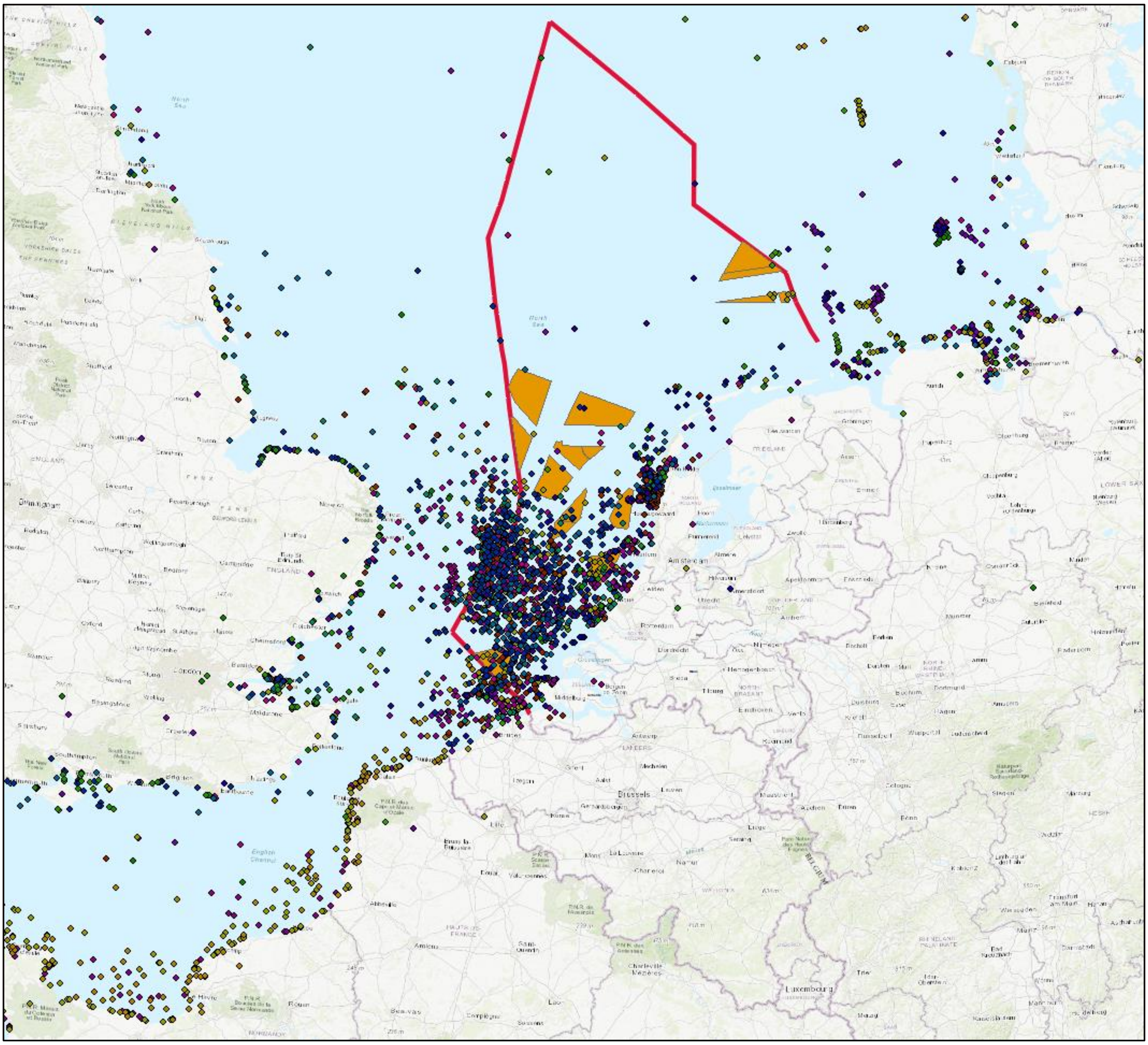

Figure 10: OSPAR-data of UXO encounters over the period 1999-2021 (dots) compared to the Offshore Wind Farm Zones (orange) within the Dutch EEZ (red line; Noordzeeloket).

2.2.5.2 Beneficial Cooperation (2005-2020)

Since the tragic accident in 2005, when a Dutch fishing vessel caught an aerial bomb in their nets which exploded on board, the Dutch and Belgian navies commenced a mine clearance operation called ‘Beneficial Cooperation’. This cooperation resulted in an increased detailed registration of all encountered UXOs in the Dutch and Belgian North Sea. The Dutch Coast Guard is supporting this operation by providing a so called ‘Explosievenkaart’ (Vissersbond, 2020). This explosives chart gives a general overview of the most common UXOs in the North Sea, to help fishermen recognize an UXO and to notify the Coast Guard when encountering one.

The resulting Beneficial Corporation dataset consists of 1.846 UXO encounters over the period 2005-2020, see Figure 11. Of these UXO encounters, about 52% consisted of aerial bombs, 15% of artillery grenades and 12% of naval mines, see *Table* 5. The majority of the UXO encounters occurred in the second quarter (April-June) of each year: 631 UXO encounters. The first (429) and third quarter (421) of the reported years are almost equal in UXO encounters, while the last quarter (365) is the 'quietest'. As expected, the majority of the UXO encounters are a result of fishing activities (68%) followed by dredging and sediment extraction (23%) and UXO offshore surveys (6%).

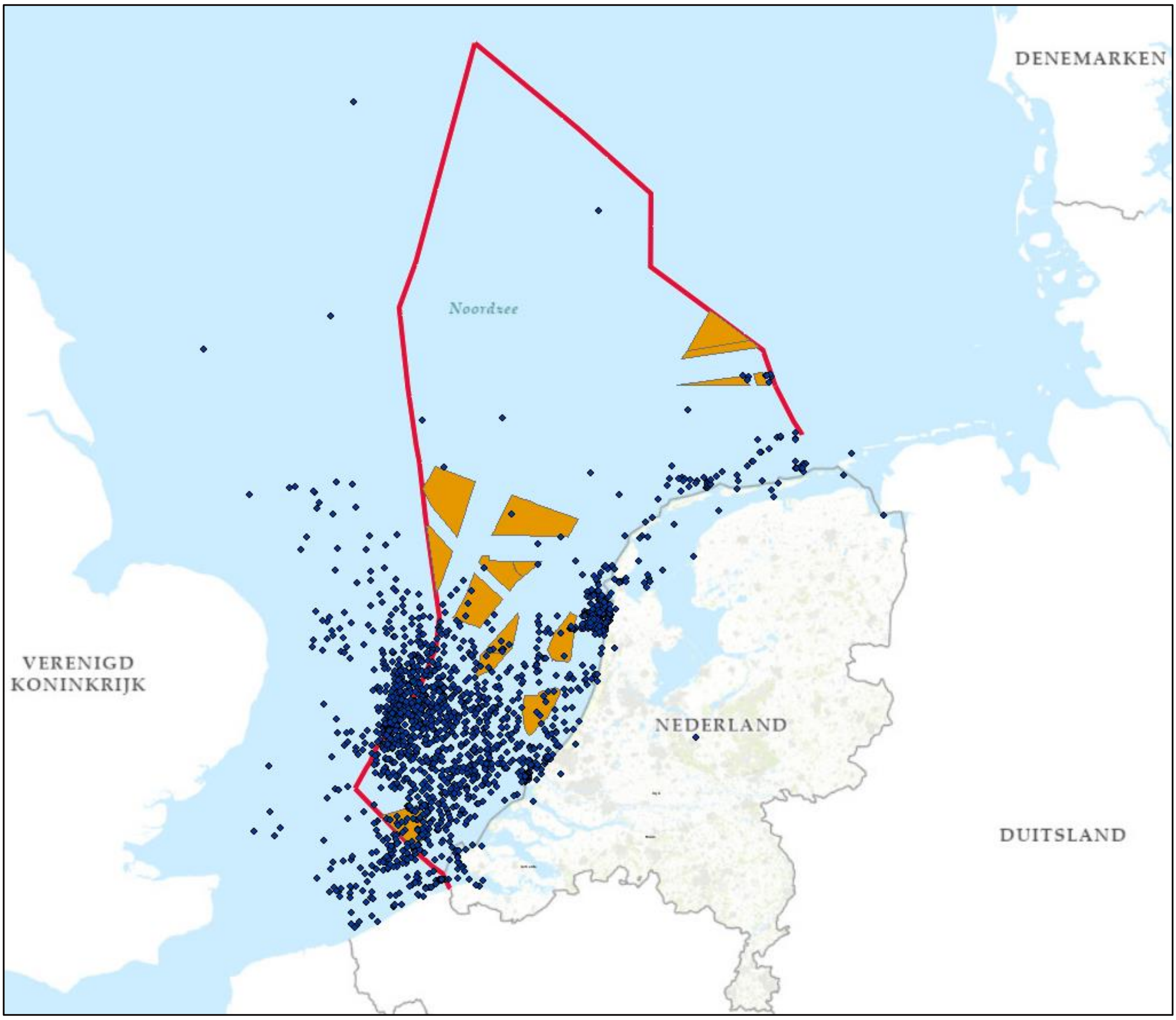

Figure 11 Beneficial Cooperation Data showing encountered UXOs between 2005-2020 (dots) compared to the Offshore Wind Farm Zones (orange) within the Dutch EEZ (red line; Noordzeeloket).

Table 6 UXO encounters divided by category (data Beneficial Cooperation).

UXO category	Number of encounters	Percentage (t=1846)
Aerial bombs	964	52%
Artillery shells	272	15%
Naval mines	225	12%
Torpedoes	28	2%
Depth charges	45	2%
Other or unknown	312	17%

Detailed information (like caliber, NEQ, state, etc.) of the encountered UXO is most of the time not recorded by the Royal Netherlands Navy, due to limited underwater vision, lack of time, etc. Nevertheless, it is possible to take a representative sample of the 964 aerial bombs that were encountered since 152 registrations do have information on the particular caliber of the bomb. The majority of the encountered aerial bombs consisted of 500 and 1.000 lb bombs, as can be seen in Table 7.

Table 7 Aerial bomb caliber, encounters and rounded percentages.

Aerial bomb caliber	Number encountered	Percentage (t=152)
250 lb	25	16,4
500 lb	75	49,3
1000 lb	46	30,3
2000 lb	5	3,3
4000 lb	1	0,7

2.2.5.3 Mine Registration of the Dutch Coast Guard (2020-2022)

For the last period, we have made use of the Mine Registration by the Dutch Coast Guard. This registration forms the basis for the Dutch Beneficial Cooporation data. Since 2020, the amount of encountered and cleared UXOs on the North Sea is also reported in the annual report of the Ministry of Defense. In the last couple of years, the yearly amount of encounterend and cleared UXOs is a bit lower than in the previous two decades:

- 2020: 60
- 2021: 69
- 2022: 51

2022 is the only year where we have the complete records of the Dutch Coast Guard with regards to the UXO types of encountered UXOs. The majority consisted of aerial bombs (16), followed by depth charges (10), naval mines (5) and artillery grenades/mortars (4).

2.2.5.4 ICES Impulsive Noise register

Water Proof Marine Consultancy & Services BV collects and reports underwater noise, caused by piling, seismic surveys, explosions and SONAR, since 2015 in a so called ‘Impulsregister’ on behalf of Rijkswaterstaat. This Impulsive Noise Register of the Dutch EEZ is then send to the International Council for the Exploration of the Sea (ICES), who manages these datasets for the OSPAR-convention (ICES, n.d.).

We looked into these ‘Impulsregisters’ of the period 2015-2022 and especially to the 266 Noise Level Registrations within the category ‘Explosions’ (Waterproof B.V., 2023). These explosions registrations should correspond with the Mine Registration of the Dutch Coast Guard.

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2.3 Analysis

In the analysis of the UXO-data, we focus on the encountered UXOs in two diffetent scenarios. A worst-case scenario, were the mean UXOs per km² is calculated and extrapolated for the future Wind Farm Zones and a most-likely scenario, which also takes into account the location specific settings of the future Wind Farm Zones.

2.3.1 Worst-case scenario

In the worst-case scenario, we primarily focus on the data on offshore UXO clearances. The average of encountered UXOs per km² was analyzed for the Wind Farm Zones that have been most thoroughly cleared. These are the Wind Farm Zones that have already been surveyed and where construction is finished: Borssele, Gemini and Hollandse Kust Zuid. Number of encountered UXOs in these Wind Farm Zones are shown in Table 8.

Table 8 UXO encounters in Borssele, Hollandse Kust Zuid and Gemini offshore wind farms.

Offshore Wind Farm Zone	Size (in km²)	Encountered UXO	UXO per km²
Borssele	234,59	38	0,16
Hollandse Kust Zuid	228	52	0,23
Gemini	70	9	0,13

The mean of encountered UXO per km² of these three Wind Farm Zones (=0.17 per km²) gives us insight of the expected UXO per km²**.** For the worst-case scenario, the average number of UXOs per km² is extrapolated to the Wind Farm Zones that have not been surveyed for UXOs yet. The worst-case scenario of UXO encounters is shown in Table 9.

Table 9 Worst case scenario UXO encounters.

