Offshore Wind Farm Triton

Underwater noise
Technical report

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Contents

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Rev. 1: Added results for HSD-DBBC NAS and month of June

Summary

In connection with the environmental impact assessment for Triton Offshore Wind Farm in the Swedish part of the Baltic Sea, approximately 35 km south of Ystad, NIRAS has carried out underwater sound propagation modelling. This, to inform the impact assessment of marine mammals and fish, of the noise emission resulting from foundation installation within the offshore wind farm site.

Based on initial test calculations for two foundation scenarios; a single 14 m monopile and a 4 legged jacket foundation with 4x 4.5 m pin piles, the worst case scenario was determined to be the former. Underwater sound emission was therefore calculated for a 14 m diameter monopile foundation at four source positions within the Triton area.

A 3D acoustic model was created in dBSea 2.3.2, utilizing detailed knowledge of bathymetry, seabed sediment composition, water column salinity, temperature and sound speed profile as well as a source model based on best available knowledge. The modelling was conducted under the assumption of application of a Noise Abatement System (NAS). Modelling without (NAS) has not been conducted as pile driving without application of a NAS is considered an unrealistic scenario. Using advanced underwater sound propagation algorithms, the sound emission from each scenario was calculated in 180 directions (2° resolution).

Impact distances for relevant frequency weighted species specific threshold levels were calculated from the sound propagation models. These include safe starting distance for Harbour Porpoise (*Phocoena phocoena*) and earless seals in order to prevent Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS), based on threshold levels in (NOAA, April 2018). For Harbour Porpoise, the distance to behaviour impact was also calculated. Impact distances for TTS and injury threshold levels for Cod and Herring, as well as Injury for larvae and eggs were also calculated. All impact distances, are based on the 14 m monopile scenario with an active Big Bubble Curtain equivalent Noise Abatement System (BBC NAS) as well as for a Hydro Sound Damper Double Big Bubble Curtain (HSD-DBBC NAS). Impact distances to each threshold are shown in Table 1.1 - Table 1.2 for marine mammals and in Table 1.3 for fish. In addition, a measurable single-strike control value is given in Table 1.4 - Table 1.5 for each of the marine mammal and fish scenarios.

Threshold distances for Injury, PTS and TTS describe the minimum distance from the source, a marine mammal or fish must at least be, prior to onset of pile driving, in order to avoid the respective impact. It therefore does not represent a specific measurable sound level, but rather a safe starting position.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike.

Table 1.1: Resulting threshold impact distances for marine mammals for the worst case month of March.

Species	Mitigation	Position	Distance to impact threshold [m]		
			SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS	PTS	Behaviour
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	300	< 25	11 500
		2	225	< 25	10 900
		3	225	< 25	11 600
		4	180	< 25	11 300
	HSD-DBBC	1	< 50	< 25	6 700
		2	< 50	< 25	6 200
		3	< 50	< 25	6 400
		4	< 50	< 25	6 400
Phocid Pinniped (Harbour seal)	BBC	1	825	< 25	-
		2	400	< 25	-
		3	675	< 25	-
		4	225	< 25	-
	HSD-DBBC	1	< 50	< 25	-
		2	< 50	< 25	-
		3	< 50	< 25	-
		4	< 50	< 25	-
*: Species specific frequency weighting applied					

Table 1.2: Resulting threshold impact distances for harbour porpoise for the month of June.

Species	Mitigation	Position	Distance to impact threshold [m]		
			SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS	PTS	Behaviour
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	190	< 25	6 800
		2	160	< 25	6 200
		3	170	< 25	6 300
		4	130	< 25	4 700
	HSD-DBBC	1	< 50	< 25	4 300
		2	< 50	< 25	3 800
		3	< 50	< 25	4 000
		4	< 50	< 25	3 300
*: Species specific frequency weighting applied					

Table 1.3: Resulting threshold impact distances for fish for the worst case month of March.

Species (age, fleeing speed)	Mitigation	Position	$SEL_{C24h,\mathrm{unweighted}}$ [m]	
			TTS	Injury
Cod (Juvenile, 0.38 m/s)	BBC	1	23 900	90
		2	22 700	< 50
		3	23 400	60
		4	20 200	< 50
	HSD-DBBC	1	14 000	< 25
		2	13 200	< 25
		3	13 300	< 25
		4	10 900	< 25
Cod (Adult, 0.9 m/s)	BBC	1	19 400	< 25
		2	18 100	< 25
		3	18 700	< 25
		4	15 600	< 25
	HSD-DBBC	1	9 900	< 25
		2	8 800	< 25
		3	9 400	< 25
		4	7 200	< 25
Herring (1.04 m/s)	BBC	1	18 100	< 25
		2	17 100	< 25
		3	17 600	< 25
		4	14 500	< 25
	HSD-DBBC	1	9 100	< 25
		2	7 900	< 25
		3	8 500	< 25
		4	6 400	< 25
Larvae and eggs (0 m/s)	BBC	1	-	1 300
		2	-	1 150
		3	-	1 300
		4	-	1 050
	HSD-DBBC	1	-	550
		2	-	500
		3	-	520
		4	-	500

Table 1.4: Sound Exposure Level ($SEL_{SS@750m,<weighting>}$) from a single pile strike using maximum hammer energy, for the worst case month of March.

Species	Mitigation	Mitigation	Sound Exposure Level, at 750 m $SEL_{SS@750m}$ $[dB\ re. 1\mu Pa^2 s]$*
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	120.2
		2	118.8
		3	118.9
		4	117.5
	HSD-DBBC	1	111.6
		2	110.2
		3	110.7
		4	109.3
Phocid Pinniped (Harbour seal)	BBC	1	145.9
		2	145.5
		3	145.8
		4	145.3
	HSD-DBBC	1	141.9
		2	141.5
		3	141.8
		4	141.3
Unweighted (Fish)	BBC	1	171.1
		2	170.5
		3	170.9
		4	170.3
	HSD-DBBC	1	166.3
		2	165.8
		3	166.2
		4	165.5
*: Species specific frequency weighting applied			

Table 1.5: Sound Exposure Level ($SEL_{SS@750m,<weighting>}$) from a single pile strike using maximum hammer energy, for June month.

Species	Mitigation	Mitigation	Sound Exposure Level, at 750 m $SEL_{SS@750m}$ $[dB\ re. 1\mu Pa^2 s]$*
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	119.1
		2	117.9
		3	118.3
		4	117.5
	HSD-DBBC	1	111.2
		2	109.9
		3	110.3
		4	109.7

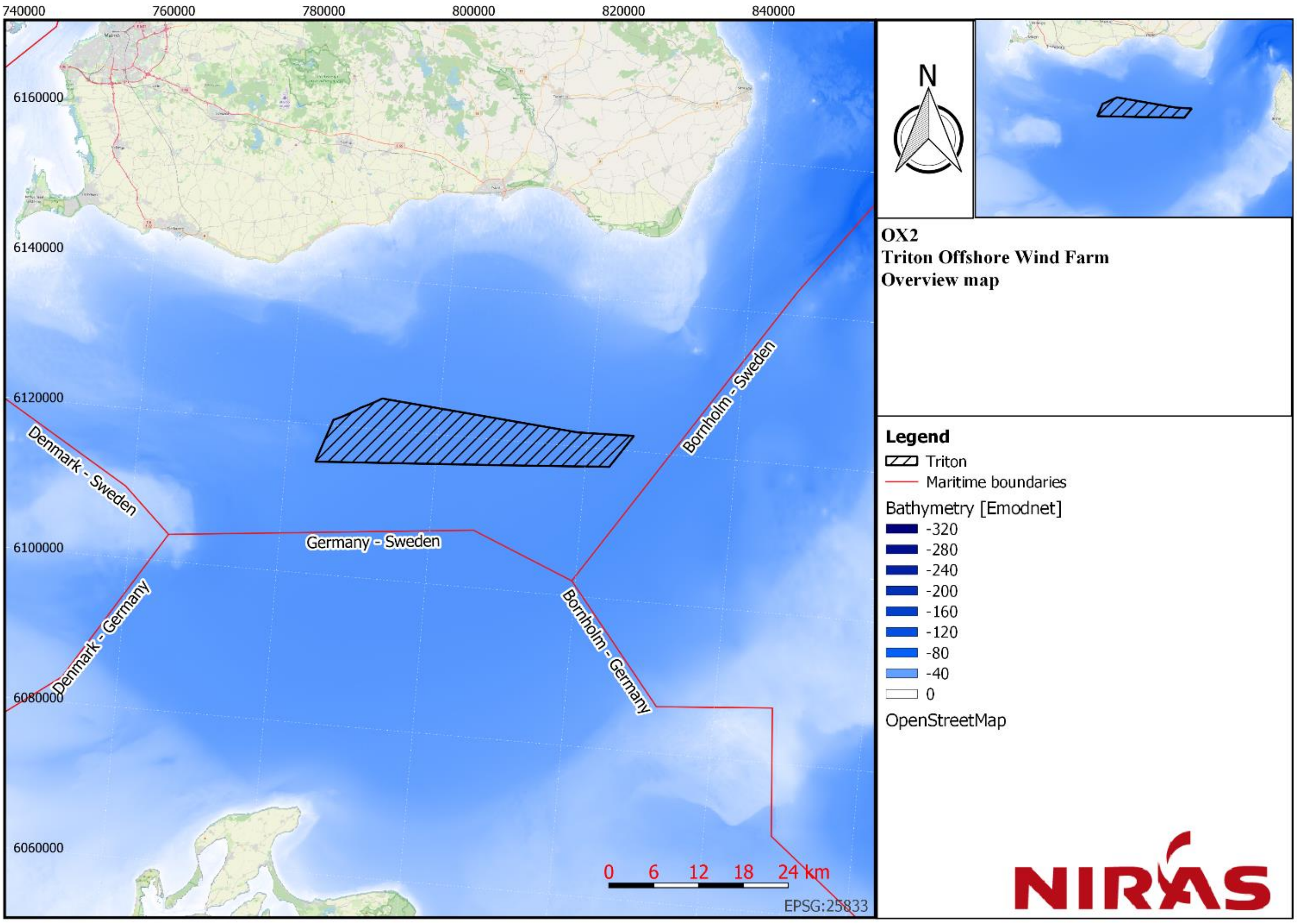
List of abbreviations

Full name	Abbreviation
Offshore Wind Farm	OWF
Sound Exposure Level	SEL
Cumulative Sound Exposure Level	SEL_{C24h}
Sound Pressure Level	SPL
Permanent Threshold Shift	PTS
Temporary Threshold Shift	TTS
National Oceanographic and Atmospheric Administration	NOAA
Noise Abatement System	NAS
Low-frequency	LF
High-frequency	HF
Very High-frequency	VHF
Big Bubble Curtain	BBC
Double Big Bubble Curtain	DBBC
Hydro Sound Damper	HSD
IHC Noise Mitigation Screen	IHC-NMS
World Ocean Atlas 2018	WOA18
Normal modes	NM
Parabolic Equation	PE

1 Introduction

This report documents the underwater sound propagation modelling in connection with the environmental impact assessment for the installation of wind turbine foundations at Triton offshore wind farm (OWF). Triton OWF site is located in the Swedish part of the Baltic sea, see Figure 1.1, approximately 35 km south of Ystad. The wind farm site is located close to the German EEZ indicated by the red line labelled "Germany-Sweden" south of the wind farm site, see Figure 1.1. From the figure it can be seen that the OWF is also relative close to the Danish EEZ (Bornholm-Sweden) indicated by the red line to the east of the wind farm.

Figure 1.1: Overview of Triton offshore wind farm site and surrounding area.



The project includes installation of up to 129 wind turbines, on monopile foundations up to 14 m diameter. The foundation type are proposed installed using impact pile driving, which, from an underwater noise perspective, carries the risk of negatively impacting nearby marine mammals and fish. In order to reduce this impact, a number of mitigating measures are included in the underwater noise calculations.

The report documents impact ranges for all relevant threshold levels outlined in the background reports for the impact on marine mammals (NIRAS A/S, 2021) and fish (Öhman, et al., 2021).

2 Purpose

The purpose of this report is to document the underwater sound propagation modelling carried out for the installation of wind turbine foundations at Triton OWF, as well as to calculate impact distances to relevant thresholds for marine mammals and fish for the worst case scenario.

3 Background

This chapter discusses general background knowledge for underwater noise, with definitions of used noise metrics, guideline requirements as well as threshold levels for quantifying the impact of noise.

3.1 Sound level metrics

In the following, the reader is introduced to the acoustic metrics used throughout the report for quantifying the sound levels.

3.1.1 Sound Pressure Level ($\mathbf{SPL_{RMS}}$)

In underwater noise modelling, the Sound Pressure Level (SPL) is commonly used to quantify the noise level at a specific position, and used for assessing the behavioural response of marine mammals as a result of noisy activities. The definition given in (Erbe, 2011) is shown in Equation 1.

$$\mathrm{SPL_{RMS}} = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{\mathrm{T}}\right)\int_{\mathrm{T}} \mathrm{p(t)}^2}\right) \quad [\mathrm{dB\ re.\ 1\mu Pa}] \qquad \text{Equation 1}$$

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. $\mathrm{SPL_{RMS}}$ can be seen as the average unweighted sound pressure level over a measured period of time. The time window must be specified for the metric. Often, a fixed time window of 125 ms, also called "fast", is used due to the integration time of the mammal ear (Jakob Tougaard, 2018). The metric is then referred to as $\mathrm{SPL_{RMS-fast}}$.

3.1.2 Sound Exposure Level ($\mathbf{SEL}$)

Another important metric is the Sound Exposure Level (SEL), which describes the total energy of a noise event (Jacobsen & Juhl, 2013). A noise event can for instance be the installation of a monopile by impact pile driving, from the start to the end, or it can be a single noise event like an explosion.

The SEL is normalized to 1 second, and is defined in (Martin, et al., 2019) through Equation 2.

$$\mathrm{SEL} = 10\log_{10}\left(\frac{1}{\mathrm{T_0 p_0^2}}\int_0^{\mathrm{T}} \mathrm{p^2(t)}\right) \quad [\mathrm{dB\ re.\ 1\mu Pa^2 s}] \qquad \text{Equation 2}$$

Where $\mathrm{T_0}$ is 1 second, 0 is the starting time and T is end time of the noise event, p is the pressure, and $\mathrm{p_0}$ is the reference sound pressure which is $1\ \mu\mathrm{Pa}$. When SEL is used for reference to a single impulse, the term $\mathrm{SEL_{SS}}$ is sometimes used. When the SEL is used to describe the sum of noise from more than a single event (e.g. several pile driving pulses), the term Cumulative SEL, or $\mathrm{SEL_{C,<duration>}}$ is typically used.

Marine mammals can incur hearing loss, either temporarily or permanently as a result of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure, and the SEL is therefore a commonly used term to assess the risk of hearing impairment as a result of noisy activities. (Martin, et al., 2019).

The relationship between $\mathrm{SPL_{RMS}}$ in Equation 1 and SEL, in Equation 2, is given by Equation 3 (Erbe, 2011).

$$\mathrm{SEL} = \mathrm{SPL_{RMS}} + 10 * \log_{10}(\mathrm{T}) \qquad \text{Equation 3}$$

3.1.3 Fleeing behavior model

As mentioned in section 3.1.2, $\mathrm{SEL_{C,<duration>}}$ is useful for determining the combined noise impact from sound sources with a duration of more than a single pulse. In the assessment of temporary threshold shift (TTS), permanent threshold shift (PTS) and injury caused by underwater noise on marine mammals and fish, $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$ is used to describe the noise dose received by the receptors. It is therefore important to include the behaviour of fish and marine mammals in the calculation of $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$. For a stationary source, such as installation of a foundation, the installation procedure, as well as the fleeing speed for the receptor, must be included. A method for implementing such conditions in the calculation of $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$ has already been done by (Energistyrelsen, 2016), for the Danish guidelines for pile driving activities, as given by Equation 4. Here, the duration is fixed to 24h to represent the daily $\mathrm{SEL}_{\mathrm{C}}$. If multiple foundations are installed in the same 24 hour window, they all have to be included in the calculation.

$$\mathrm{SEL}_{\mathrm{C24h}} = 10 * \log_{10}\left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{S_i}}{100\%} * 10^{\left(\frac{\mathrm{SEL_{Max}} - \mathrm{X}*\log_{10}(\mathrm{r_0}+\mathrm{v_f}*\Delta \mathrm{t_i}) - \mathrm{A}*(\mathrm{r_0}+\mathrm{v_f}*\Delta \mathrm{t_i})}{10}\right)}\right) \qquad \text{Equation 4}$$

Where:

- $\mathrm{S_i}$ is the percentage of full hammer energy of the i'th strike
- N is the total number of strikes for the pile installation
- $\mathrm{SEL_{Max}}$ is the source level at 1 m distance at 100% hammer energy
- X and A describe the sound propagation losses for the specific project site
- $\mathrm{r_0}$ is the marine mammal distance to source at the onset of piling
- $\mathrm{v_f}$ is the fleeing speed of the marine mammal directly away from the source
- $\Delta \mathrm{t_i}$ is the time difference between onset of piling, and the i'th strike.

The parameters related to the source level, hammer energy, number of strikes and time between each strike must be based on realistic assumptions and can be achieved through a site specific drivability analysis. The relationship between hammer energy level and pile strike number is referred to as the hammer curve.

The sound propagation parameters (X and A) must be determined through an advanced sound propagation model, in which all relevant site specific environmental parameters are taken into account.

The calculation model presented in Equation 4, is used throughout the report for all calculations of $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$. Furthermore, the Danish approach of looking at all installations occurring within a 24 hour period is adopted, and $\mathrm{SEL}_{\mathrm{C24h}}$ is therefore used for the remainder of this report.

3.2 Underwater noise impact criteria

Guidance or threshold values for regulating underwater noise during construction of OWFs (pile driving) have been developed by several different countries and international organizations. There are different approaches in the different countries when it comes to estimating impacts from pile driving on marine mammals and fish. The project area is located in Swedish waters, and Sweden does not have established guidelines for impact pile driving. A more thorough review of guidelines and threshold values from other countries, is given in (NIRAS A/S, 2021) for marine mammals and in (Öhman, et al., 2021) for fish. These thresholds are briefly described in the following, and the reader is referred to the respective reports for a more in depth description.

3.2.1 Frequency unweighted threshold levels

Assessment of the noise impact on fish, larvae and eggs are all based on frequency unweighted threshold levels using the metric $\mathrm{SEL}_{\mathrm{C24h}}$, and are presented in Table *3.1*. The threshold are adopted from (Andersson et al., 2017) and (Popper, et al., 2014).

Table 3.1: Unweighted threshold criteria for fish *(Andersson et al., 2017)*, *(Popper, et al., 2014)*.

Species	Fleeing Speed [m/s]	Species specific unweighted thresholds (Impulsive)	
		$SEL_{C24h,\text{unweighted}}$	
		TTS [dB]	Injury [dB]
Cod	0.38	185	204
Cod	0.9	185	204
Herring	1.04	185	204
Larvae and eggs	-	-	207
"-" Thresholds is not obtained for this species			

3.2.2 Frequency weighted threshold levels

For marine mammals, threshold levels for hearing impact are primarily based on a large study from the American National Oceanographic and Atmospheric Administration (NOAA), (NOAA, April 2018), where species specific frequency weighting is proposed, taking the hearing sensitivity of each species into account when estimating the impact of a given noise source.

In NOAA (April 2018) the marine mammal species, are divided into four hearing groups in regards to their frequency specific hearing sensitivities: 1) Low-frequency (**LF**) cetaceans, 2) High-frequency (**HF**) cetaceans, 3) Very High-frequency (**VHF**) cetaceans, 4) and Phocid pinnipeds (**PW**) (underwater). For this project, only the latter two hearing groups are relevant (NIRAS A/S, 2021). More details about the hearing groups and their frequency sensitivities are given in section 3.2.3. The hearing group weighted threshold criteria, can be seen in Table 3.2.

Table 3.2: Species specific weighted threshold criteria for marine mammals. This is a revised version of Table AE-1 in *(NOAA, April 2018)* to highlight the important species in the project area.

Hearing group	Representative species	Fleeing speed [m/s]	Species specific weighted thresholds (Non-impulsive)		Species specific weighted thresholds (Impulsive)		
			SEL_{C24h}*		SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS [dB]	PTS [dB]	TTS [dB]	PTS [dB]	Behaviour [dB]
Very High-Frequency Cetaceans	Harbour porpoise	1.5	153	173	140	155	100
Phocid Pinniped	Harbour seal	1.5	181	201	170	185	-
"-" Threshold is not calculated for this hearing group. *: frequency weighted level							

In addition to the PTS and TTS thresholds, it is also proposed, in the background report for marine mammals (NIRAS A/S, 2021), to consider the behavioural impact on harbour porpoise, through the single pulse criteria $\mathrm{SPL}_{\mathrm{RMS-fast,VHF}} = 100\ dB\ re. 1\mu Pa$. No behavioural impact threshold for harbour seal is considered because of lack of knowledge.

The threshold criteria for PTS and TTS are not possible to verify through measurements, as they include marine mammal fleeing behaviour. A common method for validation of the source sound emission model, defined as the source level with all mitigation measures in effect, is to measure the single strike SEL value at 750 m for a pile strike of maximum hammer energy, and compare this to model results at the same distance.

If the measured level exceeds the model results, it may indicate that source sound emission is higher than assumed in the model, and it should be determined if additional mitigation is required, or if active mitigation measures (bubble curtains or otherwise) work as intended. In this regard, source sound emission is defined as the noise output of the pile driving, with all mitigation effects active, and measured at 750 m distance. It is important to recognize, that while this measure is useful for validating the source model, it does not provide any information on the sound propagation model and therefore can't be used to determine if the calculated impact threshold distances are met.

Sound transmission loss, and thereby impact threshold distances, are greatly affected by the environmental conditions between source and receiver, and significant impact can occur beyond 750 m radius. For different times of year, the sound transmission loss can vary significantly and thereby result in several km of difference in impact threshold distances, despite measuring the same level at 750 m distance. To verify the impact threshold distances in the model, it is necessary to not only investigate the source sound emission, but also the sound transmission loss. This is typically done through multi-distance measurements, at e.g. 750 m, 3 km and a third further distance, such as the predicted behaviour impact distance.

In summary, the 750 m measurement, while useful for verifying source sound emission, can't be used as a control measurement to verify impact threshold distances.

As a final note, it is important, that frequency weighting is used for such measurements, to accurately reflect the impact on marine mammals. The proposed metric is labelled $SEL_{SS@750m,<weighting>}$, where <weighting> refers to the species specific weighting curve for harbour porpoise (VHF-weighting) and seal (PW-weighting).

3.2.2.1 Threshold distance representation

The unweighted and frequency weighted impact criteria, rely on determining the distances at which the various thresholds are likely to occur.

As such, threshold distances for Injury, PTS and TTS describe the minimum distance from the source, a marine mammal or fish must at least be, prior to onset of pile driving, in order to avoid the respective impact. It therefore does not represent a specific measurable sound level, but rather a safe starting distance.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike.

It should be noted, that for impact pile driving, a significant portion of the installation time will not be carried out applying maximum hammer energy, however a steadily increasing amount of energy from soft start (10-15% of hammer energy) through ramp up (15%-99%) to full power (100%). Depending on the soil conditions, the hammer energy requirements through the ramp up and full power phases will vary from site to site, and even between individual pile locations within a project site.

3.2.3 Frequency weighting functions

As described in the previous section, the impact assessment for underwater noise includes frequency weighted threshold levels. In this section, a brief explanation of the frequency weighting method is given.

The different mammal species do not hear equally well at all frequencies. Humans for example are most sensitive to frequencies in the range of 2 kHz - 5 kHz and for frequencies outside this range, the sensitivity decreases. This frequency-dependent sensitivity correlates to a weighting function, for the human auditory system it is called A-weighting. For marine mammals the same principle applies through the weighting function, $W(f)$, defined through Equation 5.

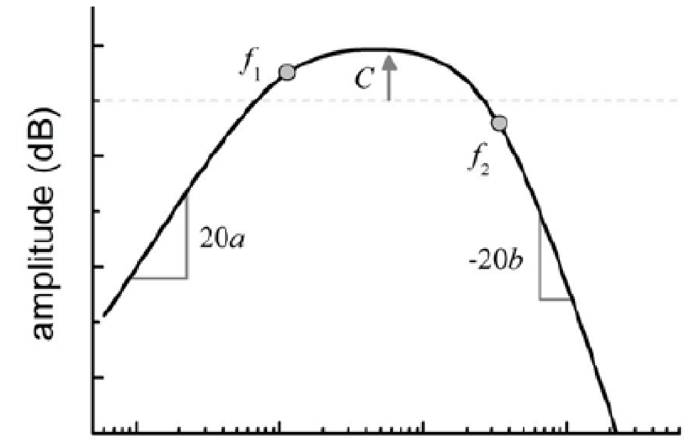
$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right) [dB] \qquad \text{Equation 5}$$

Where:

- a is describing how much the weighting function amplitude is decreasing for the lower frequencies.
- b is describing how much the weighting function amplitude is decreasing for the higher frequencies.
- f_1 is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [Hz]
- f_2 is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [Hz]
- C is the function gain [dB].

For an illustration of the parameters see Figure 3.1.

Figure 3.1:Illustration of the 5 parameters in the weighting function [NOAA, April 2018].



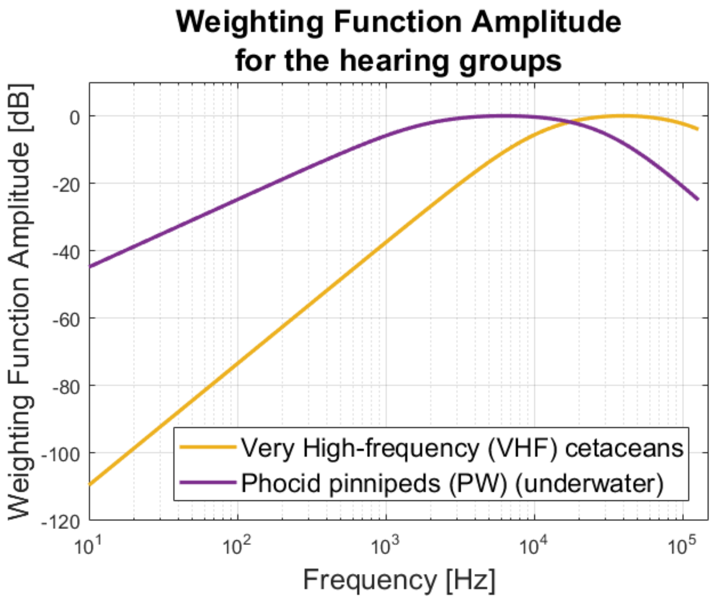
The parameters in Equation 5 are defined for the hearing groups of interest and the values are presented in Table 3.3.

Table 3.3: Parameters for the weighting function for the hearing groups *(NOAA, April 2018)*.

Hearing Group	a	b	f_2 (kHz)	f_2(kHz)	C (dB)
Very High-frequency (VHF) cetaceans	1.8	2	12	140	1.36
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75

By inserting the values in Table 3.3 into Equation 5, the following spectra is obtain for the hearing groups.

Figure 3.2: The weighting functions for all the marine mammal hearing groups in (NOAA, April 2018).



4 Source modelling methodology

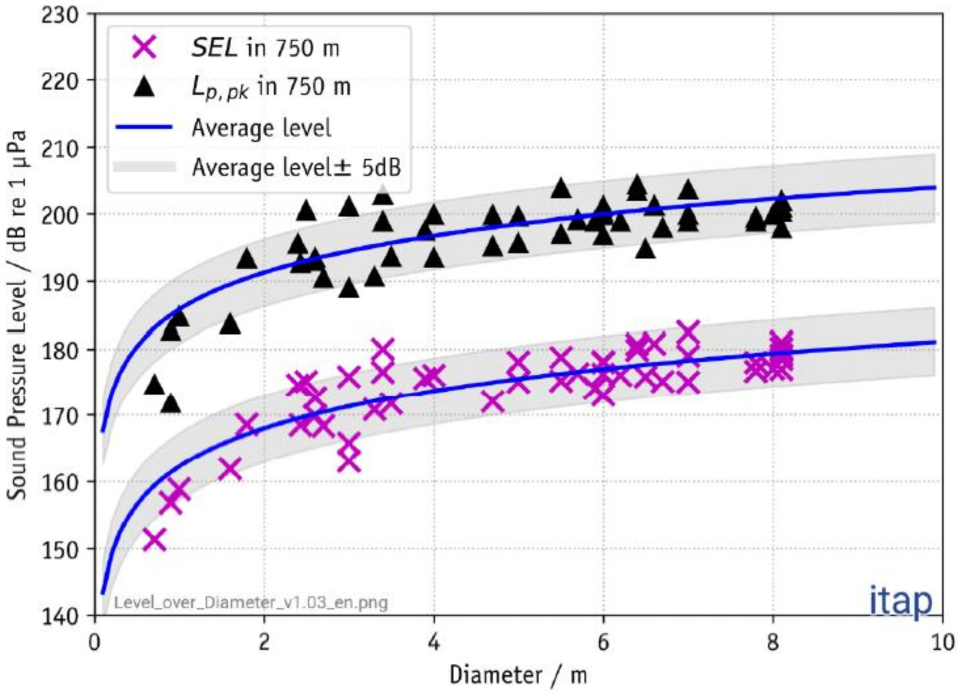
In chapter 1, it is described that pile driving activities are required for the installation of monopile foundations. Such activities are therefore expected to produce underwater sound levels that can potentially have an impact on marine mammals and fish.

To estimate the impact on marine mammals and fish, a source model is derived from project specific knowledge, as well as from available literature on pile driving source level and characteristics. This section includes discussion of the pile driving source level and frequency spectrum, as well as uncertainties related thereto. Methods for reducing pile driving noise levels are also examined.

4.1 Pile driving source level

The best available knowledge on the relationship between pile size and sound level, comes from the newest published knowledge on measured sound levels from pile driving activities in (Bellmann, et al., August 2020), which provides a graphic summary of measured sound levels at 750 m distance as a function of pile size. This is shown in Figure 4.1. The measurements are all normalized to 750 m distance from the pile.

Figure 4.1: Relationship between measured SPL and SEL levels at 750 m distance, and pile size [Bellmann, et al., August 2020]



Examining Figure 4.1, the blue curve indicates the best fit of the measurement results. For the SEL results, this relationship between pile size and measured level is approximately $\Delta\text{SEL} = 20 * \log 10\left(\frac{\text{D2}}{\text{D1}}\right)$ where D1 and D2 are the diameter of 2 piles, and ΔSEL is the dB difference in sound level between the two. This relationship indicates that, when doubling the diameter, the SEL increases by 6 dB.

In order to use this data in a underwater sound transmission model, the source level at 1 m distance must be known, and the 750 m value is therefore back-calculated to 1 m. This is done, using a combination of Thiele's equation for sound propagation (Thiele, 2002), as well as NIRAS own calibration model based on several measurements at real sites.

From Figure 4.1 it should be noted, that variations in measured sound levels for a specific pile size do occur, as indicated by the spread of datapoints, around the fitted (blue) lines. This spread gives a 95%-confidence interval of ± 5 dB which is indicated by the gray shaded areas in Figure 4.1. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations and projects. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate, than that of the average fitted line. In the following section, the different parameters which give rise to uncertainties in regard to the source level, are examined.

4.1.1 Uncertainties in determining source level

In the following, a number of parameters influencing the actual source level for any specific installation is examined briefly.

4.1.1.1 Soil resistance

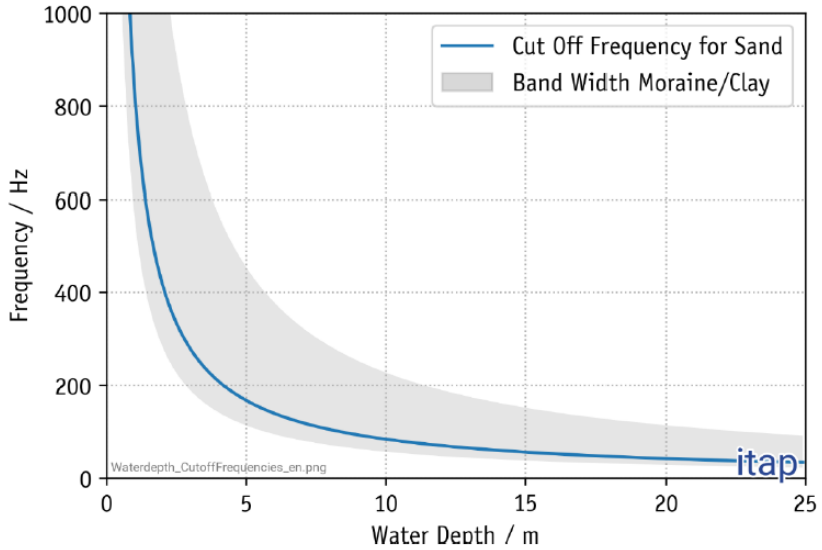
To install the foundation, the piles have to be driven into the seabed. To be able to do this the predominant soil resistance has to be overcome. In general, the larger the soil resistance, the higher the blow energy required, which in turn increases the noise output (Bellmann, et al., August 2020). For this reason, the harder, more compacted, and typically deeper, sediment layers require more force to be applied, thus increasing hammer energy and noise output as the piling progresses.