Offshore Wind Farm Zone	Size (in km²)	Estimation of encountered UXO (with a mean of 0,17 UXO per km²)
Hollandse Kust Noord	93,72	16
Nederwiek	690	117
Doordewind	460	78
IJmuiden Ver	690	117
Lagelander	230	39
Hollands Kust West (Noord)	177	30
Hollandse Kust West (Zuid)	80	14
Ten noorden van de Wadden	63,36	11
Total		422

When we consider the distribution of UXO types as found in the Beneficial Cooperation data (see paragraph 2.3.5.2) as representative of the UXO encounters in the North Sea, we can use these percentages to come up with an expected amount of UXOs per type to be encountered in the future Wind Farm Zones. The worst-case scenario of UXO encounters per UXO type is shown in Table 10.

*Table 10 Expected amount of UXOs (*rounded) per UXO category for the future Offshore Wind Farm Zones in the worst-case scenario.*

Offshore Wind Farm Zone	Aerial bombs	Naval mines	Artillery shells	Torpedoes	Depth charges	Other/unknown	Total
Hollandse Kust Noord	8	2	2	1	1	2	16
Nederwiek	61	14	18	2	2	20	117
Doordewind	40	10	12	1	1	14	78
IJmuiden Ver	61	14	18	2	2	20	117
Lagelander	20	5	6	1	0	7	39
Hollands Kust West (Noord)	15	4	4	1	1	5	30
Hollandse Kust West (Zuid)	7	2	2	0	1	2	14
Ten noorden van de Wadden	1	6	2	0	0	2	11
Total	213	57	64	8	8	72	422
Total percentage	52%	12%	15%	2%	2%	17%	100%

2.3.2 Most-likely scenario

To determine local effects in the most-likely scenario, we combined input from the UXO desk studies with the data on offshore UXO clearance. For example, not every Offshore Wind Farm Zones lies in an area that could be reached by coastal artillery. Hence, the chance of encountering UXO artillery grenades in these Wind Farm Zones is significantly reduced or even excluded. For the Wind Farm Zones where artillery grenades are excluded, the same number of UXOs is still expected, but the 15% that would normally consist of Artillery is spread evenly of the other UXO categories. This results in an expected UXO distribution as displayed in Table 11.

Table 11 Used percentages of UXO types for the most-likely scenario.

UXO type	Percentage
Aerial bombs	55%
Naval mines	15%
Torpedoes	5%
Depth charges	5%
Other or unknown	20%

For the most-likely scenario, we have made some assumptions which are based on a study conducted for Port of Rotterdam, TenneT and Rijkswaterstaat (2019) and the data on offshore UXO clearance. In the Port of Rotterdam et.al. study (2019), the authors conclude that roughly 1 aerial bomb is found per 30 km² in the total Dutch EEZ. This is more than four times lower than the worst-case assumption of 0.175 UXO per km². Therefore, we take this as a basis to calculate the total amount of expected aerial bombs per Wind Farm Zone (=total area Wind Farm Zone in km² divided by 30). Since we assume that roughly 55% of every encountered UXO is an aerial bomb (see above), we can calculate the total of expected UXOs per Wind Farm Zone (= estimated aerial bombs per Wind Farm Zone divided by 0.55). To complete the estimation, we divide the total of expected UXOs according to the already described distribution of UXO types above.

For the Wind Farm Zones above the Wadden Islands (Doordewind and Ten Noorden of de Wadden), we have concluded in subparagraph 2.2.1 that we only expect aerial bombs (probable) and naval mines (certain) (REASeuro). Therefore, we have used a different method to calculate the amount of expected naval mines. We looked into the naval mine clearances conducted for the only completed Wind Farm Zone above the Wadden Islands (Gemini). For this Wind Farm, 7 naval mines were cleared in an area of 70 km². This results in a mean of 0.10 naval mines per km², which we have used to make an estimation of expected naval mines in the Wind Farm Zones of Doordewind and Ten Noorden of de Wadden. The amount of expected aerial bombs is still based on the general assumption that 1 aerial bomb is encountered every 30 km².

Only for the Offshore Wind Farm Hollandse Kust Noord, we have made a different calculation. Since the actual amount of encountered UXOs within the Wind Farm Zone over the last couple of years (n=26, Table 7) is higher than the worst-case calculation, it seems logical to take this figure (n=26) for the most-likely scenario. We assume that in the worst-case scenario, there is an underestimation of the UXO type artillery shells. Therefore, we have chosen to use the percentages as indicated in Table 11, except for the category's aerial bombs and artillery shells. This means that the four UXO types amount up to n=13 and that another 13 UXOs need to be distributed between the category's aerial bombs and artillery shells. Since the data on encountered UXOs in the Hollandse Kust Noord Zone shows a ratio of 1:3 between bombs and shells, this has been taken as basis of the distribution between both UXO types in the most-likely scenario of this Wind Farm Zone.

The estimation of UXO encounters per UXO type for the most-likely scenario is shown in Table 12.

Table 12 Expected amount of UXOs per UXO category for the future Offshore Wind Farm Zones in the most-likely scenario.

Offshore Wind Farm Zone	Aerial bombs	Naval mines	Artillery shells	Torpedoes	Depth charges	Other/unknown	Total
Hollandse Kust Noord	3	4	10	2	2	5	26
Nederwiek	23	6	0	2	2	9	42
Doordewind	16	46	0	0	0	0	62
Ijmuiden Ver	23	6	0	2	2	9	42
Lagelander	8	2	0	1	1	3	15
Hollands Kust West (Noord)	6	2	0	1	1	2	12
Hollandse Kust West (Zuid)	3	1	0	0	0	1	5
Ten noorden van de Wadden	2	6	0	0	0	0	8
Total	84	73	10	8	8	29	212
Total percentage	39,6%	34,4%	4,7%	3,8%	3,8%	13,7%	100%

2.4 Encountered versus cleared UXOs

One drawback in the offshore UXO clearance process is that many reported encountered UXOs are lost after reporting and before they are cleared by the dispatched navy vessel. This is caused by burial, adverse weather conditions or the absence or loss (due to weather conditions) of a buoy with sonar reflection. Logging the exact coordinates of an encountered UXO is also quite challenging for UXO survey companies. Of the 11 UXO surveys studied by Crisislab (Helsloot & Helsloot, 2023), only 56 of the 110 reported objects were found by the Royal Netherlands Navy. If we look at the entire dataset of Beneficial Coorperation (2005-2020), 74% of the encountered UXOs are cleared by the Dutch Marine EOD. Since the latter percentage is derived from a bigger dataset and over a longer period, this percentage (74%) is used to calculate the UXOs that are expected to be cleared during future UXO operations for the Offshore Wind Farm Zones, see Table 13. Another reason to use the higher percentage of cleared UXOs is due to the expectation that offshore UXO surveys will improve over time, reducing inaccuracies in logging UXO positions, so that a higher percentage of the registered encountered UXOs will be cleared by the Royal Netherlands Navy.

Table 13 Estimation of cleared UXOs adjusted for the percentage of encountered UXOs.

Offshore Wind Farm Zones	Square kilometres (km²)	Estimated UXO cleared (most-likely scenario)	Estimated UXO cleared (worst-case scenario)
Hollandse Kust Noord	93,72	19	12
Nederwiek	690	31	87
Doordewind	460	46	58
IJmuiden Ver	690	31	87
Lagelander	230	11	29
Hollands Kust West (Noord)	177	9	22
Hollandse Kust West (Zuid)	80	4	10
Ten noorden van de Wadden	63,36	6	8
Total		**157**	**313**

2.5 Conclusion

In the estimation of expected UXOs to be encountered and cleared during survey and construction phase of future offshore Wind Farm Zones, we have analysed that different scenarios are possible. The worst-case scenario is built upon the assumption that UXOs are evenly distributed across the Dutch EEZ of the North Sea. Although this does not seem the most likely scenario if we look at the data on offshore UXO clearance, it gives us an upper range for harbour porpoise disturbance. The impact of UXO clearance for offshore wind farms on the North Sea harbour porpoise population will probably not be worse than this scenario. In the most-likely scenario, the amount of expected UXOs is almost halved compared to the worst-case scenario and the distribution of UXO types is more in line with the data on past cleared UXOs within the offshore Wind Farm Zones. Since the most-likely scenario makes use of more sources and calculations that take UXO type distribution into account, this scenario will probably be more credible in the future.

Table 14 Estimated UXO per Offshore Wind Farm Zones.

Offshore Wind Farm Zones	Square kilometers (km²)	Estimated UXO finds (most-likely scenario)	Estimated cleared UXO (most-likely scenario)	Estimated UXO finds (worst-case scenario)	Estimated cleared UXO (worst-case scenario)
Hollandse Kust Noord	97,72	26	19	16	12
Nederwiek	690	42	31	117	87
Doordewind Noord	460	62	46	78	58
IJmuiden Ver	690	42	31	117	87
Lagelander	230	15	11	39	29
Hollands Kust West (Noord)	177	12	9	30	22
Hollandse Kust West (Zuid)	80	5	4	14	10
Ten noorden van de Wadden	63,36	8	6	11	8
Total		212	**157**	422	**313**

3 Used procedures by EOD for UXO-clearance

Within Dutch continental waters, the Dutch Marine Explosive Ordnance Disposal (EOD) is the authority responsible for all maritime UXO disposal operations, which means that no third parties are authorized to conduct offshore UXO disposal. When the Marine EOD (MEOD) concludes that identified UXOs are unsafe to transport, these shall be detonated on site following the procedure from the handbook. For large encountered offshore UXOs, like aerial bombs, naval mines, torpedoes and depth charges, this is almost always the case. The most common clearing practice is for MEOD divers to approach the encountered UXO and apply a 12 kg donor charge to the UXO. Back on board of the minesweeper, the Marine EOD will ignite the donor charge which leads to a full (or high-order) detonation of the UXO (Interview MEOD, 2023).

Smaller UXOs (like artillery shells) are, if possible, lifted to the surface with a lifting bag and prepared on board of the minesweeper with a donor charge of 1 kg. After preparation, the small UXO is lifted back to the seabed and detonated (Interview MEOD, 2023).

The Marine EOD has several procedures to follow before conducting an UXO disposal, which for example includes safeguarding of predetermined safety distances from the detonation centre of the UXO. Since 2020, there is also increasingly awareness for the impact reduction of UXO disposals on the marine environment. These mitigating measures are being discussed in the following paragraph.

3.1 Mitigating measures

In 2020, a handbook for the disposal of explosive ordnances (DEC EODD, 2020) was developed, which is utilized by the marine EOD responsible for clearing UXOs. This handbook incorporates a list of mitigating measures aimed at reducing the impact on the marine environment, with a particular focus on the harbour porpoise, based on research conducted by the Netherlands Organisation of Applied Research (TNO) (Von Benda-Beckmann, Aarts, Lucke, et al., 2015).

These mitigating measures are assessed by Marine EOD for each UXO, with deflagration and lifting an UXO off the sea floor, which increase the risk for Marine EOD personnel, being infrequently employed. For the remaining measures, a careful evaluation is always conducted to ensure safety is not compromised. The implications of the listed mitigating measures on UXO clearance protocol are as follows:

Reduce water depth

The harmful shockwave is weaker when UXO detonation occurs closer to the water's surface. Reducing the detonation depth significantly reduces the potential impact of the detonation. Reduction of the detonation depth can be reached in the following ways:

- Move the UXO to a shallower location. When an explosive must be relocated due to safety distances, consideration should be given to whether it is possible to move the explosive to the shallowest water possible. If the explosive can be detonated at the location where it was found, it is not unnecessarily moved, and other measures are taken (DEC EODD, 2020).
- Detonate UXO’s when the tide is out. The difference between high and low tide may not be substantial, but especially in shallow waters, it can still make a difference. When practically feasible, it is preferable to schedule detonations closer to low tide rather than high tide (DEC EODD, 2020).
- Lift the UXO off the seabed into the water column or to the surface. Although the technology is there to lift an UXO off the sea floor and detonate it in the water column, it is not a preferred method. This method comes with serious safety considerations with regard to water current, wave action and fragmentation. Furthermore, any equipment that is used to lift the UXO off the sea floor will be destroyed with UXO detonation (Interview MEOD, 2023).

Deflagration instead of detonation

UXO deflagration refers to the controlled burning or slow combustion of unexploded ordnance (UXO) in a controlled and deliberate manner. This method would seriously decrease the amount of disturbance caused by UXO clearance. However, this is not preferred by the MEOD as it requires very precise donor charge placement, and it is difficult to get confirmation on whether the deflagration procedure was successful.

When it fails to completely destroy the UXO, there is a risk that detonators remain present and poses risk to divers when they have to return to the debris. Also, it is yet unclear what to do with the debris, which also has potential for chemical pollution if left on the seafloor, but may be risky, expensive and time intensive to move (with current procedures and equipment). Furthermore, if the method fails the window of opportunity to clear the UXO is lost (if the North Sea divers can only work during low tide).

Acoustic Deterrent Device

An Acoustic Deterrent Device (ADD) is a device that emits a sound targeted for mammals to make them move away from the ADD location. This reduces the number of exposed animals in the area and thus lowers the chance of any harmful effects. ADDs are very effective at short distances and therefore can prevent direct injuries from the blast wave and to a lesser extend the occurrence of PTS and TTS. PTS and TTS can occur at distances larger than which the ADD is effective at. ADDs do not prevent behavioural changes as an ADD is designed to make marine mammals take evasive actions. All vessels of the MEOD that are involved with UXO clearances are either standardly equipped with a Lofitech ADD which has an effect distance of maximum 7,5 km or take one on board if they are not. The ADD is turned on at least 10 minutes before UXO detonation or 30 minutes if possible (DEC EODD, 2020; Interview MEOD, 2023).

Seasonal fluctuations in harbour porpoise density

The Dutch North Sea is a small part of the Greater North Sea, but to illustrate seasonal fluctuations the densities of the Greater North Sea are used, see Table 15 (Gilles et al., 2016). Densities in the Dutch North Sea also show these fluctuations in harbour porpoise density. Notably, clearing unexploded ordnances (UXOs) during the fall season significantly reduces the number of harbour porpoise disturbed. Presently, UXO clearance planning does not account for harbour porpoise density, but there's a clear opportunity to integrate this data into the planning process. By doing so, UXO clearance operations can be scheduled to align with periods of lower porpoise density, minimizing the environmental impact (Interview MEOD, 2023).

Table 15 Seasonal fluctuations in harbour porpoise density in the Greater North Sea. Bron: (Gilles et al., 2016).

Parameter	Spring	Summer	Fall
Abundance (N)	372,167	361,146	228,913
CV (model)	0.006	0.001	0.003
CV (group size)	0.01	0.01	0.02
CV (weighted mean esw)	0.18	0.12	0.19
CV (ship g(0))	–	0.16	–
CV_{all} (N)	0.18	0.20	0.19
Lower 95% CI	260,658	243,827	159,264
Upper 95% CI	531,380	534,913	329,022
Density	0.91	0.88	0.56

Not stacking UXO clearances

According to the MEOD handbook, stacking UXO into one clearance doesn’t happen very often. But in the case of multiple UXOs needing to be moved and cleared it is advised to do so sequentially.

Monitoring the danger zone

During the whole UXO clearing procedure, the MEOD keeps a lookout for any marine mammals. If night vision goggles are available these will be used during night. If any marine mammals are spotted in the direct vicinity the clearance procedure is delayed until the marine mammals have cleared the area. It is unknown if these observers are trained Marine Mammal observers.

Bubble curtains

Though not listed in the DEC EODD, (2020)the use bubble screens is a technique to mitigate noise levels produced by UXO clearance. A bubble curtain can suppress sound transmission through water due to the absorption of sound waves and a density mismatch. Bubble screens are already adopted in the contruction activities of several wind farms to mitigate noise levels produced by pile driving (Dähne et al., 2017). Quarry trails with low order deflagration chargers showed that bubble curtains can have promising results, especially in combination with low order detonation and potentially high order detonation (Cheong et al., 2023). Bubble curtains have limitations regarding depth and current and can therefore not always be applied (Novik, 2023).

4 Sound and environmental effects of UXO-clearances

Impacts of UXO-clearances can have a local effect from several tens of meters to several square kilometres. The impacts are described below.

4.1 Local impacts

Detonating a UXO on the seabed has several impacts to the surrounding area, including local crater formation and the movement of sediment. Immediately following detonation, a rapid expansion of gaseous products are formed as a direct result of the detonation. This is known as the “bubble pulse”, and once it reaches the surface it will rapidly dissipate. Fragmentation of the UXO will also occur locally and does not pose a significant risk past 10 m from the UXO detonation location.

4.2 Non-local impacts

Non-local impacts are caused by the high amplitude shock and the attendant sound wave produced. The parameters below influence the sound propagation and thus determine the size of the impacted area. It is assumed that the sound level is related to the impact. The biotic variables are discussed in chapter 5 while the abiotic variables are shown in this paragraph and consist of:

1. Type of sediment
2. Water depth
3. Place in the water column or seabed
4. Net Explosive Quantity (NEQ (expressed in kg)) of an UXO
    - Included is the 12 kg donor charge for aerial bombs, naval mines, depth charges and torpedoes. For artillery a donor charge of 1 kg is used
5. UXO degradation

4.2.1 Type of sediment

The seabed in the North Sea varies throughout the North Sea, however most areas consist of sandy sediments. Therefore, the assumption is made that all offshore windfarms are constructed on sandy sediments and that the detonation of UXOs takes place on sediments consisting of sand.

4.2.2 Water depth

Water depth affects the distance sound propagates. The deeper the water depth the further sound will travel (Von Benda-Beckmann, Aarts, Sertlek, et al., 2015). In the North Sea most detonations in 2010 – 2011 occurred in water depths between 20 and 30 m depth (Von Benda-Beckmann, Aarts, Sertlek, et al., 2015). Modelling done by (Von Benda-Beckmann, Aarts, Sertlek, et al., 2015) used depths of 26 and 28 meters. In Table 16 the water depths at different offshore windfarm locations are shown. Depths vary between 20 and 40 m; however most offshore windfarms have an average depth of 30 m. Because modelled disturbance distances are modelled in a situation with a depth of nearly 30 m and most windfarms are constructed at depths of 30 m, the assumption is made that the water depth at all locations is 30 m and sound travels through the water column at 30 m depth.

Table 16 Average water depth at the different offshore windfarms.

Offshore windfarm	Average water depth (m)
Hollandse Kust Noord	20
Nederwiek	30

Offshore windfarm	Average water depth (m)
Doordewind	40
IJmuiden Ver	30
Lagelander (Noord en Zuid)	30
Hollandse Kust West	30
Ten Noorden van de Wadden	40

4.2.3 Place in the water column or seabed

In the marine environment, a fired or dropped ordnance that does not explode on impact sinks away in the water. The impact energy of an UXO is rapidly attenuated by the water it passes through and sinks to the seabed. There, the UXO will become partly buried due to scour. UXO types which are fired or dropped include aerial bombs, artillery grenades, torpedoes and depth charges.

Naval mines can roughly be distributed into two categories: buoyant and ground mines. Ground mines were laid at the seabed and unexploded ground mines are still most of the time (70%) found in the area where they were laid (UXOIntelligence, 2022). Buoyant mines were held in place by a mooring wire connected to an anchorage, the so-called mine-anchor. Most of these mine-anchors are still in the area where they were originally laid. The buoyant mines themselves are almost always torn from their anchorage due to post-war mine-sweeping operations and storms. The practice of minesweeping is to cut a buoyant mine from the mooring wire, which results in the buoyant mine floating to the surface. These are then shot by a deck gun on the minesweeper, resulting in an explosion or sinking of the mine to the seabed (UXOIntelligence, 2022). Buoyant mines that were torn from their anchorage due to storms most of the time drifted away with the currents until they stranded on the beach, against dykes, etc. If not directly found, they became buried by the tide at these sites. An example of the drifting and burial of buoyant mines are the ten buoyant mines that were found at the Afsluitdijk during the dike reinforcement in 2021 (T&A Survey, 2021).

As stated above, UXOs are almost exclusively found on the bottom of the seabed and the MEOD detonates UXOs while they are located on the seabed. Hence, the assumption is made that UXO detonation takes place when the UXO is located on the seabed.

4.2.4 Net Explosive Quantity (NEQ) of an UXO

Between and within types of UXOs NEQ charges differ. Many kinds of UXO-types are found that have very different charges of NEQ, see Table 17. NEQ is directly related to environmental effects as an increase in NEQ leads to an increase in amplitude shock and attendant sound wave. Determining effects for each possible UXO-type and corresponding NEQ charges will be too costly and time consuming, therefore standard NEQs are used in this study, see Table 18. For Aerial bombs a variety of NEQ charges are used as there are many different types of aerial bombs with vastly different NEQ charges. Ratios of how aerial bombs are divided over the different NEQ groups is shown in Table 17.

Table 17 Specifications such as category, caliber, origin, NEQ and Ferrous mass of different types of UXOs found in the North Sea. NA= Non-Applicable.

Category	Type	Calibre (lbs)	Origin	NEQ (kg) dependent on type of charge	Ferrous mass (kg) dependent on type of charge
Aerial Bomb	GP MK I-III	250	UK	30,8	81
Aerial Bomb	Demolition	300	US	62	62
Aerial Bomb	GP	500	US	120	107
Aerial Bomb	GP	1000	UK	171,5	314,5
Aerial Bomb	MC	250	UK	37	83
Aerial Bomb	MC	500	UK	101	125
Aerial Bomb	MC	1000	UK	238	311
Aerial Bomb	HC MK I	2000	UK	500	250
Aerial Bomb	HC	4000	UK	1102	605
Aerial Bomb	SAP	250	UK	19	92
Aerial Bomb	SAP	500	UK	41	181
Aerial Bomb	Fragmentation	260	US	15	103
Depth charge	Mk 7	420	UK	130	290
Naval Mine	Moored Mine EMA type IV	NA	GER	82 (guncotton)	200
Naval Mine	Moored Mine type H Mk II	NA	UK	145	>100
Naval Mine	Moored Mine Vickers Elia	NA	UK	227	>150
Naval Mine	Moored Mine EMC	NA	GER	338,5	>150
Naval Mine	Moored Mine EMD	NA	GER	150	480
Naval Mine	Moored Mine MK XIV	NA	UK	227	320
Naval Mine	Moored Mine MK XVII	NA	UK	227	223
Naval Mine	Moored Mine MK XX	NA	UK	145	320
Torpedo	Mk VII, Mk VIII	18 inch	UK	303	>400
Torpedo	G7e	21 inch	GER	280	>1500

Table 18 Overview of the UXOs and NEQs used in the calculations for disturbance distances.

UXO type	NEQ (kg)
Depth charge	130
Torpedo	290
Naval mines	227
Artillery shells	10
Aerial bombs	37
	101
	238
	500
	1102

4.2.5 UXO Degradation

As noted above, an important factor for the high amplitude shock and attendant sound wave that originates by clearing an UXO is the NEQ. In the above table, NEQ is given for different types of UXO in a 'as new' condition. Reality is that the vast majority of all UXOs in the North Sea are already in a saline environment for over 80 years. This means that the NEQ of an UXO is likely subject to significant attenuation due to corrosion and chemical degradation of the explosive components (for example TNT). Important to note is that for chemical degradation of TNT and other explosive components, the casing of an UXO should be breached. In a maritime environment, this is most likely caused by corrosion of the outer casing. Degradation of explosive components would lead to a decrease in explosive power relative to an undegraded UXO with the same NEQ.

Corrosion is influenced by salinity, water temperature and oxygen content in sediments or bottom water. Hydrodynamic conditions of the area can also affect corrosion rates, where energetic regions (strong currents speeds or wave action) tend to correlate with higher corrosion rates (Cumming & Johnson, 2019). The corrosion rate of the ammunition casings is primarily driven by the original wall thickness and used material. Thin metal casings, as used in anti-tank mines, screw threads and driving bands are suspect to a quicker process of (galvanic) corrosion then thick-walled casings of artillery grenades and aerial bombs (Den Otter et al., 2023). HELCOM has made calculations and assumptions for the Baltic Sea, which set the corrosion rate of bombshells at an estimated 0.05-0.575 mm/year, depending upon shell type (Sanderson et al., 2008). For the North Sea, this corrosion rate of UXOs is far slower as discussed below.

For the last two decades, the TNO was involved in monitoring of a Dutch ammunition dump site. This dump site is in the Eastern Scheldt, a former estuary about 12 km inland from the North Sea. Between 1945 and 1967, over 30.000 metric tons of ammunition was dumped in the 'Gat of Zierikzee' (30-55 meter water depth). Almost a third of the dump consists of gun powder, explosive components, and pyrotechnics. The other 21.000 metric tons consists of cased ammunitions, primarily artillery grenades and landmines. In 1999 and 2020, ammunition of the dump site was dived up by researchers for further analysis on corrosion and explosive leakages. Uniform corrosion measured by different types of artillery grenades and mortars amounted to 0.01-0.03 mm/year in 2001 and 0.02 mm/year in 2020 (A. Den Otter et al., 2021). This means that, in line with earlier TNO Research (van Ham et al., 2001), it takes 250 to 500 years for thick-walled casings to be complete dissolved by corrosion. As mentioned earlier, thin-walled casings, screw threads and driving bands will be dissolved over a far shorter period due to galvanic corrosion. Samples of landmines taken from the Eastern Scheldt dump site confirmed this (Den Otter et.al. 2021). Theoretical values of corrosion rates like, for example, zamak alloys range between 2.1 mm/year up to 750 mm/year in aerobic conditions. In anaerobic conditions, it would be expected to be an order of 10 smaller (Verhasselt et al., 2023).

Since the Eastern Scheldt is a former river estuary with other hydrodynamic conditions then the North Sea, we also examined a study about long-term corrosion rate in the Belgian North Sea (De Baere et al., 2021). According to a model developed by Melchers (2003) the long-term corrosion rate, that is after a period of approximately 15 years on the sea bottom at 12.5°C, is predicted to be 0.053 mm/year. After taking and analyzing samples of different Belgian North Sea wrecks, ranging from submarines from the First World War to a sunken fishing vessel in the 1970s, the De

Baere research team estimated a long-term corrosion rate of 0.016 mm/year. The difference between the Melchers model and the research findings is attributed to a high calcareous deposition in the Belgian North Sea (BNS). This deposition is higher than in northern parts of the North Sea, probably due to limestone sands and the calcareous rich geological formation (for example White Cliffs of Dover) near the BNS.