4.1.1.2 Water depth

The water depth, in shallow water, can also influence the noise emission. When the water depth decreases the cut-off frequency increases, which can be seen in Figure 4.2. Frequency content of the noise source, below the cut-off frequency, has difficulty propagating through the water column, and will be attenuated at an increased rate, compared to frequency content above the cut-off (Bellmann, et al., August 2020).

The cut-off frequency is dependent on, not only the water depth, but also the upper sediment type of the sea-bed.

Figure 4.2: Cut off frequency and its dependency on sediment type and water depth [Bellmann, et al., August 2020].

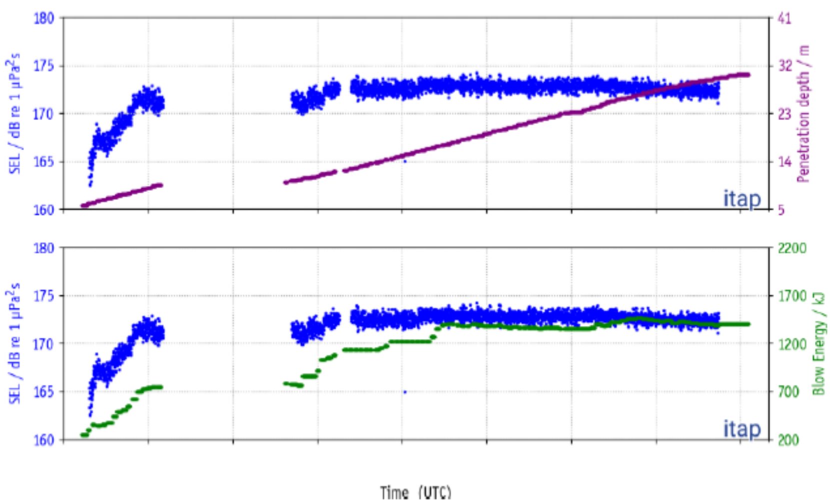


4.1.1.3 Hammer energy

An increase in hammer energy applied to a pile, will transfer more energy into the pile and therefore also results in a higher noise emission. In Figure 4.3, which shows the SEL versus penetration depth and blow energy, it can be observed how increasing the blow energy, also increases the measured SEL.

This relationship is approximated by 2-3 dB increase in measured SEL every time the blow energy is doubled. (Bellmann, et al., August 2020).

Figure 4.3: Relationship between SEL versus penetration depths and blow energy [Bellmann, et al., August 2020].



4.1.1.4 Impact hammer type

Modern impact pile drivers typically consist of a large mass, or weight, suspended inside a hydraulic chamber, where the pressurized hydraulic fluid is used to push up the weight to the desired height, after which it is dropped. The impact is then transferred through an inner construction of shock absorbers and an anvil connected to the pile top. This motion transfers a large part of the applied energy to drive the pile downwards (Adegbulugbe, et al., 2019).

Using a large impact hammer with a heavy falling mass at 50-60% of its full capacity, will for acoustic reason lead to lower noise output compared to that from a smaller impact hammer using 100% capacity to achieve the same blow energy (Bellmann, et al., August 2020).

While the two hammers will deliver the same energy to the pile, the maximum amplitude will be lower for the large impact hammer due to extended contact duration between hammer and pile-head (Bellmann, et al., August 2020). Different impact hammers can give up to several decibels difference (Bellmann, et al., August 2020).

4.1.1.5 Pile length and degree of water immersion

A pile installation can be carried out through either above sea level piling, which is when the pile head is located above water level, or below sea level piling, where the pile head is located below the water line. The former is typically the case for monopiles, while the latter is often the case for jacket piles (Bellmann, et al., August 2020). A combination of the two is also possible, where the pile head is above water at the beginning of the pile installation and is fully submerged in the late stages of the piling.

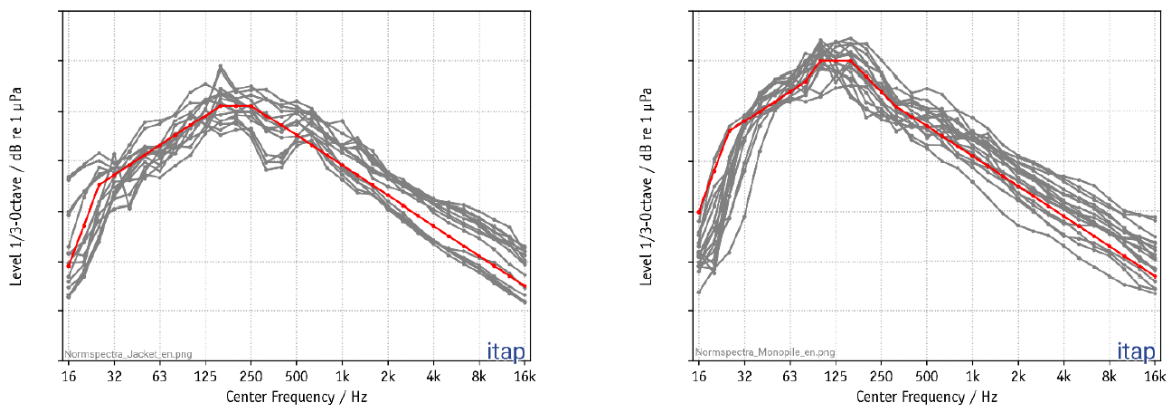
Above water level piling automatically means that part of the pile is in contact with the entire water depth, and thus has a large radiating area. For below water level piling, this is not the case, as parts of the water column might no longer be occupied by the pile, but rather the hammer. For this reason, a higher noise emission is to be expected as long as the pile head is above water level (Bellmann, et al., August 2020).

4.2 Pile driving frequency spectrum

Due to the natural variations of measured frequency content, Figure 4.4 (grey lines), between sites, piles, water depths, hammer energy levels and other factors, it is almost guaranteed that the frequency response measured for one pile will differ from that of any other pile, even within the same project.

Since it is practically impossible to predict the exact frequency spectrum for any specific pile installation, an averaged spectrum (red line), for use in predictive modelling, is proposed by (Bellmann, et al., August 2020).

Figure 4.4: Measured pile driving frequency spectrum (grey lines) at 750m, with the averaged spectrum shown as the red line [Bellmann, et al., August 2020]. The spectrum ranges from 110-180 dB.



The spectrum shown to the left in Figure 4.4 is the pile driving frequency spectrum (grey lines) measured at 750 m for pin piles with diameters up to 3.5 m. The red line indicates the averaged spectrum, and is proposed to be used as a theoretical model spectrum for sound propagation modelling of pin piles.

The right side of Figure 4.4 is showing the pile driving frequency spectrum (grey lines) measured at 750m for monopiles with diameters of minimum 6 m. The red line indicates the averaged spectrum, and is proposed to be used as a theoretical model spectrum for sound propagation modelling of monopiles for the measured spectrums.

4.3 Pile driving source mitigation

As foundation structures become larger and more knowledge come to light about marine mammal hearing, the more unlikely it is that the projects can comply with local regulation without source mitigation.

This section provides a brief description of different Noise Abatement Systems (NAS) which in one way or another reduce the noise emission from pile driving events. Knowledge on the best achievable source mitigation, currently available, is also presented.

The most frequently applied technique uses bubble curtains. Air is pumped into a hose system positioned around the pile installation at the bottom of the sea. The hoses are perforated and air bubbles leak, and rise towards the surface. This forms a curtain through the entire water column from seabed to sea surface. Due to the change in sound speed in the water-air-water bubble interface, a significant part of the outgoing noise is reflected backwards and kept near the pile, while the remaining noise energy going through the bubble curtain is greatly attenuated (Tsouvalas, 2020).

Part of the noise emission from pile driving occurs through the sediment, which is then reintroduced to the water column further from the pile. It is therefore important, that bubble curtains are not placed too close to the source, as this would reduce their effectiveness on the soil borne noise contribution. Big Bubble Curtains can mitigate some of this noise as it is partly reintroduced to the water column after a few metres. Big Bubble Curtain usually surround the construction site completely leaving no gaps where noise is emitted unhampered. Currents can cause a drift in bubbles but this difficulty can be overcome if the Big Bubble Curtain is installed in an oval rather than a circle. This system was used for example in Borkum West II, where a noise reduction of on average 11 dB (unweighted broadband) was achieved with the best configuration. This project tested different configurations. The success depended on three parameters: size of holes in the hosepipe (determines bubble sizes), spacing of holes (determines density of bubble curtain) and the amount of air used (air pressure). The best configuration was found to be with relatively small holes, a small spacing and using a substantial air pressure (Diederichs, et al., 2014).

The effect of bubble curtains can be increased further if a second bubble curtain is installed even further from the installation, thereby forming a Double Big Bubble Curtain (DBBC). The effect is greatest if the distance between the systems is at least three times the water depth (Koschinski S et al., 2013).

Another type of NAS are pile sleeves, which act as a physical wall around the pile. One such system is the Noise Mitigation Screen (IHC-NMS) where a double walled steel sleeve with an air-filled cavity is positioned around the pile, thus using the impedance difference in the water-steel-air-steel-water interfaces to reduce the sound transmission. This system was used for example at the German wind park Riffgat. Noise mitigation was assessed to be around 16-18 dB (Verfuß, 2014). Often, a pile sleeve NAS is applied in combination with a bubble curtain solution to increase the overall mitigation effect.

Another type of NAS is the Hydro Sound Damper (HSD), which is in many ways similar to the bubble curtain, however instead of using hoses with air, the curtain consist of fixed position air-filled balloons or foam-balls. The size, spacing and density of the foam balls or air-filled balloons then dictate the achievable noise mitigation. With the HSD system, it is possible to “tune” the NAS to work optimally at specific frequencies, thus allowing for project specific optimal solutions.

Cofferdams are a special type of pile sleeve. They also surround the pile, however in comparison to the IHC-NMS, the water in between the pile and the sleeve is extracted, so that the interface from pile to water becomes air-steel-water. These sleeves are deemed to reduce noise by around 20 dB, as demonstrated in Aarhus Bay (Verfuß, 2014). However, tests further offshore and in connection with the construction of wind parks have yet to be carried out (Verfuß, 2014). An inherent challenge with this solution is however that it can be difficult to keep the water out of the cofferdam, as local sediment conditions can prevent a perfect seal.

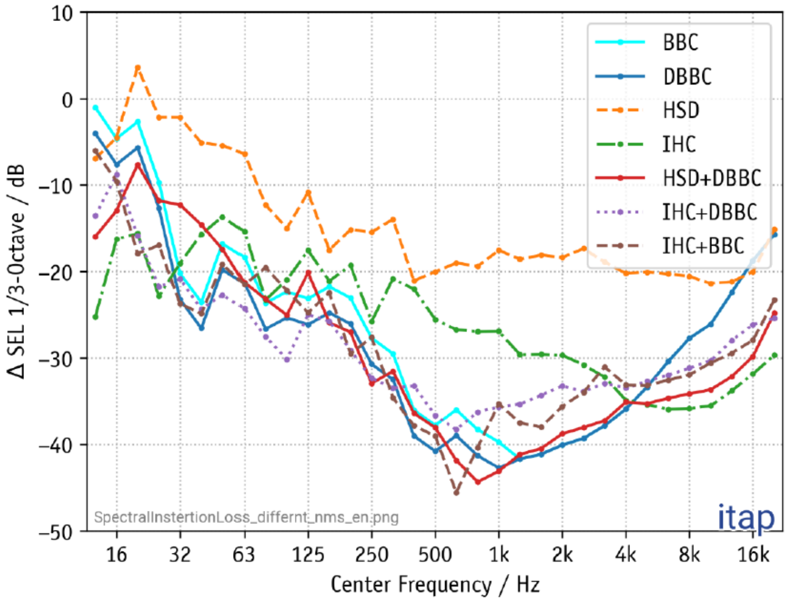
For commercially available and proven NAS, a summary of achieved mitigation levels throughout completed installations is given in (Bellmann, et al., August 2020), as shown in Figure 4.5. It must, however, be noted that the reported broadband mitigation, ΔSEL is given for a flat frequency spectrum, in order to compare the efficiency of the different mitigation systems on different pile installations. That is, the source level mitigation achievable for a source with equal acoustic energy in all octave bands, also called pink noise. Pile driving spectra however, as described in section 4.2, are far from a flat octave band spectra, and the effective noise mitigation achieved in terms of sound level measured with and without the system in use at a specific installation will therefore differ from the listed mitigation. In Figure 4.6, the broadband flat spectrum attenuation achieved with the different NAS, are instead given in 1/3 octave bands, thus showing the achieved mitigation per frequency band.

Lastly, it is important to recognize, that development of new and improved noise mitigation systems is an ongoing process, and with every offshore wind farm installed, new knowledge and often better solutions become available.

Figure 4.5: Achieved source mitigation levels on completed projects using different NAS, [Bellmann, et al., August 2020].

No.	Noise Abatement System resp. combination of Noise Abatement Systems (applied air volume for the (D)BBC; water depth)	Insertion loss ΔSEL [dB] (minimum / average / maximum)	Number of foundations
1	IHC-NMS (different designs) (water depth up to 40 m)	13 ≤ 15 ≤ 17 dB IHC-NMS8000 15 ≤ 16 ≤ 17 dB	> 450 > 65
2	HSD (water depth up to 40 m)	10 ≤ 11 ≤ 12 dB	> 340
3	optimized double BBC*1 (> 0,5 m^3/(min m), water depth ~ 40 m)	15 – 16	1
4	combination IHC-NMS + optimized BBC (> 0,3 m^3/(min m), water depth < 25 m)	17 ≤ 19 ≤ 23	> 100
5	combination IHC-NMS + optimized BBC (> 0,4 m^3/(min m), water depth ~ 40 m)	17 – 18	> 10
6	combination IHC-NMS + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	19 ≤ 21 ≤ 22	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	15 ≤ 16 ≤ 20	> 30
8	combination HSD + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	18 – 19	> 30
9	GABC skirt-piles*2 (water depth bis ~ 40 m)	~ 2 – 3	< 20
10	GABC main-piles*3 (water depth bis ~ 30 m)	< 7	< 10
11	„noise-optimized" pile-driving procedure (additional additive, primary noise mitigation measure; chapter 5.2.2)	~ 2 - 3 dB per halving of the blow energy	

Figure 4.6: Frequency dependent noise reduction for Noise Abatement Systems, [Bellmann, et al., August 2020].



5 Underwater noise modelling scenarios

The foundation structure for the turbines is expected to be either monopiles up to 14 m diameter, or jacket foundations with 3-4 legs using pin piles up to 4.5 m diameter. The details of the different project scenarios are outlined below, based on information received by OX2. For the pile installation procedure, this includes a soft start as well as technical descriptions provided by COWI for the ramp up phase, and a conservative estimate for the full power phase of the installation.

Based on the knowledge presented in chapter 4, a source model is proposed for each of the scenarios. The source models each assume the use of a source mitigation measure equal to the BBC NAS, documented in section 4.3. This, as a consequence of the extremely high unmitigated source levels, which makes it unlikely that installation without an effective NAS will be allowed. The BBC NAS has been used in many previous installations, primarily at German offshore wind farms, and is one of the best tested available NAS currently commercially available.

Prior to detailed sound propagation modelling, each scenario is evaluated from a noise emission point of view, to determine the worst case scenario with regards to the impact on marine mammals and fish. This is covered in further detail in section 5.3.

In the following, the two foundation scenarios considered in this project are described in detail, followed by an evaluation of which is considered to be worst-case.