Findings from the Belgium study endorses to a great extent the results of the TNO-research at the Eastern Scheldt dump site. Even if we take the Melchers long-term corrosion rate of 0.0533 mm/year as the guiding principle for the long-term corrosion of UXOs in the Dutch EEZ, it will take 200 years for a typical 75 mm artillery shell to lose its wall casing of 10.6 mm, after dumping in the North Sea. Therefore, it is safe to say that outer degradation of UXOs has a marginal impact on deterioration of the explosive contents within the casing. This is also exemplified by the fact that explosive content of sampled landmines in the Eastern Scheldt appeared most of the time intact, even when they were no longer enclosed by a metal casing (Den Otter et al., 2023). Important to note is that chemical compounds like TNT and RDX were chosen as the main filling of explosives due to their relative stability, which relates with a poor solubility. According to models, the release of TNT from submerged munitions will be very slow with predicted concentrations in the water near the munition in the order of nanograms per liter(Cumming & Johnson, 2019). Therefore, we can safely assume that the wartime NEQ of encountered UXOs is still valid when an UXO is cleared. Observations that explosions are smaller than expected based on the assumed NEQ are attributed to a mismatch in UXO-identification, see paragraph 6.1.2.

5 Estimation of ecological effects on cetaceans

Species have different type of sensitivities to disturbance. For marine mammals, underwater sound plays an important role in general, and of cetaceans in particular. Cetaceans evolved to have acute hearing abilities for perceiving and analyzing acoustic signals that are biologically significant to them in an environment that has a naturally diverse range of sounds. Because sound propagates in water farther and with greater integrity than light, these animals rely primarily on their hearing rather than vision for social interaction, communication, navigation, predator avoidance and foraging (Tyack, 2008). Interference of their hearing ability as a result of underwater explosions may therefore significantly, directly or indirectly, affect their reproduction and longevity, including indirect effects such as stranding, loss of important social bonds (e.g. contact between mother and calf), loss of prey, impaired communication, etc., with significant population level consequences (National Research Council, 2003).

The harbour porpoise is the most abundant marine mammal species in the waters of the Dutch Continental Shelf (DCS) and adjacent waters, followed by the harbour seal (*Phoca vitulina*) and the grey seal (*Halichoerus grypus*). Harbour porpoises possess extremely sensitive hearing making them vulnerable to noise-induced effects from anthropogenic activities at sea (Kastelein et al., 2010b, 2013; Lucke et al., 2009). Small cetacean species, like the harbour porpoise, are at greater risk of injury from both the shock wave and blast injuries (Ketten 2004; von Benda-Beckmann et al., 2015). In this report, the harbour porpoise is used as an indicator species for marine mammals in the North Sea as it is the most sensitive and abundant marine mammal on the DCS. Grey- and harbour seals are less sensitive for underwater sounds than harbour porpoises. Therefore, ecological effects of UXO clearances on harbour populations are not directly indicative for populations of grey- and harbour seals. However, if measures are taken to reduce the effect of underwater sounds produced by UXO clearances on harbour porpoise populations, this will in addition be beneficial for populations of grey and harbour seals.

The impacts of an UXO detonation have the potential to cause injury or death to cetaceans (Von Benda-Beckmann, Aarts, Sertlek, et al., 2015). The highest risks to cetaceans are:

1. Behavioural change, such as disturbance to feeding, mating, breeding, and resting;
2. Auditory impairment, resulting in a temporary or permanent hearing loss such as temporary threshold shift (TTS) and permanent threshold shift (PTS); or
3. Trauma caused by the blast wave, resulting in immediate or eventual mortality.

In this study the first two impacts, behavioural change and auditory impairment are investigated. Auditory impairment is split up into TTS and PTS. TTS and PTS are in this report of greater concern than blast wave trauma due to larger affected areas and coherently, an increased probability of affecting a large number of animals. We assume that by using an ADD the chance of a cetacean being close to the UXO is mitigated and therefore the effect of blast trauma is less of a concern than TTS and PTS. According to the MEOD, ADDs are part of the standard procedure in UXO clearances and it rarely happens that no ADD is used (Interview MEOD, 2023). The effect of blast trauma is not investigated further in this study.

Essential parameters in calculating disturbance of harbour porpoises (avoidance, TTS and PTS) are:

- Number of UXOs
- Disturbed area
- Harbour porpoise density

The number of UXOs found and estimated are shown in chapter 2. Harbour porpoise density will be analyzed in paragraph 5.2. The disturbed area is affected by a variety of parameters, see Figure 12. Sensitivity to sound and thresholds are discussed in paragraph 5.1.1. The disturbed area for each kind of disturbances is calculated in paragraph 5.1.1.

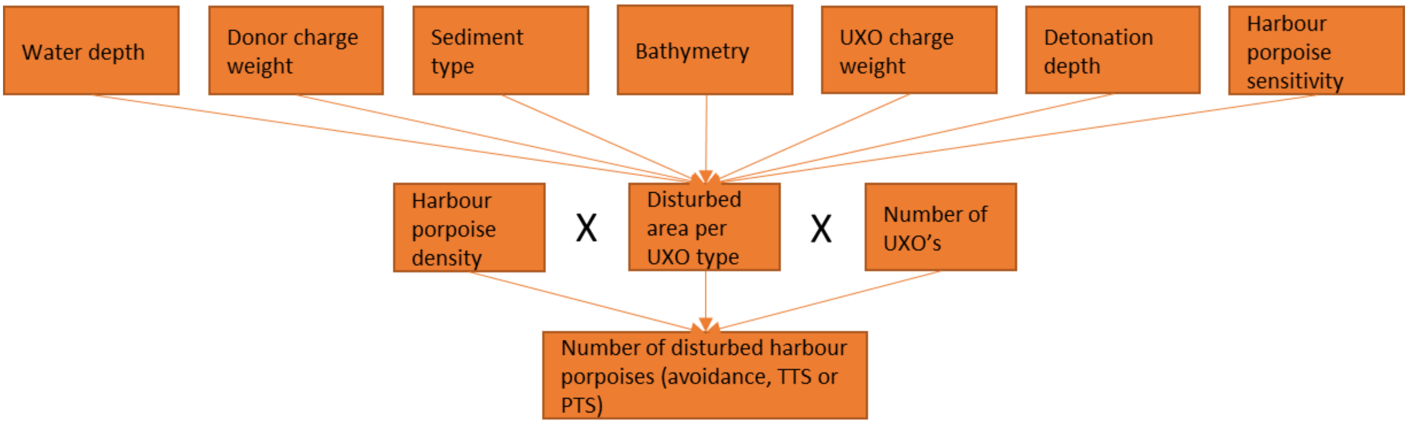

Figure 12 Flowchart for calculating harbour porpoise disturbance in the form of avoidance, TTS or PTS.

5.1 Disturbance

As shown in Figure 12 the disturbed area is affected by biotic parameters, in this case, harbour porpoise sensitivity to sound and abiotic parameters. For the abiotic parameters, only the NEQ (kg) is varied throughout this analysis. For the other abiotic parameters, the assumption is made that these are static. The sensitivity of harbour porpoises is discussed in paragraph 5.1.1

5.1.1 Sensitivity

The hearing range for harbour porpoises is between 100 kHz and 140 kHz (Kastelein et al., 2010a; E. B. L. Southall et al., 2019). Multiple studies on the effects of impulse sounds on the hearing range of harbour porpoises have been published. These effects may manifest themselves in the form of a behavioral response, such as faster breathing and swimming away (avoidance) from the source of the sound, or in the form of a physiological effect on hearing in which animals suffer a Temporary Threshold Shift (TTS) or a Permanent Threshold Shift (PTS) as a result of prolonged exposure to increased sound levels (Benda-Beckmann et al., 2020; Heinis et al., 2022).

Disturbance of animals by sound varies per individual and depends on the context in which the animal is subjected to the sound. Tyack & Thomas, (2019) emphasize the importance of using a dose-response curve when estimating the number of animals that are potentially influenced by sound. However, in this study a rudimentary calculation is used as modelling a dose response curve would be too time consuming, therefore discrete thresholds are used for avoidance, TTS and PTS disturbance.

There is currently no agreed lower threshold for behavioural response from underwater noise for marine mammal species. Behavioural responses induced by an UXO clearance makes an individual spend energy that it wouldn't have spent otherwise. Southall et al., (2007) argues that the onset of behavioural disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient impact on hearing (i.e., TTS). SEAMARCO observations (unpublished) showed that porpoises panicked at an unweighted SPL of 133 dB re 1 μPa2 (SEL = 127 dB re 1 μPa2s; weighting correction -2 dB) to an intermittent tonal sound, with a pulse duration of 300 ms at 11 kHz (including strong harmonics to above 100 kHz) (Von Benda-Beckmann, Aarts, Lucke, et al., 2015). However, no published research is available for the exact UXO clearance induced behavioural response threshold. A best guess threshold for behavioural response is used in this report based on the threshold for TTS (Benda-Beckmann pers. comm 04-10-2023) to give an indication of the magnitude of underwater noise produced by UXO clearances. This number is not converted into harbour porpoise disturbance days, as is standard with other offshore wind park construction activities (Heinis et al., 2022). The lack of insight into the duration or intensity of a behavioural response complicates the comparison of the number of harbour porpoises that show a change in behaviour, with responses to activities that have a more robust foundation in empirical research, like pile driving (Heinis et al., 2022). The fact that pile driving results in repetitive pulses compared to the single strikes that is produced by an UXO clearance makes the limit set as behavioural change with pile driving not applicable to UXO clearances. Instead, the limit at which TTS occurs is backed more by scientific research and can give an indication of the ecological effect of UXO clearances compared to other activities concerning offshore wind park construction.

TTS results in a temporary reduction in hearing ability, and therefore may affect the individuals' fitness temporarily (as recommended in Southall et al., (2007) for a single pulse. PTS results in a permanent reduction in hearing ability, and therefore affects the individuals' fitness permanent.

Explosions cause large peak sound levels that occur only once, when the an explosive is detonated. Because of this the detonation of an explosive does not lead to a cumulation so sound, such as the piling of a wind turbine. That is why in this study SELss values are the metrics used for the thresholds (see text box below). Von Benda-Beckmann et al., (2015), identified hearing impact thresholds on harbour porpoises from single UXO detonations in shallow water (<50 m), and the likelihood of both TTS and PTS occurring at different SELss, see Table 19.

The thresholds used for TTS is 164 dB re 1 µPA^{2}s and for PTS is 179 dB re 1 µPA^{2}s. For harbour porpoise behavioural response, no set threshold is used due to the lack of empirical research. Based on Pers. comm 04-10-2023 with von Benda-Beckmann (Acoustic and sonar expert, TNO) the behavioural response disturbance distance is extrapolated from the TTS-distance, see paragraph 5.1.2.3.

Acoustic metrics

TTS and PTS thresholds are commonly presented as both un-weighted peak Sound Pressure Levels (SPL) (given in units relative to 1 µPa), unweighted broadband Sound Exposure Levels (SEL (given in units relative to 1 µPA^{2}s)) and marine mammal hearing weighted (VHF-weighted) sound exposure levels ((SEL (given in units relative to 1 µPA^{2}s)) (Southall et al., 2019).

In shallow water, estimation of peak sound pressure is challenging because the estimate is very sensitive to bandwidth and geometry (which is poorly known). Uncertainties in geometry lead to small phase uncertainties in arrivals of different sound paths, which can have a large effect on the predicted peak pressure. The estimate of peak sound pressure, therefore, would require a sensitivity study on top of the existing computation load for a single time series. In Von Benda-Beckmann et al., (2015) peak overpressures for which trauma from explosions were observed in harbour porpoises were related instead to effective shallow water SEL thresholds.

SEL single strike (SELss) are the maximum sound level a species may be exposed to before there is a risk of the effect occurring. Therefore, at sound levels up to this level, the effect would not occur. SEL cumulative allows for the assessment to consider whether the total sound level that the individual receives as it flees the area will cumulatively lead to an effect over the period of time assessed. As dual criteria, the onset of PTS or TTS is considered to have occurred when either one of the two metrics is exceeded (Joint Nature Conservation Committee, 2010; National Marine Fisheries Service, 2018).

Table 19 Thresholds related to temporary and permanent hearing loss caused by a single underwater explosion in shallow water (< 50 m) on harbour porpoise. "Very likely" indicates a probability exceeding 95% and "unlikely" indicates a probability of less than 5%. "Increasingly likely" is in between 5% and 95% probability.