5.1 Scenario 1: 14 m monopile

In Scenario 1, turbines are installed on a 14 m monopile foundation, which is a single hollow steel pipe. The technical specification and the pile driving procedure used for this scenario is given in Table 5.1.

Table 5.1: Technical specifications and pile driving procedure for Scenario 1

Technical specification for Scenario 1			
Foundation		Monopile	
Number of piles per foundation		1	
Impact hammer energy		7000 kJ	
Pile Diameter		14 m	
Noise Abatement System Applied		Big Bubble Curtain (BBC), Hydro Sound Damper Double Big Bubble Curtain (HSD-DBBC)	
Total number of strikes pr. pile		10400	
Pile driving procedure			
Name	Number of strikes	% of maximum hammer energy	Time interval between strikes [s]
Soft start	200 400	10%	2 1.2
Ramp-up	1000 500 500 800 2400	20% 40% 60% 80% 60%	1.2
Full power	4600	100%	3.2

5.1.1 Pile driving source level and spectrum, scenario 1

In section 0 the technical specification and the pile driving procedures are stated for Scenario 1. By applying the knowledge presented in section 4.1 and 4.2, regarding source level and source frequency spectrum, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL}_{@750\mathrm{m}} = 184.5\ \mathrm{dB\ re.\,1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL}_{@1\mathrm{m}} = 227.7\ \mathrm{dB\ re.\,1\ \mu Pa^2 s}$.

As the project is on a very early stage, detailed drivability analysis for each foundation is not yet available, and a worst-case approach with regards to source level is therefore taken, based on all available data for the pile installation procedure and site specific conditions. To ensure a worst-case approach, a 2 dB increase to the source level is therefore included, resulting in $\mathrm{SEL}_{@1\mathrm{m}} = 229.7\ \mathrm{dB\ re.\,1\ \mu Pa^2 s}$. The source level is presented in all relevant metrics and combinations between frequency weighting both with and without the BBC NAS in Table 5.2 for reference.

Table 5.2: Source Level for 14 m monopile, with and without weighting and mitigation.

Frequency weighting	Source level ($\mathrm{SEL}_{@1\mathrm{m}}$) [dB re. 1μPa²s]		
	Unmitigated	With BBC NAS	With HSD-DBBC NAS
Unweighted	229.7 dB	210.3 dB	205.2 dB
VHF Cetaceans	183.6 dB	159.8 dB	151.5 dB
Phocid Pinniped	208.5 dB	184.0 dB	180.0 dB

5.2 Scenario 2: Jacket foundation with 4.5 m pin piles

In Scenario 2, turbines are installed on a jacket foundation with either 3 or 4 legs, each anchored to the seabed using pin piles up to a diameter of 4.5 m. For a worst case consideration, the jacket foundation is assumed to have 4 legs. The technical specification and the pile driving procedure used for this scenario is given in Table *5.3*.

Table 5.3: Technical specifications and pile driving procedure for Scenario 2

Technical specification for Scenario 2			
Foundation		Jacket (4 legs)	
Number of piles per foundation		4	
Impact hammer energy		7000 kJ	
Pile Diameter		4.5 m	
Noise Abatement System Applied		Big Bubble Curtain (BBC)	
Total number of strikes pr. pile		10400	
Pile driving procedure			
Name	Number of strikes	% of maximum hammer energy	Time interval between strikes [s]
Soft start	200 400	10%	2 1.2
Ramp-up	1000 500 500 800 2400	20% 40% 60% 80% 60%	1.2
Full power	4600	100%	3.2

5.2.1 Pile driving source level and spectrum, scenario 2

In section 5.2 the technical specification and the pile driving procedures are stated for scenario 2. By applying the knowledge presented in section 4.1 and 4.2, regarding source level and source frequency spectrum, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL_{@750m}} = 175.5\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL_{@1m}} = 217.4\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$.

As the project is on a very early stage, detailed drivability analysis for each foundation is not yet available, and a worst-case approach with regards to source level is therefore taken, based on all available data for the pile installation procedure and site specific conditions. To ensure a worst-case approach, a 2 dB increase to the source level is therefore included, resulting in $\mathrm{SEL_{@1m}} = 219.4\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. The source level is presented in all relevant metrics and combinations between frequency weighting both with and without the BBC NAS in Table 5.2 for reference.

Table 5.4: Source Level for 4.5 m jacket pin pile, with and without frequency weighting and BBC NAS.

Frequency weighting	Source level ($\mathrm{SEL_{@1m}}$) [dB re. 1μPa²s]	
	Unmitigated	With Big Bubble Curtain (BBC)
Unweighted	219.4 dB	198.4 dB
VHF Cetaceans	180.5 dB	156.8 dB
Phocid Pinniped	202.3 dB	174.3 dB

5.3 Evaluation of worst case scenario

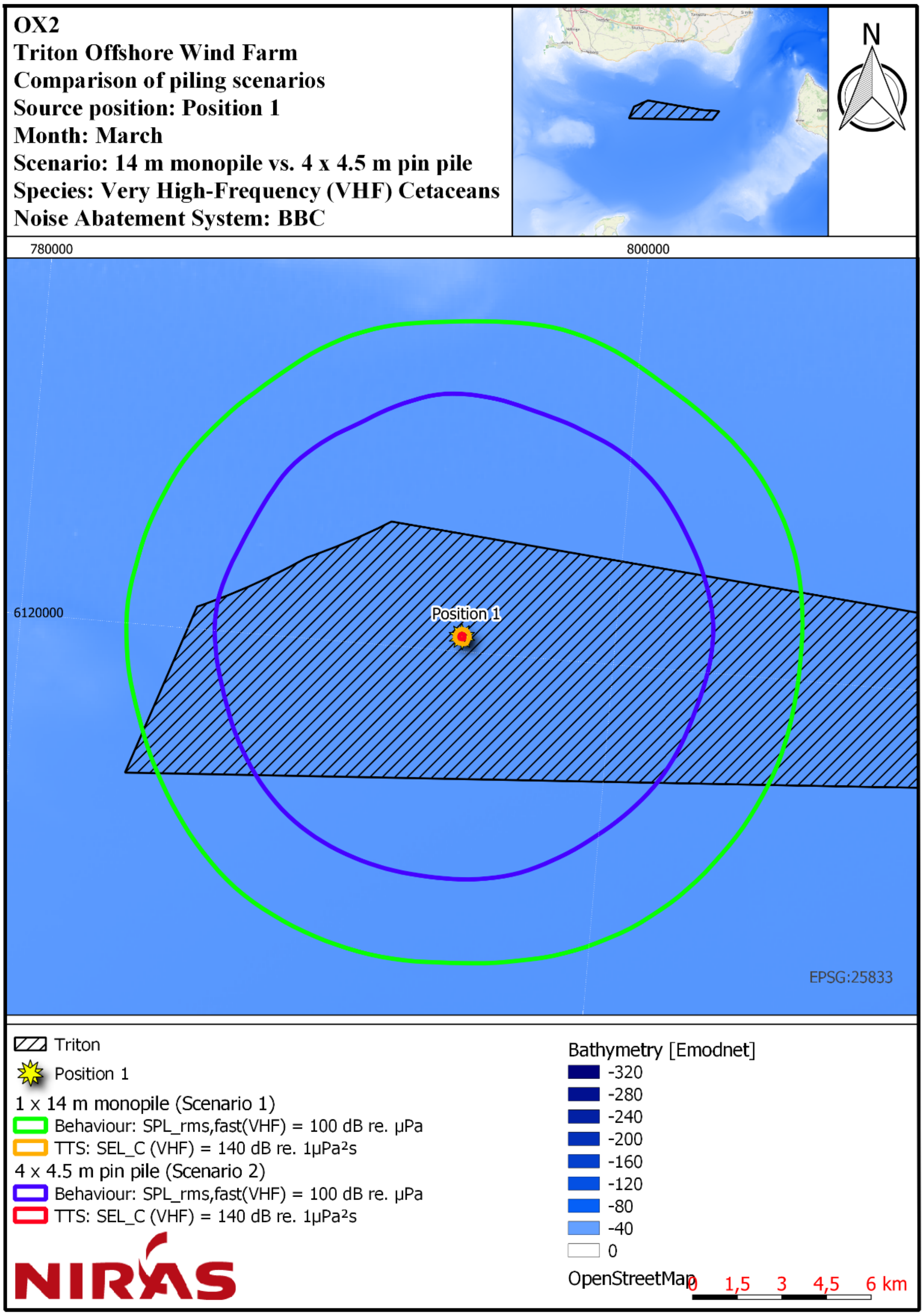
Based on the mitigated frequency weighted source levels, combined with the pile installation procedures, it is assessed, that the 14 m monopile installation will result in the largest threshold impact distances for both PTS, TTS and likely behavior reaction for marine mammals. Also for fish, the injury and TTS distances will be larger for the monopile due to the higher unweighted source levels.

One deviation could be for the TTS and PTS distances for marine mammals, given the longer installation procedure for the jacket foundation (4 piles instead of 1), whereby the noise emission would occur for a longer period of time, thus potentially resulting in higher cumulative sound exposure level (SEL_{C24h}), compared to the single pile foundation of the monopile.

On direct comparison of source levels, both unweighted SEL and PW-weighted SEL when BBC is applied are significantly separated by more than 9 dB between scenario 1 (larger) and scenario 2 (lower). It is therefore guaranteed, that the impact distances for the thresholds based on these metrics, will be worst case for scenario 1, the monopile.

For VHF-weighted SEL when BBC is applied however, the difference in source level is 3 dB. For behavior, which considers a single pulse/hammer strike, the difference in source level is significant enough to confidently consider the monopile as the worst case scenario. For TTS and PTS however, the duration of the pile installation is taken into account, and the larger number of piles in scenario 2, could potentially outweigh the difference in source level. To determine whether this is the case, a test calculation was carried out for the same position within the site. The impact distance contours for the TTS and behavior thresholds for harbor porpoise for scenario 1 and 2 respectively, are shown in Figure 5.1. It should be noted, that this comparison does not reflect final modelling results, but is purely for the purpose of comparison between foundation types.

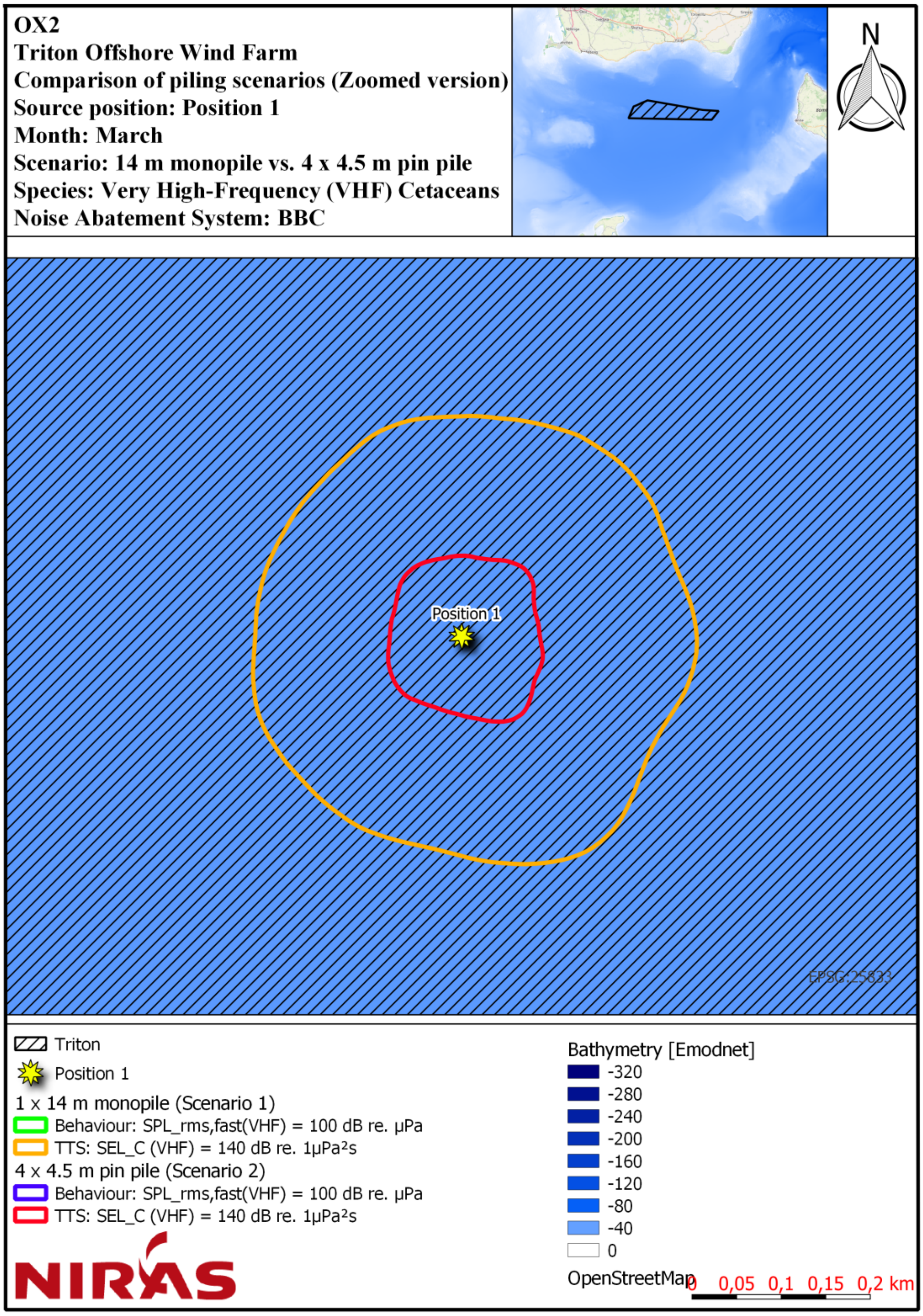
Figure 5.1: Comparison of TTS and behaviour impact distances for installation of Scenario 1: 1x14 m monopile foundation in orange and green, and Scenario 2: jacket foundation (4x4.5 m pin piles) in red and blue. Both scenarios including a BBC NAS.



From Figure 5.1, it is observed, that the 14 m monopile exceeds the impact range of the 4 x 4.5 m pin piles in both threshold parameters for TTS and behavior. For the TTS parameter, the calculation shows that, despite the increased number of piles for the jacket foundation, the monopile foundation still causes a larger impact distance.

This is not easily observed from Figure 5.1 as the distances for both scenarios are very short, however in Figure 5.2, a zoomed in version of Figure 5.1, the difference is more clear.

Figure 5.2: Zoomed in version of Figure 5.1, illustrating the differences in TTS impact distances between scenario 1 and 2.



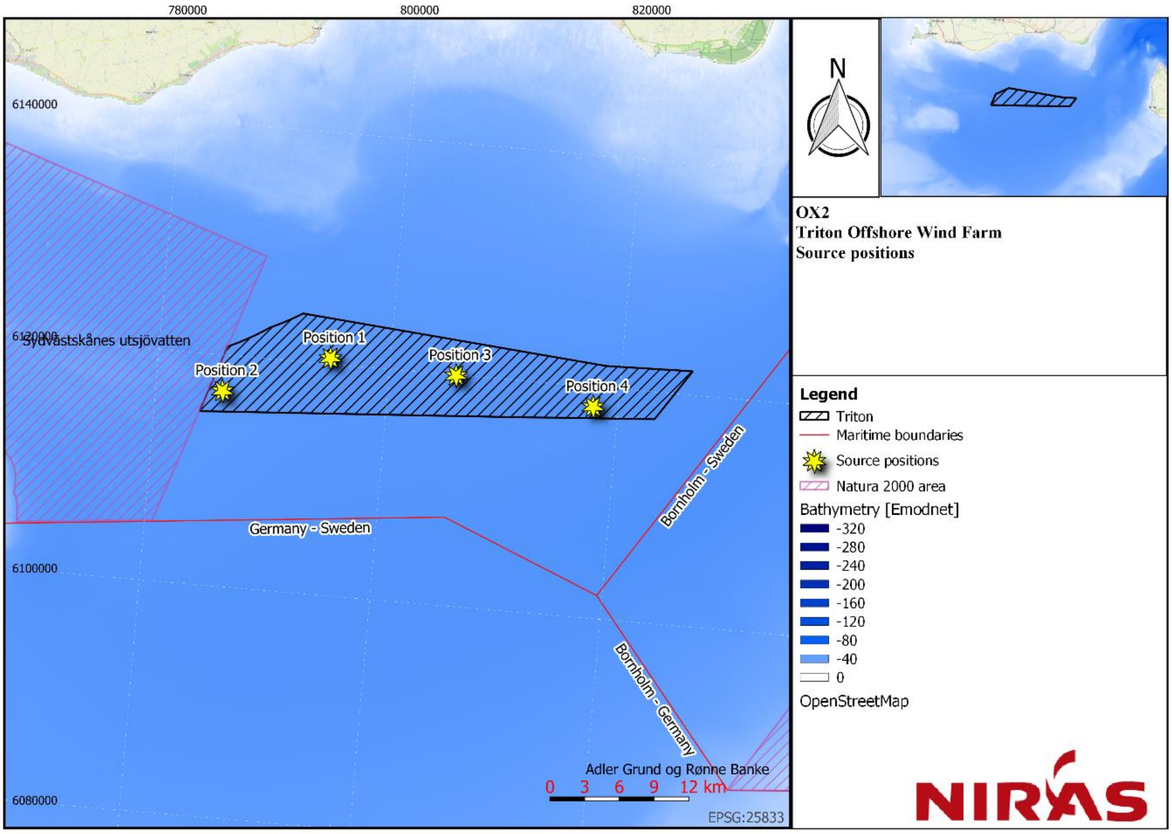
With regards to both behaviour and TTS, the monopile is therefore considered to be worst case. As the monopile foundation is proven to represent the worst case scenario for all impact thresholds, full calculations are only carried out using the monopile as a source, with the BBC NAS applied, as well as with HSD-DBBC NAS applied.