<table>
<tr><th>SEL (unweighted dB re 1 µPA^{2}s)</th><th>Noise induced TTS</th><th>Noise induced PTS</th><th>Blast wave-induced ear trauma</th><th>Permanent hearing loss</th></tr>
<tr><td>>203</td><td rowspan="4">Very likely</td><td rowspan="2">Very likely</td><td>Very likely</td><td rowspan="2">Very likely</td></tr>
<tr><td>190-203</td><td>Increasingly likely</td></tr>
<tr><td>179-190</td><td>Increasingly likely</td><td rowspan="3">Unlikely</td><td>Increasingly likely</td></tr>
<tr><td>164-179</td><td rowspan="2">Unlikely</td><td rowspan="2">Unlikely</td></tr>
<tr><td><164</td><td>Unlikely</td></tr>
</table>

5.1.2 Disturbance distances and area

The disturbance distances for behavioural response, TTS and PTS are determined and calculated in this paragraph.

ARCADIS

5.1.2.1 PTS

To calculate the disturbance distances of different NEQs Figure 13 is used. Figure 13 displays the range at which the PTS sound limit for harbour porpoises is exceeded plotted against NEQ of an UXO. This figure is based on the paper of Von Benda-Beckmann et al., (2015). With the NEQs and a water depth of 30 m, see paragraph 4.2.2 for the assumption of water depth, the disturbance distance is estimated, see Table 20. For example, at a NEQ of 100 kg the effect distance at a depth of 30 m is ca. 7 km.

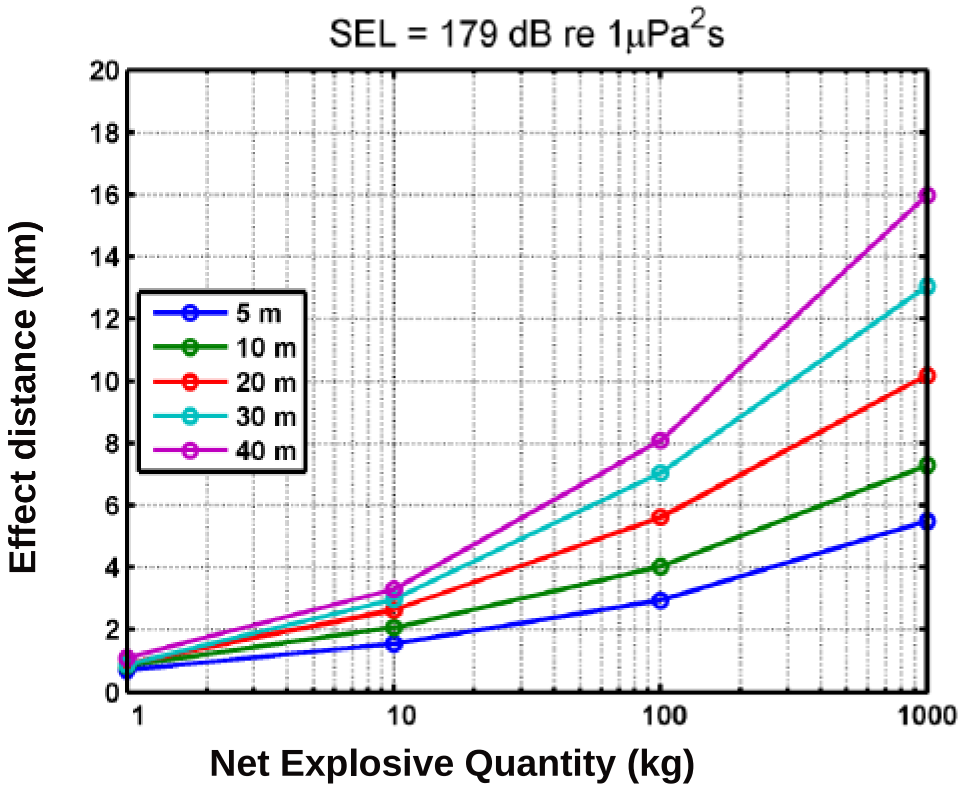

Figure 13 Safety distances in kilometres of which it is very likely no PTS occurs in Harbour porpoise for different Net explosive quantities at different water depths. Lines of different colours indicate different depths of the water column in which UXOs are detonated. In this study a depth of 30 m is used (the turquoise line).

In Table 20 the disturbance distances for different NEQs at which PTS occurs are summarized. NEQ assumptions are summarized in paragraph 4.2.4.. Harbour porpoise density is given in a number per square kilometre that doesn't take water depth into account. Therefore, planar sea surface area is used for calculating harbour porpoise disturbance. The assumption is made that sound travels equally in all directions, thereby disturbing an area with the shape of a circle. The surface area can be calculated with the formulae for circle surface area = r^2*PI, in which r is the disturbance distance. The area in which PTS can occur is shown in Table 20.

Table 20 Harbour porpoise PTS disturbance distances and surface areas for different NEQs with different net explosive quantities at 30 m depth based on Figure 13.

UXO NEQ (kg)	PTS distance (km)	PTS surface (km^2)
1	1	3
10	3	28
37	5,5	95
101	7	154
125 - 130	7,5	177

UXO NEQ (kg)	PTS distance (km)	PTS surface (km^2)
227 - 238	8,5	227
250	9,5	284
290	10	314
500	11	380
1000	13	531

5.1.2.2 TTS

In a variety of reports and papers the TTS disturbance range is calculated for different sizes of UXO's (Robinson et al., 2020, 2022; Salomons et al., 2021; Von Benda-Beckmann, Aarts, Sertlek, et al., 2015). Figure 14 shows the modelled effect distances for a harbour porpoise at 1 m above the bottom of the seabed as a function of SEL thresholds.

In Figure 14 roughly three clusters of lines can be seen, which represent UXOs with a NEQ of 10 kg (yellow line), 125 kg (blue line) and 250 kg (orange line). Based on this and personal communication with Von Benda-Beckmann (04-10-2023) effect distances for TTS can be estimated. For example, the blue line crosses the TTS-threshold (purple dashed line) at 12 km.

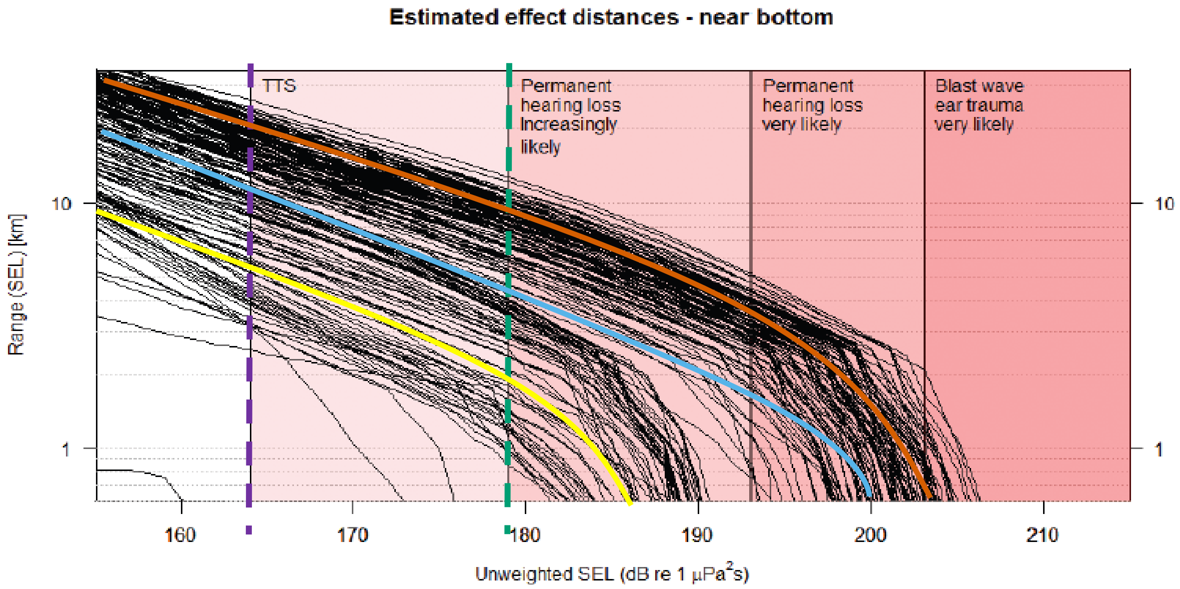

Figure 14 Modelled effect distances for a harbour porpoise at 1 m above the bottom of the seabed as a function of SEL threshold. Each black curve indicates a single explosion in the years 2010 and 2011. Vertical lines bordering the pink shaded areas represent the TTS (purple-dashed line), PTS (green-dashed line) and ear trauma onset threshold values. Averages of the three clusters, NEQ 10 kg (yellow line), 125 kg (blue line) and 250 kg (orange line) are shown(Von Benda-Beckmann, Aarts, Sertlek, et al., 2015).

Based on the three distances from Figure 14 a regression is fit to extrapolate the effect distances for NEQs higher than 250 kg or lower than 10 kg, see Figure 15. It is important to note that this regression is very rudimentary and is only used to gain a grasp of potential different TTS distances for the different UXOs.

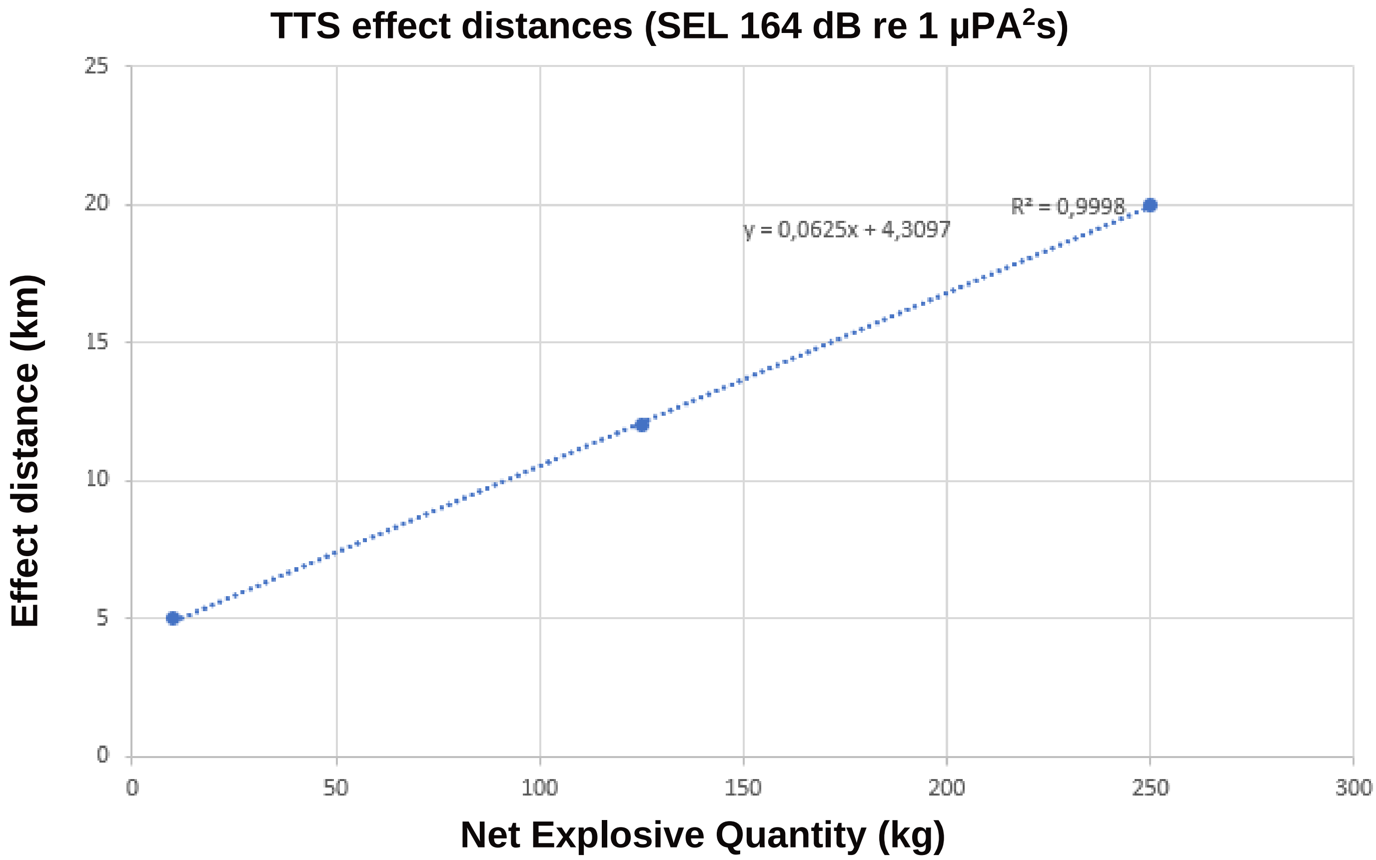

Figure 15 Regression line based on the effects distances for TTS and NEQ of Benda-Beckmann 2015 and personal communication with Benda-Beckmann (04-10-2023). In this formula y is the effect distance and x the NEQ of an UXO. With this regression line UXOs with a higher NEQ than 250 kg or lower NEQ than 1 kg can be extrapolated.

The formula for the regression line is:

Effect distance in kilometres =0,063 * NEQ (kg) + 4,3097

With this formula effect distances for UXO's with smaller e.g.1 kg or larger e.g. 1000 kg NEQs are extrapolated, see Table 21. For example, according to the regression the effect distance of a NEQ of 290 kg is 22,4 km (0,0625*290 + 4,3097). Based on these disturbance distances the TTS-disturbed area is calculated in the same manner as described in paragraph 5.1.2.1.