5.4 Source positions

It was chosen to carry out underwater sound propagation modelling for installations at four different source positions, representing different representative worst case locations within the wind farm site, from an underwater sound propagation perspective. The source positions were chosen from their location relative to maximum expected sound propagation, and are shown in Figure 5.3. The locations are spread throughout the area to cover the variations in environmental conditions in the area. Position 2 is located in the southwest corner, next to the Natura 2000 area "Sydvästskånes utsjövatten". The bathymetry becomes significantly shallower in the westward direction toward the Natura 2000 area and the top sediment type is changing in that direction as well. Position 1, 3 and 4 are representative points in regard to both the bathymetry and top sediment in the offshore wind farm area.

For estimating the impact on the specific Natura 2000 sites the worst case underwater noise propagation has been used and the impact range contours have been moved to the position within the site that will cause the largest overlap between the Natura 2000 site and the impact ranges.

Figure 5.3: Source positions chosen for sound propagation modelling.



There is no final layout for the wind farm at this stage of the process, and it has also not been decided whether more than one foundation will be installed per day. The sound propagation modelling, carried out in this report assumes a single pile installation within any 24 hour period, and the results therefore reflect this.

5.4.1 Installation of two foundations simultaneously

If two foundations were to be installed within a 24 hour period, sound propagation and foundation type considered equal, it is assumed that the noise emission from each is similar.

If the two foundations were to be installed at the same time, this would likely result in increased PTS and TTS impact distances (up to a factor 2 increase), as these thresholds are based on the time-dependent noise emission relative to the fleeing speed of the marine mammal.

The further apart the two foundations, the lower the difference in PTS/TTS relative to the single foundation scenario. However, with larger spacing, a trapping effect can occur, where a marine mammal would swim away from one foundation, only to get closer to the installation of the second foundation, thus not achieving a linear decrease in received sound exposure level with time. In this scenario, it is difficult to predict what kind of cumulative sound exposure level, the marine mammal would receive over the span of the installations.

Inversely, the closer the foundations, the lower the risk of trapping, but also the closer to 2x single foundation threshold distances would be expected. One method for reducing the increase in impact distances for concurrent installations, would be to add a time-delay to the installation of the second foundation, such that the marine mammals are able to create distance between themselves and the pile installation(s), before both piling activities are active.

Another aspect of concurrent installations, is that it will likely result in increased behavior distances, which, in a simple approach would increase to the sum of the behavior affected area of both foundation locations. There is however also a secondary effect, where the noise emission from one pile installation would cause positive and destructive interference with the noise emission from the second pile installation, resulting in local variations of ±3 dB, and thereby potentially increasing the impact distance for behavior significantly. Installation of two foundation simultaneously is therefore not recommended.

5.4.2 Installation of two foundations sequentially

If installation of two foundations is however carried out sequentially, where the second pile installation is started as soon as the former is completed, the effects on underwater noise exposure become significantly less uncertain. In a closely spaced scenario, the marine mammals that would be affected by the second pile installation, would already have had significant time to vacate the underwater noise impacted area, thereby limiting the increase in impact on marine mammals. For behavior, the impact distance would not be affected by interference patterns (which will be the case if installation of two pile installations occurs at the same time), nor would it equate the sum of impact areas for both installations, rather it would shift from one location to the next. For PTS and TTS, the impact distances would likely not increase more than 10-20%, as the marine mammals are already far from both installation sites and therefore receiving minimal additional impact from the installation of the second installation. It is however important that the second installation is not delayed significantly in time after the completion of the first, as this would allow for marine mammals to return to the area.

Thus installation of two foundations (positioned next to each other) sequentially will not increase the impact ranges for behavioural avoidance responses and only cause a minor increase in the TTS and PTS impact ranges. Sequential installation will prolong (double) the daily time period where pile driving is taking place, however the total installation period will correspondingly be halved. Under the assumption, that installation will occur every day, the effective installation period for pile driving activities would be reduced from approximately two months to one month.

6 Underwater sound propagation modelling methodology

This chapter provides a brief overview of underwater sound propagation theory and the software program used in the modelling, followed by a description of the inputs used for the propagation model. This includes environmental and source input parameters.

The chapter concludes with documentation of the sound propagation modelling results in both graphic representation, and in numerical form.

6.1 Underwater sound propagation theory

This section is based on (Jensen, et al., 2011) chapter 1 and chapter 3 as well as (Porter, 2011), and seeks to provide a brief introduction to sound propagation in saltwater. The interested reader is referred to (Jensen, et al., 2011) chapter 1, for a more detailed and thorough explanation of underwater sound propagation theory.

Sound pressure level generally decreases with increasing distance from the source. However, many parameters influence the propagation and makes it a complex process.

The speed of sound in the sea, and thus the sound propagation, is a function of both pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean and as such are very location dependent.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance, as stated by Snell's law, Equation 6.

$$\frac{\cos(\theta)}{c} = \text{constant} \qquad \text{Equation 6}$$

Where:

- θ is the ray angle [°]
- c is the speed of sound $\left[\frac{m}{s}\right]$.

This relationship implies that sound waves bend toward regions of low sound speed (Jensen, et al., 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in the sound being able to travel far with very low sound transmission loss.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes reduced transmission loss, and thus a minimal loss of sound energy. This scenario will always be the worst case situation in terms of sound transmission loss. For some sound propagation models, this can introduce an overestimation of the sound propagation, if the surface roughness is not included.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled steeper towards the seabed rather than the sea surface, and it will thus be the nature of the seabed that determines the transmission loss. Depending on the composition of the seabed some of the sound energy will be absorbed by the seabed and some will be reflected. A seabed composed of a relatively thick layer of soft mud will absorb more of the sound energy compared to a seabed composed of hard rock, that will cause a relatively high reflection of the sound energy.

In any general scenario, the upward refraction scenario will cause the lowest sound transmission loss and thereby the largest sound emission. In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year.

As an example, in the inner Danish and Swedish waters, as Kattegat, Skagerrak and the Baltic Sea, an estuary-like region with melted freshwater on top, and salty sea water at the bottom, the waters are generally not well-mixed and great differences in the relation between temperature and salinity over depth can be observed. Furthermore, this relationship depends heavily on the time of year, where the winter months are usually characterized by upward refracting or iso-velocity sound speed profiles. In the opposite end of the scale, the summer months usually have downward refracting sound speed profiles. In between the two seasons, the sound speed profile gradually changes between upward and downward refracting.

In the North Sea, a gradual shift in sound speed profile from near-iso speed in the winter, to downward refracting in the summer is observed based on temperature and salinity readings throughout the year. The readings comes from the NOAAs World Ocean Atlas database (WOA18), freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, (NOAA, 2019).

The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and media sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the more rough the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption, causing the sound to travel relatively far. In rough seas states, the sound energy will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss. As previously mentioned, this is not always possible to include in sound propagation models, and the transmission loss can therefore be underestimated, leading to higher noise propagation than what would actually occur.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient dependent on chemical conditions of the water column. This parameter has been approximated by Equation 7 (Jensen, et al., 2011):

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11\mathrm{f}^2}{1+\mathrm{f}^2} + \frac{44\mathrm{f}^2}{4100+\mathrm{f}^2} + 3.0 \times 10^{-4}\mathrm{f}^2 \qquad \left(\frac{\mathrm{dB}}{\mathrm{km}}\right) \qquad \text{Equation 7}$$

Where f is the frequency of the wave in kHz. This infers that increasing frequency leads to increased absorption.

6.2 Sound propagation models

There are different algorithms for modelling the sound propagation in the sea, all building on different concepts of seabed interaction and sound propagation. The most commonly used for long distance modelling tasks are Ray tracing, Normal Modes (NM), and Parabolic Equation (PE).

Ray tracing has a good accuracy when working with frequencies above 200 Hz, however in very shallow waters, the minimum frequency would be higher, as the rays need space to properly propagate. Different techniques can be applied for ray tracing to improve and counteract certain of its inherent shortcomings (Jensen, et al., 2011). Ray tracing furthermore, is the only algorithm that inherently supports directional sources, that is, sources that do not radiate sound equally in all directions.

The normal mode algorithm makes it possible to calculate the sound field at any position between the source and receiver. Since the modes grow linearly with frequency, the algorithm is usually used for low frequencies, because at high frequencies it is hard to find all the modes which contributed to the sound field (Wang, et al., 2014).

Last is the parabolic equation method, which is usually used for low frequencies, due to increasing computational requirements with frequency squared. This method is generally not used for frequencies higher than 1 kHz. The method is however more accepting of discontinuous sound speed profiles (Wang, et al., 2014).

In Table 6.1, an overview of the application range of the different sound propagation models is shown.

Table 6.1: An overview which indicates where the different sound propagation models are most optimal *(Wang, et al., 2014)*

Shallow water - low frequency	Shallow water - high frequency
Ray theory	Ray theory
Normal mode	Normal mode
Parabolic equation	Parabolic equation
Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable	

6.3 Underwater sound modelling software

NIRAS uses the underwater noise modelling software: dBSea version 2.3.2, developed by Marshall Day Acoustics.

The software uses 3D bathymetry, sediment and sound speed models as input data to build a 3D acoustic model of the environment and allows for the use of either individual sound propagation algorithms or combinations of multiple algorithms, based on the scenario and need. For shallow water scenarios, a combination approach is usually preferred due to the individual algorithm limitations presented.

6.4 Environmental model

In this section, the environmental conditions are examined to determine the appropriate input parameters for the underwater noise model. The sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. In the following, the input parameters are described in greater detail.

6.4.1 Bathymetry

dBSea incorporates range-dependent bathymetry modelling and supports raster and vector bathymetry import.

Figure 6.1 shows the bathymetry map for Europa, where darker colours indicate deeper areas, and lighter colours indicate more shallow water. The resolution of the map is 115 x 115 metres. EMODnet has created the map using Satellite Derived Bathymetry (SDB) data products, bathymetric survey data sets, and composite digital terrain models from a number of sources. Where no data is available EMODnet has interpolated the bathymetry by integrating the GEBCO Digital Bathymetry (EMODnet, 2021).

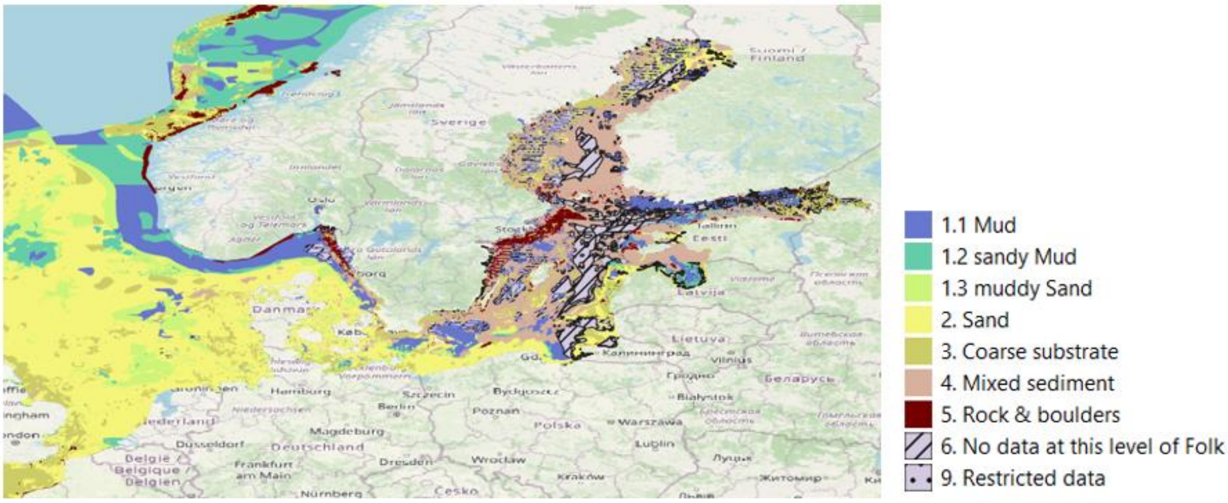
Figure 6.1: Bathymetry map over European waters from Emodnet, where light blue indicates shallow waters and dark blue indicates deeper waters. [EMODnet, 2021].

6.4.2 Sediment

In dBSea, the sound interaction with the seabed is handled through specifying the thickness and acoustic properties of the seabed layers all the way to bedrock. It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform. The thickness and acoustic properties of the layers, from seabed all the way to bedrock, is generally obtained thought literature research in combination with available site specific seismic survey findings.

For determining the top layer type, the seabed substrate map (Folk 7) from https://www.emodnet-geology.eu/ is generally used. This map is shown in Figure 6.2.

Figure 6.2: A section of the seabed substrate map, (Folk 7) [EMODnet, 2021].



6.4.3 Sound speed profile, salinity and temperature

The sound propagation depends not only on bathymetry and sediment but also on the season dependent sound speed profile. To create an accurate sound speed profile, the temperature and salinity must be known throughout the water column for the time of year where the activities take place.

NIRAS examined NOAAs WOA18, freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, (NOAA, 2019) which contains temperature and salinity information at multiple depths throughout the water column.

For each of the sediment model positions, the nearest available sound speed profile, as well as average temperature and salinity will be extracted for the desired months.

6.5 dBSea settings and environmental parameters in the project

In the following, the project specific input parameters are summarized.

6.5.1 dBSea settings

For this project, the dBSea settings listed in Table 6.2 were used.

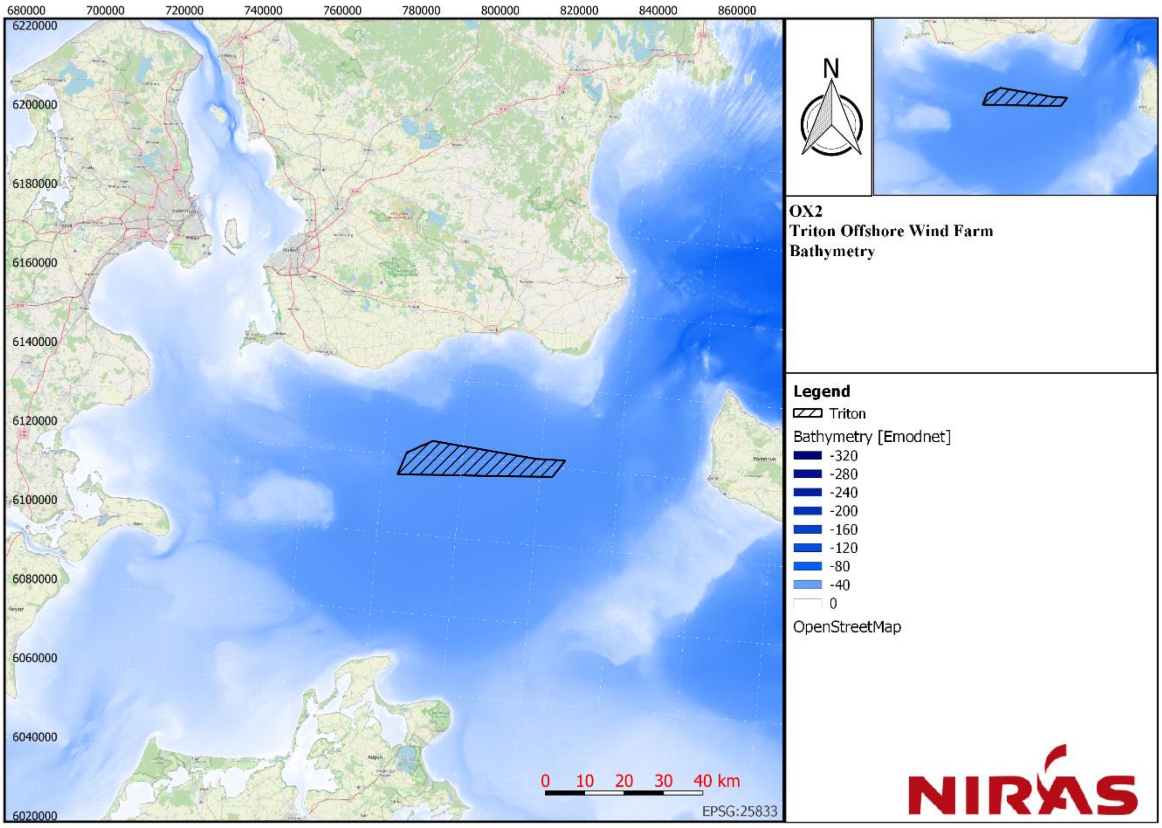
Table 6.2: dBSea Settings

Technical Specification		
Octave bands		1/1
Grid resolution (range, depth)		50 m x 1 m
Number of transects		180 (2°)
Sound Propagation Model Settings		
Model	Start frequency band	End frequency band
dBSeaModes (Normal Modes)	16 Hz	1 kHz
dBSeaRay (Ray tracing)	2 kHz	16 kHz

6.5.2 Bathymetry

The bathymetry implemented for this project, is shown in Figure 6.3, and includes the wind farm site and around 125 km to each side (extracted from the bathymetry map in section 6.4.1). In the area of relevance, the bathymetry ranges from a depth of 100 m, indicated by the darker colours, to a depth of 0 m (land), indicated by the lighter colours.

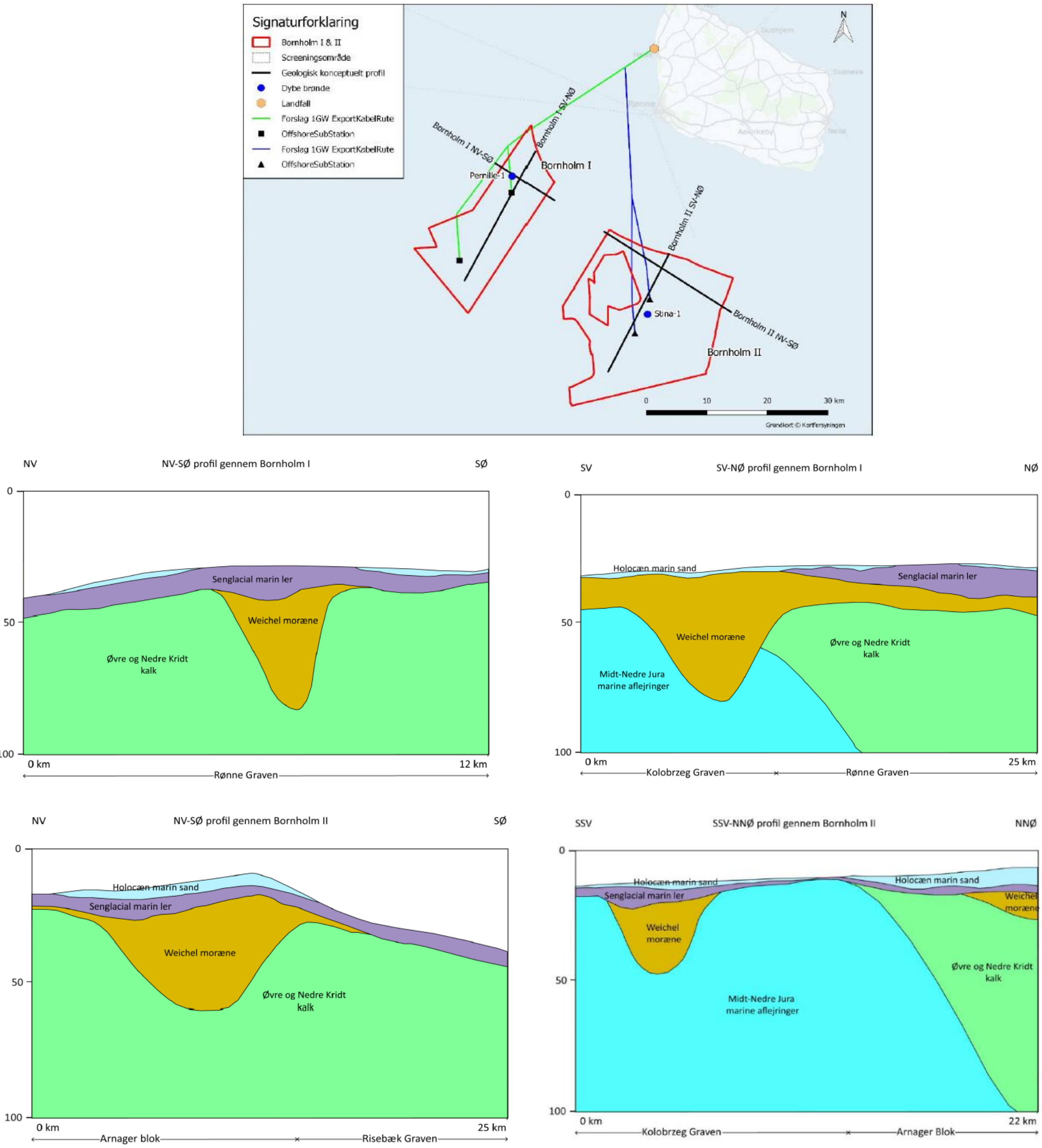
Figure 6.3: Bathymetry map for Triton project area and surroundings.



6.5.3 Sediment

It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform and the information available is often scarce. The thickness of the layers, from seabed all the way to bedrock, is estimated based on existing literature on research conducted in the area as well as available seismic profiles. (COWI, 2020) provided information on local layer depths through sediment profiles, see Figure 6.4. These profiles are from seismic survey transects obtained near the project area, and are therefore included in the sediment model layer composition.

Figure 6.4: Interpreted geological sediment profiles from (COWI, 2020).

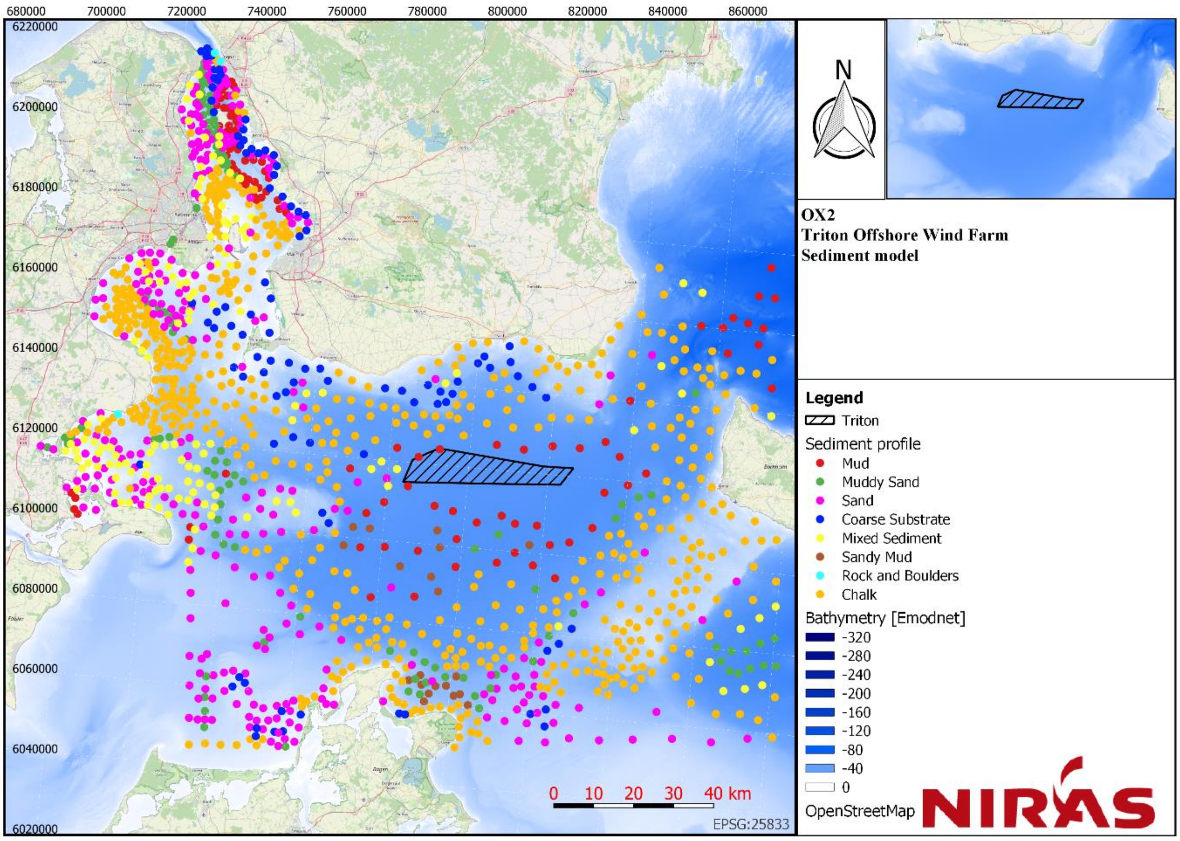


To be able to make a detailed model that takes the seabed substrate into account as well as the varying bathymetry, a 1348 point sediment model was made. Figure 6.5 shows the distribution of the sediments points with the corresponding seabed sediment from Folk 7 (EMODnet, 2021).

The sediment model uses the information from the seabed substrate map to determine the top layer type, while the literature was used to determine average thickness at the different positions. Below the top layer, literature indicates that chalk is already reached. By looking at Figure 6.4 it can be noted that there are very local valleys of moraine. These are not considered in this sediment profile since they are very local and obtained from over 20 km from the wind farm site.

As observed in Figure 6.5, the information is very limited for the area of Triton. It must therefore be pointed out, that when geotechnical survey results are available, an update to the sediment model, and thereby the sound propagation model, should be carried out, to better represent the actual conditions. It is likely that the basic model currently used will simplify sound propagation, however a worst case approach is taken to ensure that a more detailed revision of the model is unlikely to result in lower sound transmission loss.

Figure 6.5: Sediment model for Triton project area and surroundings.



6.5.4 Sound speed profile

Figure 6.6 shows the extracted sound speed profiles at the available positions. Note that the gridded layout of the sound speed profiles indicate their respective position geographically.

Examining Figure 6.6, this would indicate March as the theoretical worst case month and June-July as the theoretical best case. As no specific installation time is yet known, it was decided, in cooperation with OX2, to work with the worst case approach, however also to determine the variation between worst case and best case. In Figure 6.7 the sound speed profiles for the worst case month of March are shown.

In theory, there should be a stronger sound attenuation in the summer months, where a downward refracting sound speed profile is observed, however as described in section 6.4.2, the knowledge of the sediment composition within the site is very limited, and believed to be composed of a very thin overburden on a thick chalk layer. It is therefore considered likely that sound energy is contained in the water column to a greater degree than would be the case if a thick sandy overburden was present, and it is likely that seasonal variations in sound speed profile, temperature and salinity will only affect the sound absorption of the higher frequencies.

To test this, an initial test run was carried out, for the months of January, March, June and September, examining the sound transmission loss in a single direction. The test showed insignificant variation over all months, when examining broadband results without any frequency weighting, as well as when utilizing PW-weighting (for harbor seal). However when applying the frequency weighting for harbor porpoise (VHF-weighting), significant variation was observed, with the March month results being worst case, and June being best case. It was therefore chosen, to carry out full calculations for the month of March to represent worst case for all marine mammals and fish, and to add calculations for VHF-weighted thresholds for the month of June, to inform on a best case scenario.

Figure 6.6: Sound speed profiles for Triton project area.

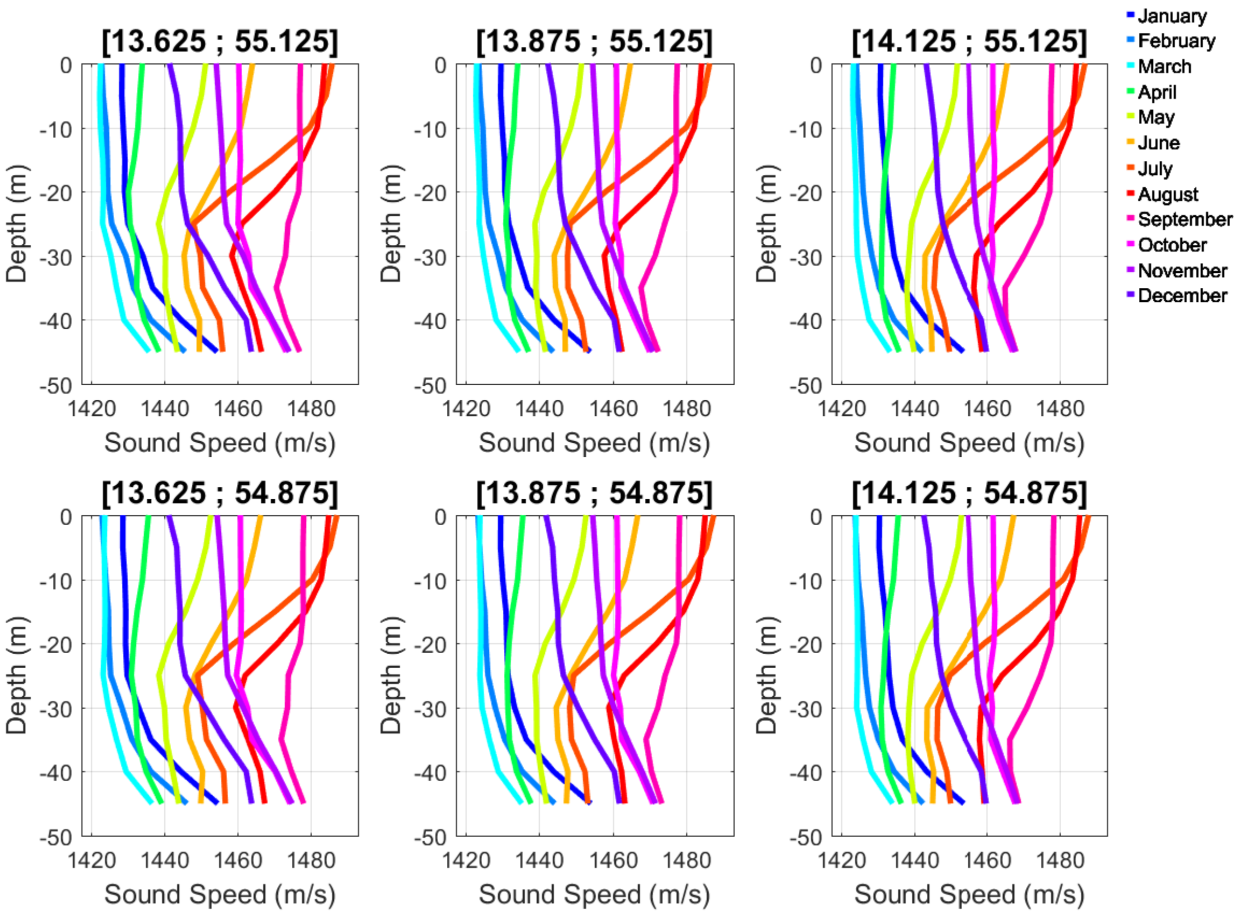
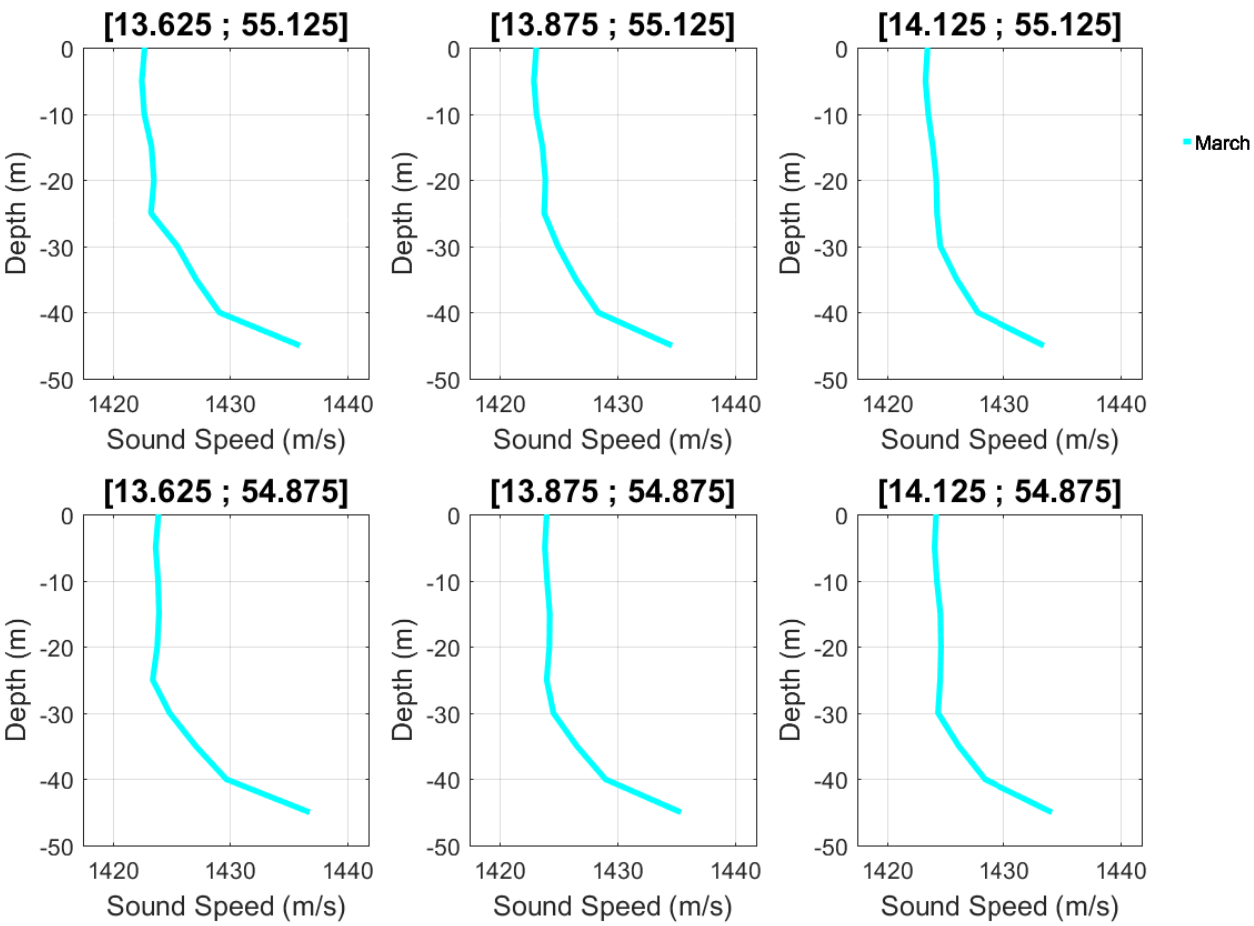