Table 21 Harbour porpoise TTS disturbance distances and surface areas for different NEQs. The distances of NEQs smaller than 10 kg and larger than 250 kg are extrapolated based on distances from Figure 14 and given by Benda-Beckmann (pers.comm 04-10-2023). It is important to note that this regression is very rudimentary and is only used to gain a grasp of potential different TTS distances for the different UXOs.

UXO NEQ (kg)	TTS distance (km)	TTS surface (km²)
1	4,4	60
10	5	77
37	6,6	138
101	10,6	354

UXO NEQ (kg)	TTS distance (km)	TTS surface (km²)
125	12,0	452
130	12,4	486
227	18,5	1.075
238	19,2	1.156
250	20,0	1.257
290	22,4	1.581
500	35,6	3.973
1102	73,2	16.826

5.1.2.3 Behavioural response

Not much is known about the threshold at which behavioural response in harbour porpoise occurs when detonating UXO's. According to Benda-Beckmann pers.comm. (2023) the disturbance distance for behavioural response is a factor 3 larger than the TTS-disturbance distances. The disturbance distances and surface areas for behavioural response are shown in Table 22.

Table 22 Harbour porpoise behavioural response disturbance distances and surface areas for different NEQs.

UXO NEQ (kg)	Behavioural distance (km)	Behavioural surface (km²)
1	13,1	540
10	15	689
37	19,9	1.240
101	31,9	3.190
125	36,0	4.072
130	37,3	4.372
227	55,5	9.674
238	57,6	10.406
250	60,0	11.310
290	67,3	14.231
500	106,7	35.753
1102	219,6	151.437

5.2 Harbour Porpoise Densities

For the harbour porpoise densities data from Gilles et al., (2020) is used. Gilles et al., (2020) gives detailed harbour summer densities which are also used in the 'Framework for Assessing Ecological and Cumulative Effects 2021 (KEC 4.0) – marine Mammals' (Heinis et al., 2022). Because disturbance distances are so large an average harbour porpoise density of 1,2 ind./km² for the whole DCS is used for the different scenarios. This 1,2 animals/km² is based on the calculated harbour porpoise density of the DCS of 62.771 individuals and the total surface area of 57.500 km² of the DCS, which lead to roughly 1,1 (62.771/57500) animals/km². Based on Gilles et al., (2020) and as a precaution measure a slightly higher harbour porpoise density of 1,2 animals/km² is used.

5.3 Disturbance scenario's

In the following paragraphs the number of harbour porpoise affected by behavioural response, TTS and PTS due to UXO clearances are described. Two scenarios are calculated: worst-case scenario and most-likely scenario. The worst-case scenario uses the conservative approach with regards to harbour porpoise density and number of UXOs expected in each wind farm area. Parameters used for both scenarios are given in Table 23.

Table 23 Parameters used for the worst-case and most-likely scenarios. Highlighted parameters indicate parameters that differ between the worst-case and most-likely scenario.

Parameter	Worst-case scenario	Most-likely scenario
Water depth	30 m	30 m
Donor charge weight	1kg for small (10 kg) UXOs and 12 kg for large (>10 kg) UXOs	1kg for small (10 kg) UXOs and 12 kg for large (>10 kg) UXOs
Sediment	Sand	Sand
UXO location	Located on seabed	Located on seabed
Number of UXOs	Maximum estimation, see paragraph 2.3.1	Data driven estimation, see paragraph 2.3.2
UXO degradation	No degradation, see paragraph 4.2.5	No degradation, see paragraph 4.2.5
Harbour porpoise density	Gilles et al 2020	Gilles et al 2020
Harbour porpoise location	1 meter above seabed	50/50 distribution of harbour porpoise. 1 meter above seabed and 1 meter below surface
Harbour porpoise sensitivity	See paragraph 5.1.1	See paragraph 5.1.1
Time of year	Summer	Summer

Table 18 presents the Net Explosive Quantity (NEQ) for various types of unexploded ordnance (UXO) used in this calculation. Except for aerial bombs, this information has been condensed into a single numerical value. Aerial bombs have been categorized into five size classes, as delineated in Table 17, to encompass the most frequently encountered types. Although aerial bombs with NEQs of 500 kg and 1102 kg are infrequently encountered, their presence poses significant risks, and they have been included in this analysis. The proportions of previously encountered size classes of aerial bombs are given in Table 7 and were used to estimate the quantities for each size class. Due to the rarity of aerial bombs in the 500 kg and 1102 kg size classes, they have been treated separately in the calculations, as the proportions of these size classes were sometimes too low to be assigned to individual wind farm zones.

With the information provided above disturbance-, TTS and PTS zones for different sizes UXOs could be calculated. Figure 16 provides an overview of the sizes of these zones for single UXO detonation with a NEQ of 101 kg.

Figure 16 Surface areas in which harbour porpoise behavioural response (green), TTS (blue) and PTS (red) occurs for a single UXO clearance with a net explosive quantity of 101 kg, which is equal to the most found aerial bomb.

5.3.1 Sample calculation

In this paragraph a sample calculation is provided to explain how the numbers for each scenario were developed. The worst-case scenario for offshore wind farm Nederwiek is taken as an example here.

Step 1: Expected UXOs
From Table 10 the number and types of expected UXOs is used. Most of types of UXOs have different variants and countries of origin but nevertheless are very similar in net explosive quantity, except for aerial bombs. Aerial bomb sizes range from 30 kg to over 1000 kg. Therefore, the number of aerial bombs has been subdivided according to how often each size is encountered proportionally, see Table 7. This sometimes leads to a lower number of expected aerial bombs due to rounding. Note that no NEQ is assigned to UXOS categorized as 'other' as these will be added later in the calculation. This results in the following expected UXOs in Nederwiek (Table 24):

Table 24 Number of expected UXOs in Nederwiek OWF. UXOs have been subdivided into categories with their corresponding size.

UXO type	NEQ	Worst case #UXO
Aerial bombs	37	8
	101	22
	238	14
	500	1

UXO type	NEQ	Worst case #UXO
	1102	0
Naval mines	227	10
Artillery grenades	10	13
Torpedo	290	2
Depth charge	130	2
Other		15
Total		**87**

Step 2: Calculate disturbed areas
In paragraph 5.1.2 an analysis is provided on the distances of the three types of disturbance (behavioural response, TTS and PTS) for different sizes of UXOs. Using these distances, a disturbed area can be calculated for a UXO of a given size. A single aerial bomb with a NEQ of 37 kg results in +/-1.240 km^2 where avoidance behaviour occurs, +/-138 km^2 where TTS occurs and +/-95 km^2 where PTS occurs. The disturbed areas per UXO type is then multiplied with the number of that type (Table 25). In the case of Nederwiek, 8 UXOs with NEQ of 37 kg are expected which lead to around 10.000 km^2 where avoidance behaviour occurs, and around 1.000 km^2 where TTS and PTS occur.

Table 25 Number of expected UXOs in Nederwiek with corresponding disturbed areas per UXO type (large numbers are abbreviated by 1K=1.000).

UXO type	NEQ	Worst case #UXO	Total area with behavioural response (km^2)	Total area with TTS (km^2)	Total area with PTS (km^2)
Aerial bombs	37	8	10K	1K	1K
	101	22	70K	8K	3K
	238	14	1146K	16K	3K
	500	1	36K	4K	400
	1102	0	0	0	0
Naval mines	227	10	97K	11K	2K
Artillery grenades	10	13	9K	1K	400
Torpedo	290	2	18K	3K	600
Depth charge	130	2	9K	1K	400
Other		15			
Total		**87**	**404K**	**45K**	**11K**

Step 3: Correct for UXOs of unknown size
In Nederwiek 15 UXOs were found that are of unknown size. As these can be a variety of sizes this is added on proportionally to the number of 'other' UXOs found. In this case 15/87 are categorized as 'other' so the affected area gets added 15/87 part of it (Table 26).

Table 26 Addition of UXOs categorized as 'other' (large numbers are abbreviated by 1K=1.000).

Total	Total area with behavioural response (km^2)	Total area with TTS (km^2)	Total area with PTS (km^2)
Total without 'other' UXOs	404K	45K	11K
Total with 'other' UXOs	474K	53K	13K

Step 4: Calculate behavioural response affected harbour porpoises, harbour porpoises experiencing TTS and harbour porpoises experiencing PTS.
When multiplying the harbour porpoise density of 1,2 animals/km^2 with the disturbed area the number of disturbed harbour porpoises can be calculated. Note that the number of disturbed animals also includes the number of animals experiencing TTS and PTS as these animals are also impacted by a behavioural response. Similarly, in this calculation the number of animals experiencing TTS also includes the number of animals experiencing PTS as even with PTS hearing can partly recover and it is not yet exactly clear in which hearing range TTS and PTS occur. As a result of predicted UXO clearances in the Nederwiek Wind Farm Area, 63k animals experience TTS, 16k of which also experience PTS.

Table 27 Final step in calculating harbour porpoise affected by behavioural response and number of harbour porpoises experiencing TTS or PTS (large numbers are abbreviated by 1K=1.000).

Total	Behavioural response (# of harbour porpoise)	TTS (# of harbour porpoise)	PTS (# of harbour porpoise)
Affected area	474K	53K	13K
Animal density	1,2	1,2	1,2
Affected animals	569K	63K	16K

Step 5 (only for the most-likely scenario).
The worst-case scenario assumes that all harbour porpoises that are affected by the sound impulse reside near the sea floor where the noise levels are the highest. In reality, only a proportion of the harbour porpoise will reside near the sea floor and the rest will reside near the sea surface or in the water column. Noise levels are genrally lower here, which will result in a reduction in the estimated number of diturbed harbour porpoises. The last step in the calculation for the disturbed harbour porpoises in the most-likely scenario is the reduce the number of affected harbour porpoises (behavioural response, TTS and PTS) according to the percentages in paragraph 5.3.3.

5.3.2 Worst-case scenario

In Table 28 an overview is given for the number of behavioural responses, TTS and PTS affected harbour porpoises per windfarm. For this calculation the worst-case assumptions are used, which are:

- The worst-case expected amount of UXOs (Table 10),
- All harbour porpoises are situated 1 m above the seabed.

The worst-case calculation has resulted in around 2.3 million cases where a harbour porpoise shows a behavioural response, 258 thousand cases of TTS and 60 thousand cases of PTS, see Table 28. Because each UXO clearance is a separate occasion, animals can experience the different disturbance types (Behavioural response, TTS and PTS) on multiple occasions. This is why the sum of behavioural response vastly outnumbers the entire harbour porpoise population of the North Sea.

Due to the way the number of UXO types are calculated, some of the 500 kg and 1102 kg aerial bombs are overlooked in the calculation as their numbers are too low to be assigned to an individual wind farm. These types of aerial bombs are added on separately in the calculation due to their enormous impact (10th and 11th row of Table 28).

Table 28 Results of the worst-case scenario harbour porpoise disturbance calculations (large numbers are abbreviated by 1K=1.000).

Offshore windfarm	Number of UXOs	Behavioural response (# of harbour porpoise)	TTS (# of harbour porpoise)	PTS (# of harbour porpoise)
Hollandse Kust Noord	16	80K	9K	2K
Nederwiek	117	569K	63K	16K
Doordewind	78	388K	43K	11K
IJmuiden Ver	117	569K	63K	16K
Lagelander	39	237K	26K	6K
Hollands Kust West (Noord)	30	140K	16K	4K
Hollandse Kust West (Zuid)	14	58K	6K	2K
Ten noorden van de Wadden	11	64K	7K	2K
500 kg aerial bombs	1	43K	5K	500
1102 kg aerial bombs	1	182K	20K	1K
Total		**2.330K**	**258K**	**60K**

5.3.3 Most-likely scenario

In Table 29 an overview is given for the number of behavioural responses, TTS and PTS affected harbour porpoises per windfarm. For this calculation the following assumptions are used:

- The most-likely expected amount of UXOs (Table 10),
- 50% of harbour porpoises are situated 1 m above the seabed and 50% of the harbour porpoises are situated 1 m below the surface.

The number disturbed harbour porpoises (behavioural response, TTS or PTS) calculated in the worst-case scenario does assume that harbour porpoises that are within the disturbance radius all reside near the sea floor on the moment of shock wave impact. More realistically, some part of the harbour porpoises in the affected area would reside near the surface where sound intensity (SEL) generally is lower (Von Benda-Beckmann, Aarts, Sertlek, et al., 2015). Von Benda-Beckmann et al. (2015) modelled that if it is assumed that 50% of the harbour porpoises reside near the surface and it would lead to a reduction in PTS of almost 40% and a reduction in TTS of around 30%. Von Benda-Beckmann et al. (2015) doesn't model disturbance distances and therefore also doesn't model the reduction in disturbed harbour porpoises with the near surface assumption. But if the trend found with the reduction in PTS and TTS is continued a reduction in harbour porpoises affected by behavioural response of around 10% - 15% could at least be expected. In the most-likely scenario, first the numbers of disturbed harbour porpoises (behavioural response, TTS and PTS) are calculated in a similar way to the worst-case scenario, but with the input from Table 10. A reduction is then applied according to the percentages mentioned in this paragraph.