Figure 6.7: Sound speed profile for the worst case month in the project area of Triton.



7 Results

Calculations were carried out for source model Scenario 1: installation of a 14 m monopile with a BBC NAS applied, at the four chosen positions. All impact thresholds are shown in numerical form in Table 7.1 for fish, and in Table 7.2 - Table 7.3 for marine mammals. In addition to the numerical results, the TTS and behaviour are shown in noise contour maps for harbour porpoise in Figure 7.1 - Figure 7.4, for the month of March. Results for HSD-DBBC March calculations are shown in Appendix 2 ; for June calculations for BBC in Appendix 4, and for June calculations with HSD-DBBC applied in Appendix 6.

As previously mentioned, threshold distances for PTS and TTS describe the minimum distance from the source, a marine mammal or fish must at least be deterred to, prior to onset of pile driving, in order to avoid the respective impact. It therefore does not represent a specific measurable sound level, but rather a safe starting distance.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike. It should be noted, that for pile strikes not at full hammer energy, the impact distance will be shorter.

Table 7.1: Resulting threshold impact distances for fish for the worst case month of March.

Species (age, fleeing speed)	Mitigation	Position	$SEL_{C24h,\text{unweighted}}$ [m]	
			TTS	Injury
Cod (Juvenile, 0.38 m/s)	BBC	1	23 900	90
		2	22 700	< 50
		3	23 400	60
		4	20 200	< 50
	HSD-DBBC	1	14 000	< 25
		2	13 200	< 25
		3	13 300	< 25
		4	10 900	< 25
Cod (Adult, 0.9 m/s)	BBC	1	19 400	< 25
		2	18 100	< 25
		3	18 700	< 25
		4	15 600	< 25
	HSD-DBBC	1	9 900	< 25
		2	8 800	< 25
		3	9 400	< 25
		4	7 200	< 25
Herring (1.04 m/s)	BBC	1	18 100	< 25
		2	17 100	< 25
		3	17 600	< 25
		4	14 500	< 25
	HSD-DBBC	1	9 100	< 25
		2	7 900	< 25
		3	8 500	< 25
		4	6 400	< 25
Larvae and eggs (0 m/s)	BBC	1	-	1 300
		2	-	1 150
		3	-	1 300
		4	-	1 050
	HSD-DBBC	1	-	550
		2	-	500
		3	-	520
		4	-	500

Sound propagation modelling for the unweighted SEL thresholds, indicate a low level of variation of sound propagation within the site. The local variations, for fish, are due to local differences in environmental conditions. It is assessed that any other position would not result in greater impact distances.

Table 7.2: Resulting threshold impact distances for marine mammals for the worst case month of March.

Species	Mitigation	Position	Distance to impact threshold [m]		
			SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS	PTS	Behaviour
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	300	< 25	11 500
		2	225	< 25	10 900
		3	225	< 25	11 600
		4	180	< 25	11 300
	HSD-DBBC	1	< 50	< 25	6 700
		2	< 50	< 25	6 200
		3	< 50	< 25	6 400
		4	< 50	< 25	6 400
Phocid Pinniped (Harbour seal)	BBC	1	825	< 25	-
		2	400	< 25	-
		3	675	< 25	-
		4	225	< 25	-
	HSD-DBBC	1	< 50	< 25	-
		2	< 50	< 25	-
		3	< 50	< 25	-
		4	< 50	< 25	-
*: Species specific frequency weighting applied					

Table 7.3: Resulting threshold impact distances for harbour porpoise for the month of June.

Species	Mitigation	Position	Distance to impact threshold [m]		
			SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS	PTS	Behaviour
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	190	< 25	6 800
		2	160	< 25	6 200
		3	170	< 25	6 300
		4	130	< 25	4 700
	HSD-DBBC	1	< 50	< 25	4 300
		2	< 50	< 25	3 800
		3	< 50	< 25	4 000
		4	< 50	< 25	3 300
*: Species specific frequency weighting applied					

Sound propagation modelling for the frequency weighted thresholds, show low variation in behaviour, PTS and TTS distances for harbour porpoise, but a relatively high variation in TTS for seals, between the four source positions. The control measure for the calculated scenarios in March month, $SEL_{SS@750m,<weighting>}$, is given in Table 7.4 for each of the source positions, for the two marine mammal species and fish. In Table 7.5, the control measure values for harbour porpoise in June are given. These indicate very similar maximum levels at 750 m. As previously described in section 3.2.2, the 750 m measurement, while useful for verifying source sound emission, is not valid as a control measurement to verify impact threshold distances.

Table 7.4: Sound Exposure Level ($SEL_{SS@750m,<weighting>}$,) from a single pile strike using maximum hammer energy for the worst case month of March.

Species	Mitigation	Mitigation	Sound Exposure Level, at 750 m $SEL_{SS@750m}$ $[dB\ re. 1\mu Pa^2 s]$*
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	120.2
		2	118.8
		3	118.9
		4	117.5
	HSD-DBBC	1	111.6
		2	110.2
		3	110.7
		4	109.3
Phocid Pinniped (Harbour seal)	BBC	1	145.9
		2	145.5
		3	145.8
		4	145.3
	HSD-DBBC	1	141.9
		2	141.5
		3	141.8
		4	141.3
Unweighted (Fish)	BBC	1	171.1
		2	170.5
		3	170.9
		4	170.3
	HSD-DBBC	1	166.3
		2	165.8
		3	166.2
		4	165.5
*: Species specific frequency weighting applied			

Table 7.5: Sound Exposure Level ($SEL_{SS@750m,<weighting>}$) from a single pile strike using maximum hammer energy, for June month.

Species	Mitigation	Mitigation	Sound Exposure Level, at 750 m $SEL_{SS@750m,VHF}$ $[dB\ re. 1\mu Pa^2 s]$
Very High-Frequency Cetaceans (Harbour porpoise)	BBC	1	119.1
		2	117.9
		3	118.3
		4	117.5
	HSD-DBBC	1	111.2
		2	109.9
		3	110.3
		4	109.7

In addition to the impact distance results in Table 7.1 - Table 7.3, calculations of worst case area of effect has also been carried out. This is given as the total area affected by noise over the behaviour threshold limit, and is shown in Table 7.6. Total impact areas for PTS and TTS for harbour porpoise are all below 1 km^2.

Table 7.6: Area affected for behaviour impact threshold criteria for harbour porpoise.

Month	Position	Area of threshold effect for harbour porpoise [km^2]	
		Behaviour [$SPL_{RMS-fast,VHF}$]	
		with BBC	With HSD-DBBC
March (Worst case)	1	390	122
	2	338	110
	3	391	121
	4	368	113
June	1	130	52
	2	99	40
	3	114	45
	4	63	30

Calculations of overlap with the nearby Natura 2000 sites was also carried out. From Figure 5.3 it can be seen that the Natura 2000 site called "Sydvästskånes utsjövatten" is the only one which is of interest for this project. To assume the absolute worst case, the source is placed 750 m from the nearest Natura 2000 site, where overlap would be maximized. The presented overlap area is thus only to be considered from a worst case perspective, as it is not certain whether a turbine will be placed in that specific location. For the nearest relevant Natura 2000 sites, the worst case overlap is given in Table 7.7 - Table 7.8, which correspond to position 2. A graphic representation of the worst case overlap in position 2 is shown in Appendix 1, Appendix 3, Appendix 5 and Appendix 7 for March month with applied BBC, March with HSD-DBBC, June with BBC and June with HSD-DBBC respectively.

Table 7.7: Overlap with Natura 2000 sites (worst case for any location within the site further from the Natura 2000 site than 750 m for the worst case month of March.

Natura 2000 site	Mitigation	Natura 2000 site total area [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site [%]
Sydvästskånes utsjövatten	BBC	1151	137	11.9%
	HSD-DBBC	1151	40	3.5%

Table 7.8: Overlap with Natura 2000 sites (worst case for any location within the site further from the Natura 2000 site than 750 m for the month of June.

Natura 2000 site	Mitigation	Natura 2000 site total area [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site [%]
Sydvästskånes utsjövatten	BBC	1151	35	3 %
	HSD-DBBC	1151	12	1 %

Figure 7.1: Noise contour map for position 1, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of March.

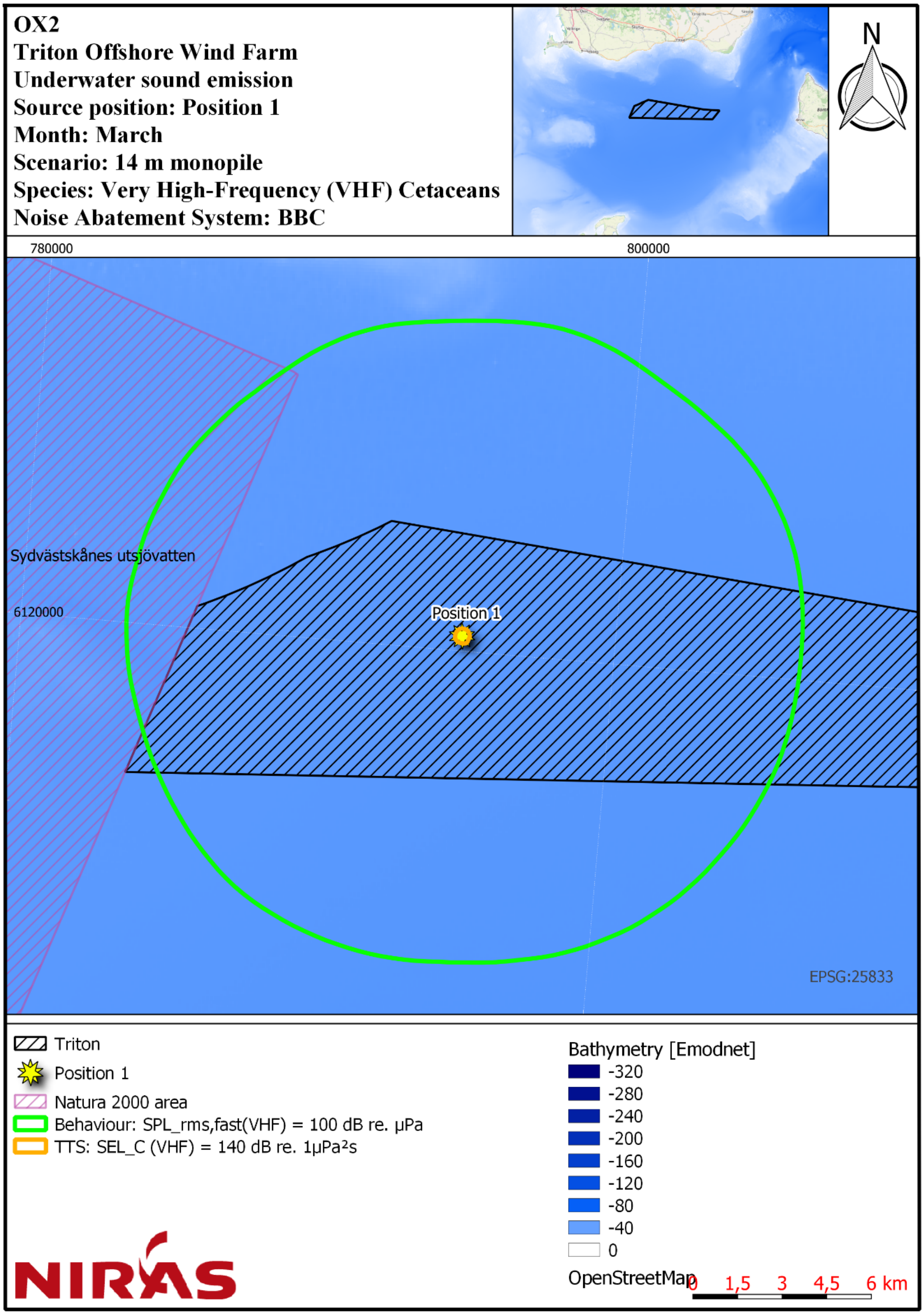


Figure 7.2: Noise contour map for position 2, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of March.