This has resulted in around 1.2 million behavioural responses, 113.000 cases of TTS and 21.000 cases of PTS, see Table 29.

Table 29 Results of the most-likely scenario harbour porpoise disturbance calculations (large numbers are abbreviated by 1K=1.000).

Offshore windfarm	Number of UXOs	Behavioural response	TTS	PTS
Hollandse Kust Noord	26	89K	8K	2K
Nederwiek	42	225K	21K	4K
Doordewind	62	469K	43K	8K
IJmuiden Ver	42	214K	20K	4K
Lagelander	15	72K	7K	1K
Hollands Kust West (Noord)	12	65K	6K	1K
Hollandse Kust West (Zuid)	5	26K	2K	500
Ten noorden van de Wadden	8	67K	6K	1K
Total		**1.227K**	**113K**	**21K**

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6 Discussion

Construction of offshore windfarms in the period 2023 - 2036 are expected to lead, depending on the scenario, to 157-331 UXOs that need to be cleared. These UXOs have NEQs ranging from small (several kg) to very large (one thousand kg). It is estimated that a total of around 1.2 million behavioural response of harbour porpoises occur, 113.000 impacts of TTS and 21.000 are impacts of PTS. The Greater North Sea population is roughly 373.000 animals (Gilles et al., 2020; Heinis et al., 2022). In the Dutch part of the North Sea, this concerns an average of 63.000 animals, i.e. 17% of the total. This means that the total harbour porpoise population is impacted multiple times, however cumulative effects of multiple UXO clearances are not included in these calculations. For the calculation of the impact of UXO-clearances on the number of harbour porpoises affected by behavioural response, TTS and PTS many parameters are of importance. In paragraph 6.1 the assumptions used for these parameters are discussed. In paragraph 6.2 potential mitigating measures are discussed. In paragraph 6.3 the knowledge gaps are discussed.

6.1 Assumptions

For the calculation of the impact of UXO-clearances many parameters are used. In this paragraph we will discuss several parameters and the assumptions we have made. These parameters are:

- Number of UXOs
- UXO misidentification
- Harbour porpoise density and time of year
- Harbour porpoise location in the water column
- Multiple exposures
- Multiple disturbances

6.1.1 Estimation of UXOs

Little literature and historical documentation can be found about the actual probability of encountering UXO at sea. For the North Sea, some rough estimates are given by the earlier mentioned Port of Rotterdam et.al. (2019) and the Swedish company UXOIntelligence. Only recently, a Dutch research foundation Crisislab has conducted an exploratory study on the Risk Assessment for UXO in the North Sea (Helsloot & Helsloot, 2023). The goal of this study was to formulate the risk that UXOs in the North Sea pose to human health and safety and the acceptability of that risk. As part of this equation, Crisislab looked into the probability of encountering an UXO at sea.

In the Crisislab, (2023) study, the number of UXO per square kilometer was calculated several times with different input data. These densities of UXOs at sea have been derived from the following datasets:

- UXO encounters at 11 UXO surveys (2014-2020)
    - Differentiation between risk and non-risk areas
- UXO encounters by sand dredgers (2008-2014)
- Expected and actual UXO at the Hollandse Kust Zuid Cable routes
- Expected and actual UXO for the Borssele export cables

This leads to the following UXO density results:

Table 30 UXO densities for the North Sea (Crisislab 2023).

Dataset	Size (in km²)	UXO per km2
UXO surveys	55,6	0,927
• *Risk area*		*0,927*
• *Non-risk area*		*0,326*
Sand dredging	718,2	0,441
Cable routes HKZ (actual)	**7,65**	**0,131**
• *Nearshore area (expected)*		*1,3*

Dataset	Size (in km²)	UXO per km2
• *Further at sea (expected)*		*0,5*
Cable routes Borssele (actual) • *Expected*	**13,15**	**0,456** *3,6*

If we compare these densities with our own calculations (0,17 UXO per km² in the worst-case scenario and between 0,06-0,13 per km² in the most-likely scenario), then we see that the estimations of Crisislab are far higher. One of the main reasons why there is such a big difference is the ground principle of Crisislab that they use the most ‘conservative’ estimates for their risk calculations on the probability of UXO accidents and fatalities. This gives an overestimation of the amount of UXOs encountered, as most strikingly seen in the discrepancy between the actual encountered UXOs at Borssele and HKZ and the expected (calculated) amount in the above table.

As stated earlier, we use in our research the available UXO data of the whole (Dutch) North Sea as a starting point, compared to the Crisislab datasets. The Crisislab scope of research is more focused on the (coastal) parts of the North Sea where sand dredging and most of the UXO surveys (for cable routes and the nearshore Wind Farms) were conducted in the past. In these areas, a higher amount of UXOs are expected due to naval warfare in the convoy routes, shooting and exercise areas of artillery and the position of former minefield (with ground mines). This also leads to an overestimation of UXO densities in the Crisislab study, while in our study the encountered UXOs are spread out over a greater area in the worst-case scenario. In the most-likely scenario, we focus on the most likely distribution of the different UXO types across the entire North Sea which leads to lower UXO densities compared to the coastal zones. But since almost all future Offshore Wind Farm Zones are not projected in the coastal zones, this gives in our view a better estimation than the Crisislab study.

Post report discussion Arcadis/Wozep team

After and during delivery of the report the Wozep team and Arcadis found out that the original scope of the project was too narrow to cover all the nuances and challenges of this topic in general. The report covers more than the original idea, but it is still subject to debate and follow-up discussions. Some of those were already discussed with the Wozep team and to add to the context of the report those have been added in these orange blocks. The author of these are Arcadis and the Wozep team.

Both Arcadis and Wozep expected more robust data to be available to provide insights into the UXO effects. For example, for the calculation to determine the density of UXOs different sources were used, which are:

- OSPAR database
- Beneficial Cooperation Data
- Mine registration
- ICES impulsive noise register

These sources originate from different sources, serve different purposes, and cover varying periods over which data was collected. They partly contradict each other. The report did not conduct a thorough comparison of the differences among these sources.

Discrepancies were found among the sources in terms of the reported density of UXOs in the areas studied. The data from these sources varied due to their different origins, objectives, and collection periods. This lack of harmonization in data may have led to conflicting information and challenges in accurately estimating the density of UXOs in the designated areas.

In the maps displayed in this report, the number of reported UXOs in the northern part of the DCS is significantly lower than the southern part. In verbal communication Arcadis reported that this difference is caused by a significantly smaller chance to find UXOs and ammunition because there are less human activities (such as fishery) in the northern part. On the otherside the maps show that during the Second World War more bombers between airports/bases in Great Britain and Germany flew over the southern part of the DCS. One can assume that the estimate in the Arcadis-report based on the uniformal density of UXOs and ammunition on the seabed for the northern part of the DCS is too high, see chapter 2.

The total estimated number of clearances in the report ranges between 157 (in the most-likely scenario) and 313 (worst-case scenario). Furthermore, it is assumed that all encountered ammunition can be cleared and that this actually happens. It is known that a small percentage of the reported UXOs are not found by the Marine Explosieven Opruimingdienst (MEOD).

6.1.2 UXO misidentification

Part of the process after encountering an UXO is that the reporting party needs to identify the encountered UXO to the Dutch Coast Guard. Therefore, an ‘Explosievenkaart’ has been developed by the Coast Guard. The chart gives a general overview of the most common UXOs in the North Sea and is especially for fishermen an aid to recognize UXOs they encounter. Main purpose of the chart is to make the recognition of an UXO and the notification of it to the Coast Guard easier. Therefore, the chart gives some general silhouette pictures of UXOs. This means that the UXO encounters reported to the Coast Guard of Navy in many cases do not refer to the reality, since fishermen are not EOD specialists. The risk of misidentification is increased by two other factors: the different UXOs on the chart are not always given in the right proportions, which makes it hard to tell an aerial bomb apart from a large artillery shell or ground mine. The second factor which often leads to misidentification between those UXO types is caused by the pictures of aerial bombs. These UXO are pictured with their tails, however the tail is seldomly attached to a bomb when encountered. Therefore, aerial bombs are often misidentified and reported as artillery shells or ground mines (Dekker & Moonen Bsc, 2023).

These misidentifications are most of the time not corrected in the datasets of Beneficial Coorperation, OSPAR or the Royal Netherlands Navy. Although the Marine EOD often see a smaller explosion as expected for the reported UXO type during clearing operations, they maintain the Coast Guard reported UXO type in the dataset. Main reason for this decision is that in case of doubt about the identity of a reported UXO, the Marine EOD must stick to a worst-case scenario for the safety of their own personnel. Apart from safety, it is quite hard for the Marine EOD to give a 100% true identification of the encountered UXO due to limited underwater vision for divers or remotely operated vehicles (ROVs). Encountered UXOs are also often partly obscured by sand or aquatic vegetation (de Bruin, pers. comm 13-12-2023).

The only way to get a better insight in these misidentifications is to compare the explosion force/frequency of impulsive sound of every cleared UXO with the reported UXO type. Rijkswaterstaat reports the underwater noise, caused by piling, seismic surveys, explosions and SONAR, every year in a so called ‘Impulsregister’. We looked into the ‘Impulsregisters’ of the period 2015-2022 and of the 266 Noise Level Registrations within the category ‘Explosions’, we could link 183 to an UXO clearance operation. The explosion noise levels themselves are subdivided in the categories ‘medium, high and very high’ which are linked to the following equivalent of TNT charge mass:

- Medium: 2,11-21 kg
- High: 22-210 kg
- Very high: above 210 kg

As reported in paragraph 4.2.4, the NEQ or TNT charge mass of the most encountered offshore UXO types (namely aerial bombs and naval mines) are in the categories high and very high. The NEQ of artillery shells, with the exemption of small aerial bombs, correspondent primarily with the category medium. But if we look at the noise levels of the 183 cleared UXOs we could link to the registrations in the Impulse registers, we see that a lot of aerial bombs and naval mines also fall into the noise category medium, contrary to the expected NEQ. So, at first sight this is clear evidence of UXO misidentification, since we already excluded UXO degradation (paragraph 4.2.5) as a cause for the smaller explosions.

Table 31 Identified UXOs per Noise Level Category.

Noise level	Aerial bombs	Naval mines	Artillery shells	Torpedoes	Depth charges	Other/unknown	Total
Medium	28	34	26	0	3	19	110
High	9	12	8	3	4	22	58
Very high	8	3	0	0	4	0	15

Nevertheless, it remains puzzling that 34 out of 49 naval mines fall into the noise category medium. If we dive deeper into this puzzle, we find that 17 of these 34 naval mines were reported as spherical naval mines who can’t be mixed up with the cylindrical shaped aerial bombs and artillery shells. So, the only explanation for a lower explosion force of these 17 naval mines can be found in the assumption that these mines had already been partially cleared in the past. Hereby is it important to note that the majority of the 17 spherical naval mines were cleared in the same year, which suggests that the UXO clearance operation was conducted in an old naval minefield where previously cleared mines are more likely to be found.

Despite the above-mentioned discrepancy between noise levels and reported UXO types, we do not see this as a problem for our dataset. Misidentification primarily originates from UXOs encountered by fishermen, while we assume that the accuracy of identification by UXO survey companies should be a lot higher. Therefore, the difference in noise levels between encountered and cleared UXOs for the future Offshore Wind Farm Zones are considered to be negligible.

Post report discussion Arcadis/Wozep team

It is noted that in practice (verbal communication of a Defense officer during a meeting) the explosive power is often (much) less than expected based on the identification of the type of UXO. There is no registration of type of UXOs. There are two studies where measurements of explosions have been carried out. However, they provide a mixed picture and the models used are not very good. Furthermore, the studies do not contain data on aircraft bombs, which are common in the DCS. Lepper et al., (2024), found that observations from Great Belt and North Sea measurements suggested many real UXO, although not all, if high-ordered do not generate levels at the full potential of the original historic explosive charge. In the discussion of this report two possible explanations have been raised about differences in expected explosions:

- Incorrect identification (e.g. by fishermen instead of professionals). The argument that future identification by surveyors of the wind areas will result in a much smaller mismatch overlooks the differences present in the databases as a result, see paragraph 6.1.2.
- "Degradation of the ammunition due to corrosion and leakage of explosive charge. The calculation assumes that there is no degradation of the explosives. There are conflicting explanations in the literature regarding this, see paragraph 4.2.5.

Arcadis and Wozep have several recommendations for the follow-up of this research. These are discussed in the conclusion.

6.1.3 Harbour porpoise density and time of year

Harbour porpoise density on the Dutch North Sea changes throughout the year. Table 32 illustrates the seasonal fluctuations in harbour porpoise density in the Greater North Sea (Gilles et al., 2016). In our study we have used the most recent density data from Gilles et al., (2020). This data only contained the summer densities of harbour porpoises in the Greater North Sea. Based on the data in Gilles et al. (2020) a single density value (1,2 animals/km^2) was calculated for the whole Dutch North Sea. Based on this density the number of impacted harbour porpoises were calculated. In this calculation no differentiation between the seasons was used. When adjusting for the seasons the number of impacted harbour porpoises will, depending on the season, be higher or lower. Based on Gilles et al., (2016), the number of harbour porpoise impacted can be reduced by clearing unexploded ordnances (UXOs) during the fall season. However, in terms of practicality the fall season is not the best season for UXO clearnances to a higher chance of the weather being bad. Moreover, Postponing an UXO clearance to the fall season after finding it in spring or summer would also be impossible due to the high dynamics of the sea floor.

Table 32 Seasonal fluctuations in harbour porpoise density in the Greater North Sea (Gilles et al., 2016).

Parameter	Spring	Summer	Fall
Abundance (N)	372,167	361,146	228,913
CV (model)	0.006	0.001	0.003
CV (group size)	0.01	0.01	0.02
CV (weighted mean esw)	0.18	0.12	0.19
CV (ship g(0))	–	0.16	–
CV_{all} (N)	0.18	0.20	0.19
Lower 95% CI	260,658	243,827	159,264
Upper 95% CI	531,380	534,913	329,022
Density	0.91	0.88	0.56

The calculations in this report do not account for the size and borders of the Dutch EEZ. Instead have chosen to use the habour porpoise density in the Dutch EEZ for parts where UXO disturbance would overlap with areas outside of the Dutch EEZ. UXO disturbance distances are large and easily cross the border of the Dutch EEZ (Figure 16). Taking the border of the Dutch EEZ into account would lead to an UXO on the border having half the disturbance of an UXO far from the border. Detailed UXO locations are impossible to predict and are not within the scope of this report. Harbour porpoises are mobile animals and are a migratory species. Therefore, the harbour porpoises in the Ducth EEZ are part of the bigger population in the entire southern North Sea and vice versa (Ministerie van LNV, 2014).

6.1.4 Harbour porpoise location in the water column

As mentioned in paragraph 5.3.3 Von Benda-Beckmann et al. (2015) modelled that if it is assumed that 50% of the harbour porpoises reside near the surface it would lead to a reduction in PTS of almost 40% and a reduction in TTS of around 30%. Von Benda-Beckmann et al. (2015) doesn't model disturbance distances and therefore also doesn't model the reduction in disturbed harbour porpoises with the near surface assumption. But if the trend found with the reduction in PTS and TTS is continued a reduction for behavioural response of around 10% - 15% could be expected. However, this reduction for behavioural response has many uncertainties. These uncertainties are linked to multiple parameters such as harbour porpoise sensitivity and the reduction of PTS and TTS impacted harbour porpoises. There is no further information known to us that links harbour porpoise placement in the water column to UXO-disturbances. Which enables us to verify the 10-15% reduction in behavioural change impacted harbour porpoises. As there is no other data available known to us, we have used the 10-15% reduction in this study.

6.1.5 Multiple exposures

For each UXO-clearance the impacted area is calculated and based on this and the harbour porpoise density the number of impacted harbour porpoises are calculated. The total impact of UXO clearances sums the impacts of all these single UXO-clearances. This leads to an overestimation of the number of impacted harbour porpoises as multiple exposures are not included. Little knowledge on the swimming behaviour, habitat use and (seasonal) migration pattern of harbour porpoises in Dutch waters is known. Therefore, it is not possible to assess whether how many multiple exposures of individual animals occur. However, when corrected for the number of multiple exposures the number of impacted harbour porpoises will be lower than calculated in this study.

6.1.6 Multiple disturbances

In the calculations, the number of disturbed animals also includes the number of animals experiencing TTS and PTS as these animals are also impacted by a behavioural response. Similarly, the number of animals experiencing TTS also includes the number of animals experiencing PTS as even with PTS hearing can partly recover and it is not yet exactly clear in which hearing range TTS and PTS occur. Therefore, it is not possible to exclude in the calculations the number of harbour porpoises that are impacted by PTS from harbour porpoises affected by TTS or behavioural responseTherefore, the number harbour porpoises affected by behavioural response in Table 29 includes the number of TTS and PTS disturbed animals.

6.2 Mitigation measures

There are several shot-term action mitigation measures which are 'low-hanging fruit' and more long-term actions to further develop promising mitigation concepts. The short-term actions, which are implemented without a big impact on the ongoing clearance procedures, and which are already part of the procedure used by the MEOD, see paragraph 3.1, are:

- Use of proper acoustic deterrent devices prior to clearing activities, to deter harbour porpoises from the explosion site. It is advised to activate the deterrent device 30 minutes prior to the detonation.
- Use of dedicated and trained visual observers prior to explosions.

These measures may be sufficient to avoid direct mortal injury but are insufficient to avoid PTS or TTS. For larger explosions the use of bubble screens should therefore be considered. This technology has been shown to work for larger explosions, and systems are commercially available. By using bubble screens as mitigating measure, the number of harbour porpoises impacted is decreased. However, it is unknown in what magnitude the disturbance will decrease. This technique is currently not adopted by the MEOD as it requires an enormous investment in material and the resulting time investment per UXO detonation makes clearance hard to plan as the MEOD usually has a one-hour time window (*Interview MEOD*, 2023).

In the longer term, it is advised to develop feasible and cost-effective mitigation options. Options that are interesting to pursue but require more research to judge their effectiveness and feasibility, are:

- Generation of an air pocket using delayed charges
- Detonate explosive close to sea surface
- Methods for re-acquiring explosives after longer time-scales (~ several months) to allow for temporal avoidance
- Acoustic and visual harbour porpoise monitoring concepts
- Deflagration

We believe the most beneficial measure to reduce the impact on harbour porpoises, when clearing UXOs, is deflagration. UXO deflagration refers to the controlled burning or slow combustion of unexploded ordnance (UXO) in a controlled and deliberate manner. This method would seriously decrease the amount of disturbance caused by UXO clearance and generates lower noise levels compared to high order detonation. This can vastly decrease the number of harbour porpoises experiencing disturbance. Lepper et al. (2024) found a decrease of around 15 – 20 dB (SEL) in amplitude noise levels when low order deflagrations were applied instead of high order detonation. Similar levels are found in Robinson et al. (2020). Moreover, noise levels corresponded to the NEQ of the charge mass rather than the explosive quantity of the UXO. This mitigation measure will likely have the largest impact in decreasing the disturbance of harbour porpoise. In recent years, this method of UXO clearance has become commonly prescribed and used by UXO clearing surveys in the United Kingdom and the United States (UK Government Policy Paper 2022; Seagreen 2022; NOAA 2022). Deflagration is currently not adopted by the MEOD as the MEOD does not possess technology and knowledge to use this approach, and there are certain risks involved that the MEOD has not yet overcome (*Interview MEOD*, 2023).

6.3 Knowledge gaps

The predicted impact contains considerable uncertainties, which can be attributed to the following knowledge gaps that were identified in this study:

- Lack of data for behavioural response onset in harbour porpoises due to impulsive sounds
- Lack of data on harbour porpoise sensitivity to UXO-clearances
- Lack of data on behavioural response reduction bases on the position of harbour porpoises in the water column
- Lack of data on TTS-disturbance distances for different NEQs

6.3.1 Lack of data for behavioural response onset in harbour porpoises due to impulsive sounds

In this study we used the TTS-threshold as the threshold at which an effect on the fitness of individual harbour porpoises can occur. At lower sound levels the harbour porpoises are affected by a behavioural response. However, the impact and duration of behavioural responses of harbour porpoises due to UXO-clearances are unknown. More research is therefore necessary.

6.3.2 Harbour porpoise sensitivity to UXO-clearances

The uncertainties in the sensitivity of harbour porpoises to underwater sound is the biggest contributor to the large uncertainties in the estimated impact. When sensitivities levels of harbour porpoises to underwater piling sound are used the number of disturbed harbour porpoises is very large. However, it is very likely that harbour porpoises respond differently to an exploding ordnance than to the continuous piling of turbines. Currently studies on potential behavioral effects and impacts of harbour porpoises to single detonation events are scarce. More studies of behavioural responses to various levels of detonation transients are therefore necessary.

As mentioned in Von Benda-Beckmann et al., (2015), in order to better judge the risk of injury (hearing damage) to porpoises requires better understanding of the TTS growth, affected frequency range and recovery for broadband impulsive sound sources, and better understanding characteristics of the shock-wave, such as field vs. far field loading effects, exponential vs sinusoidal bursts, and synergistic effects of rate of pressure increase, peak pressure, waveform and duration rise time, determine the risk of injury, and their interactions. This is required to allow for better extrapolation of the small-scale controlled experimental conditions to real-life (large explosive, large distances, and shallow water) environments.

Post report discussion Arcadis/Wozep team

Arcadis has included an estimate of the disturbed number of harbor porpoise in the report. This estimate is based on the knowledge built around the effects of pile driving noise. As mentioned in the discussion, harbour sensitivity is different between pile-driving and UXO detonation. Similar to Arcadis, Wozep has also observed that disturbances of UXOs are fundamentally different from disturbances caused by piling. UXOs involve single impacts instead of repeated impacts. The harbor porpoise disturbances should not be confused with the harbor porpoise disturbance days used in the KEC. The effects will therefore only last briefly at most and will almost have no lasting impact on the population.

6.3.3 Behavioural response reduction

As mentioned in paragraph 6.1.4 the number of harbour porpoises that had a behavioural response due the clearing of UXOs is affected by the location of the harbour porpoise in the water column. More research on the movement patterns of harbour porpoises within the water column is needed to get a better idea of the number of impacted harbour porpoises.

6.3.4 TTS-disturbance distances for different NEQs

PTS-disturbance distances are based of Figure 13 which in-turn is based on a study of Von Benda-Beckmann et al., (2015). There is not a graph or figure like figure 13 that shows TTS-disturbance distances versus the NEQ at different depths. TTS-disturbance distances are thereofore based of Figure 14. However, in this figure there are roughly only three NEQ clusters with a NEQ of 10 kg (yellow line), 125 kg (blue line) and 250 kg (orange line). Based on this and personal communication with Von Benda-Beckmann (04-10-2023) TTS-disturbance distances for these three clusters were estimated. Based on the NEQs and disturbance distances an extrapolation was done to see what the TTS-disturbance distances were for NEQs at smaller than 10 kg and larger than 250 kg. This extrapolation was done by creating a regression line, see Figure 15. This regression line is based on only three data points. To allow for a better extrapolation of TTS-disturbance distances for different NEQs more data points are needed.

7 Conclusion

For all scenario's the number of harbour porpoises disturbed is large and the clearance of UXOs has a major impact on the harbour porpoise population density of the North Sea. However, there are many uncertainties when calculating the impact of UXO clearances on the harbour porpoise community of the North Sea. These uncertainties are attributed to the following factors:

- Uncertainties in reported UXOs
- Estimation of the number of UXOs
- Harbour porpoise densities
- Lack of data of sensitivity of harbour porpoises exposed to explosion shockwaves and broadband impulsive sound
- Multiple exposures of harbour porpoises, related to lack of knowledge on movement patterns and habitat use of harbour porpoises

From an ecological perspective, mitigating measures are essential to reduce the impact on the harbour porpoise community. Short-term options, of which the MEOD uses some, see paragraph 6.2, need to be used to mitigate the impact of harbour porpoises. These measures are:

- Use of acoustic deterrent devices
- Use of trained marine mammal observers for visual monitoring
- Use of bubble screens for larger explosives

We believe the most beneficial measure to reduce the impact on harbour porpoises, when clearing UXOs, is deflagration. Therefore, it is advised to include deflagration as a standard mitigating measure. However, more research on creating a reliable method for deflagration is needed. Furthermore, there are other potential next steps which could help to better understand the impact of UXO clearances, gain more knowledge of the uncertainties or mitigate the impact. We advise to:

- Incorporate the disturbance of the harbour porpoise by the clearance of UXOs is in such an order of magnitude that it is advised to include it in the next KEC.
- Prescribe European Protected Species Risk Assessments on UXO clearance for windfarm construction, including a marine mammal mitigation plan.
- Bring different stakeholders (Marine EOD, UXO Survey Companies, Rijkswaterstaat, TNO, Ministry of Agriculture, Nature and Food Quality) together to discuss the impact of UXO clearances on marine mammals.
- Execute more research on the sensitivity of harbour porpoises to single signal disturbances, such as clearing of explosives and their movement patterns within the water column in the North Sea.

Discussion and follow-up

Based on the above mentioned considerations concerning the estimated numbers and effects, we assume that the estimated number of harbor porpoises with TTS and PTS, even in the 'most-likely' estimation identified by Arcadis, is an overestimation of reality. There are several knowledge gaps mentioned by Arcadis, paragraph 6.3, which go into further detail. Potential causes for these knowledge gaps aren't mentioned but these are:

- A persistent lack of clarity regarding the responsibilities of the various ministries concerning UXOs at sea.
- Scarcely available acoustic measurements, partly due to clearances being planned and executed on a very short notice. Research is needed on how such measurements can be made possible.

To deal with these issues the following recommendations are done by Arcadis and the Wozep team:

- Registration of categories of explosive power upon detonation at sea could be a valuable addition to the available information.
- Additionally, we recommend doing a recalculation to the number of clearances and the number of animals affected when more robust data is available.

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Colophon

ENVIRONMENTAL EFFECTS OF UXO-CLEARANCES
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CLIENT
Rijkswaterstaat

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