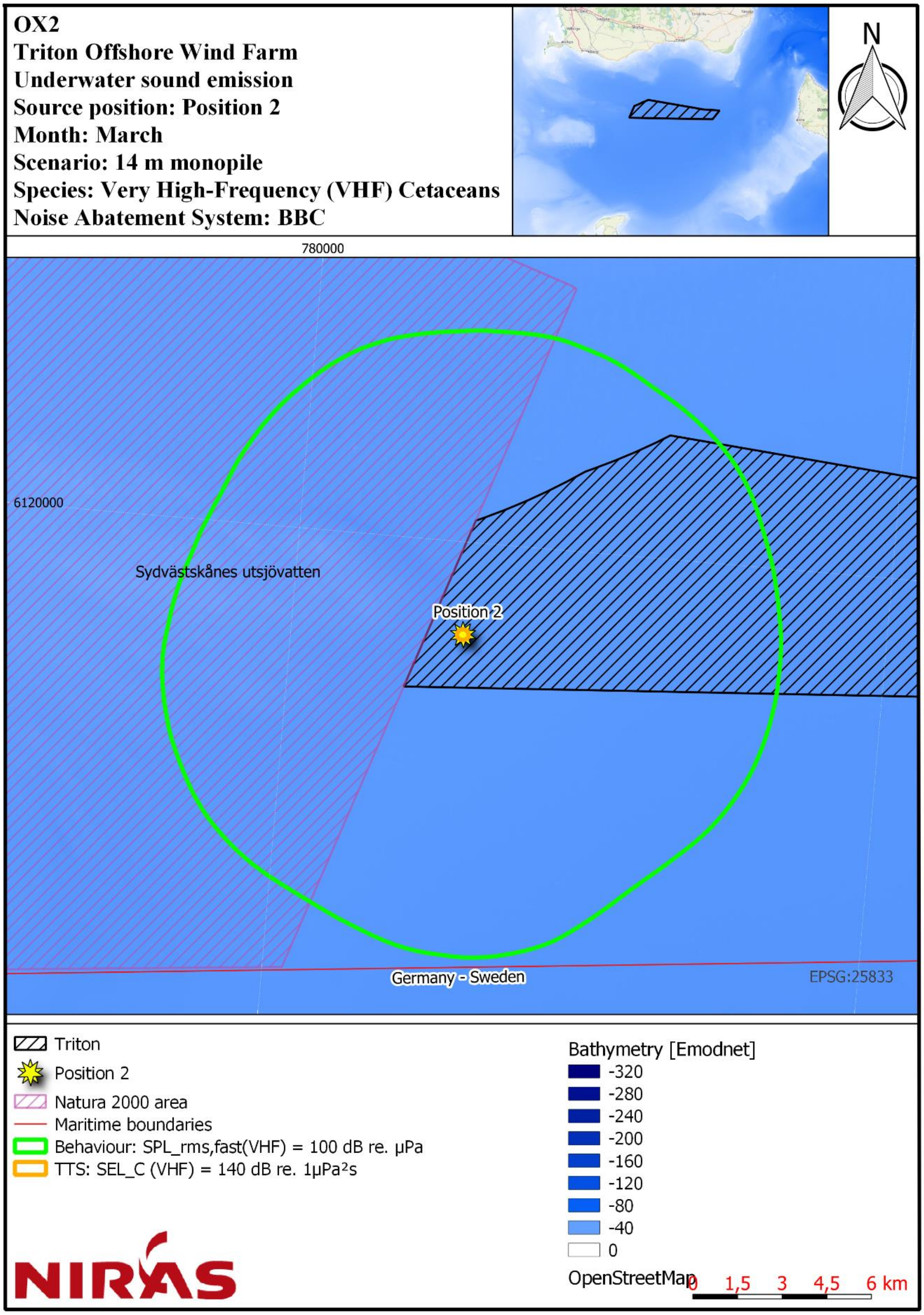


Figure 7.3: Noise contour map for position 3, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of March.

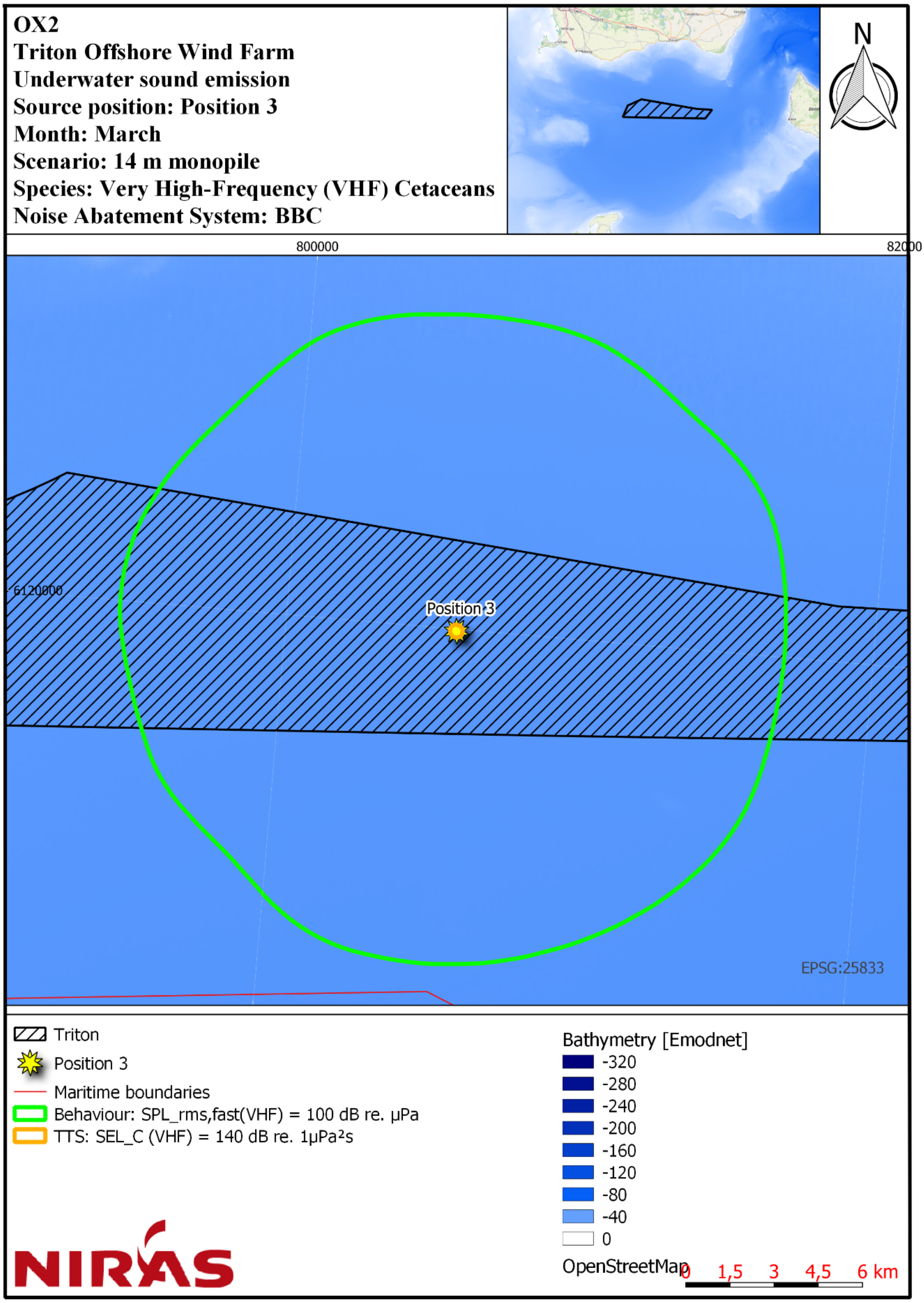
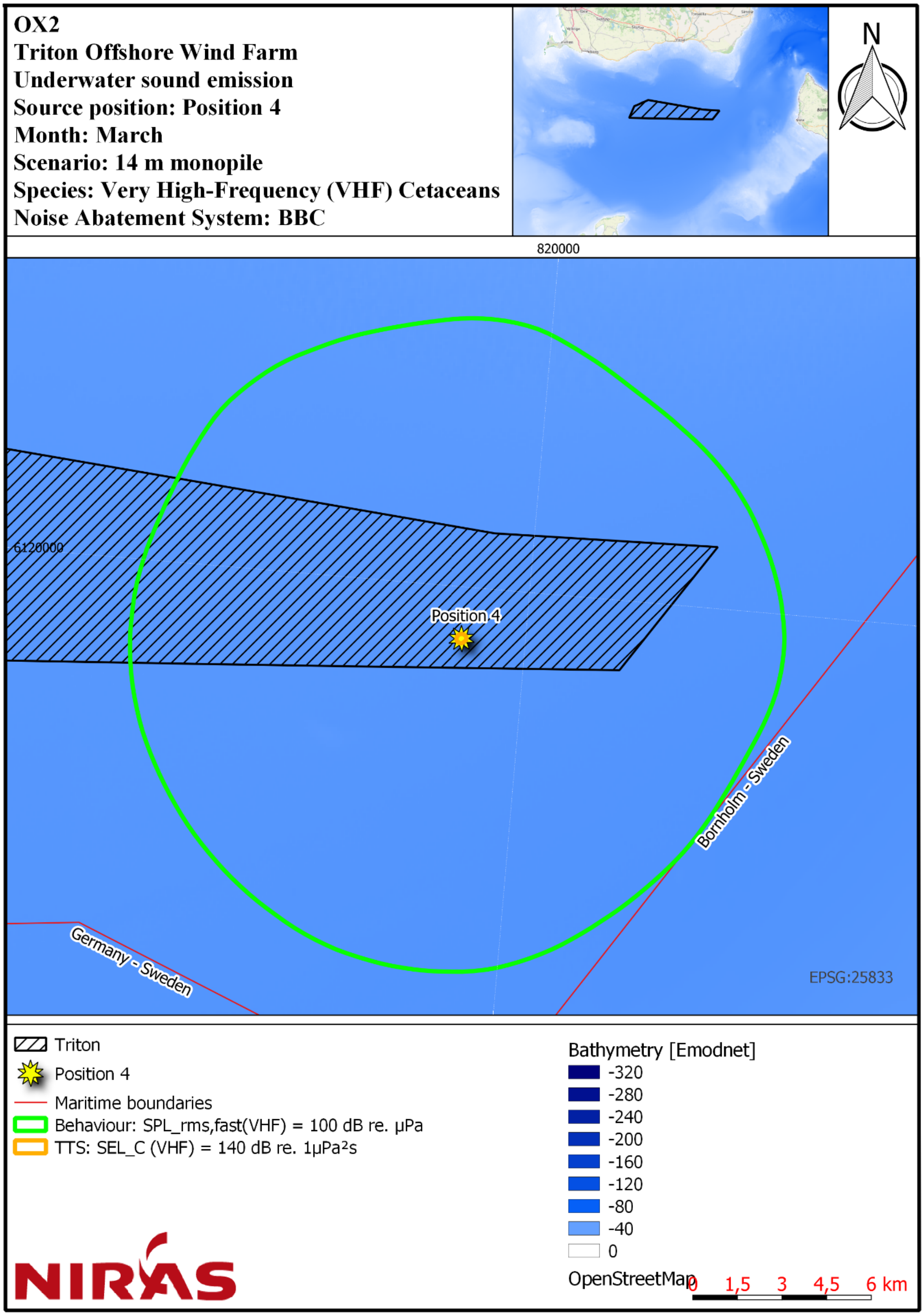


Figure 7.4: Noise contour map for position 4, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of March.



8 Conclusion

For harbour porpoise, calculations showed that permanent threshold shift (PTS) is unlikely to occur for marine mammals located further than 25 m away from the source at the onset of piling activities if a Big Bubble Curtain (BBC) equivalent Noise Abatement System (NAS) was applied. This is also the case if a Hydro Sound Damper Double Big Bubble Curtain (HSD-DBBC) equivalent NAS is applied. In regard to the temporary threshold shift (TTS), this is unlikely to occur in harbour porpoise located further than 300 m from the source at onset of piling with a BBC NAS, decreasing to 50 m with an HSD-DBBC NAS.

The behaviour effects of harbour porpoise are likely to occur within an 11.6 km (BBC), 6.7 km (HSD-DBBC) radius of the installation for the part of the installation where 100% hammer energy is applied. For lower hammer energies, such as during soft start and ramp up, the distance will be shorter.

For harbour seal, calculations showed that PTS is unlikely to occur within animals located further than 25 m from piling at the onset of piling activities where either a BBC or HSD-DBBC NAS was applied. In regard to TTS, this is likely to occur in harbour seals located within 825 m (BBC), 50 m (HSD-DBBC) from the source at onset of piling.

For cod and herring, impact distances between 14.5 km – 23.9 km were found for TTS when BBC was applied, reduced to 6.4 km – 14 km with HSD-DBBC. The variation is primarily a function of the fleeing speed, with faster fleeing speed resulting in overall lower impact ranges. Injury distances were all found to be below 25 m when the fleeing speed was 0.9 or 1.04 m/s. The injury distances is likely to occur within 90 m for (juvenile) cod with fleeing speed of 0.38 m/s. For larvae and eggs, injury distances up to 1.3 km were calculated with BBC applied, and up to 550 m for HSD-DBBC.

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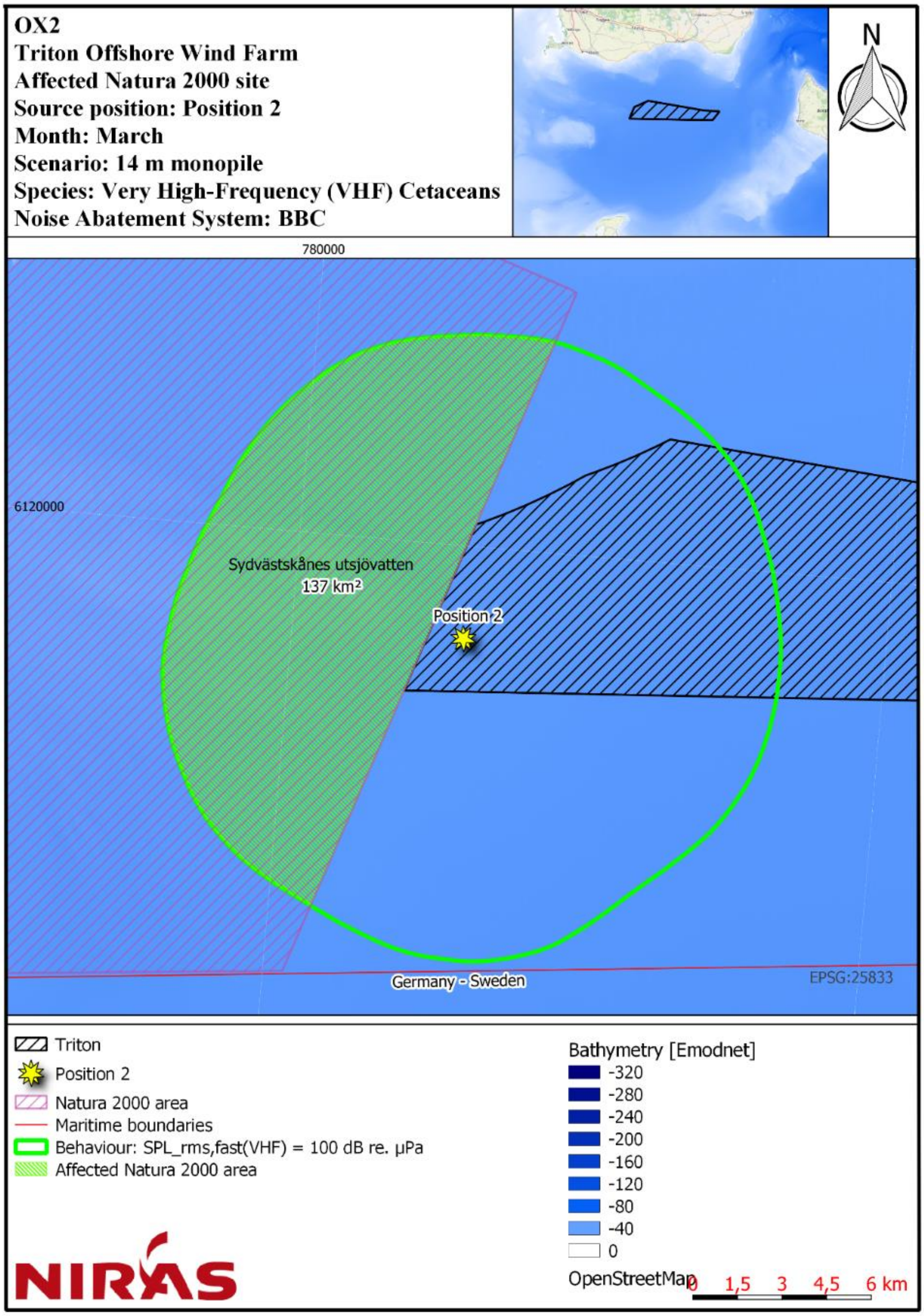
Appendix 1 – Affected Natura 2000 area, March, BBC

Figure A.1: Noise contour map for position 2, showing impact distance for behaviour with VHF-weighting together with the affected Natura 2000 area when BBC NAS is applied in March.



Appendix 2 - Underwater sound emission, March, HSD-DBBC

Figure A.2: Noise contour map for position 1, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of March.

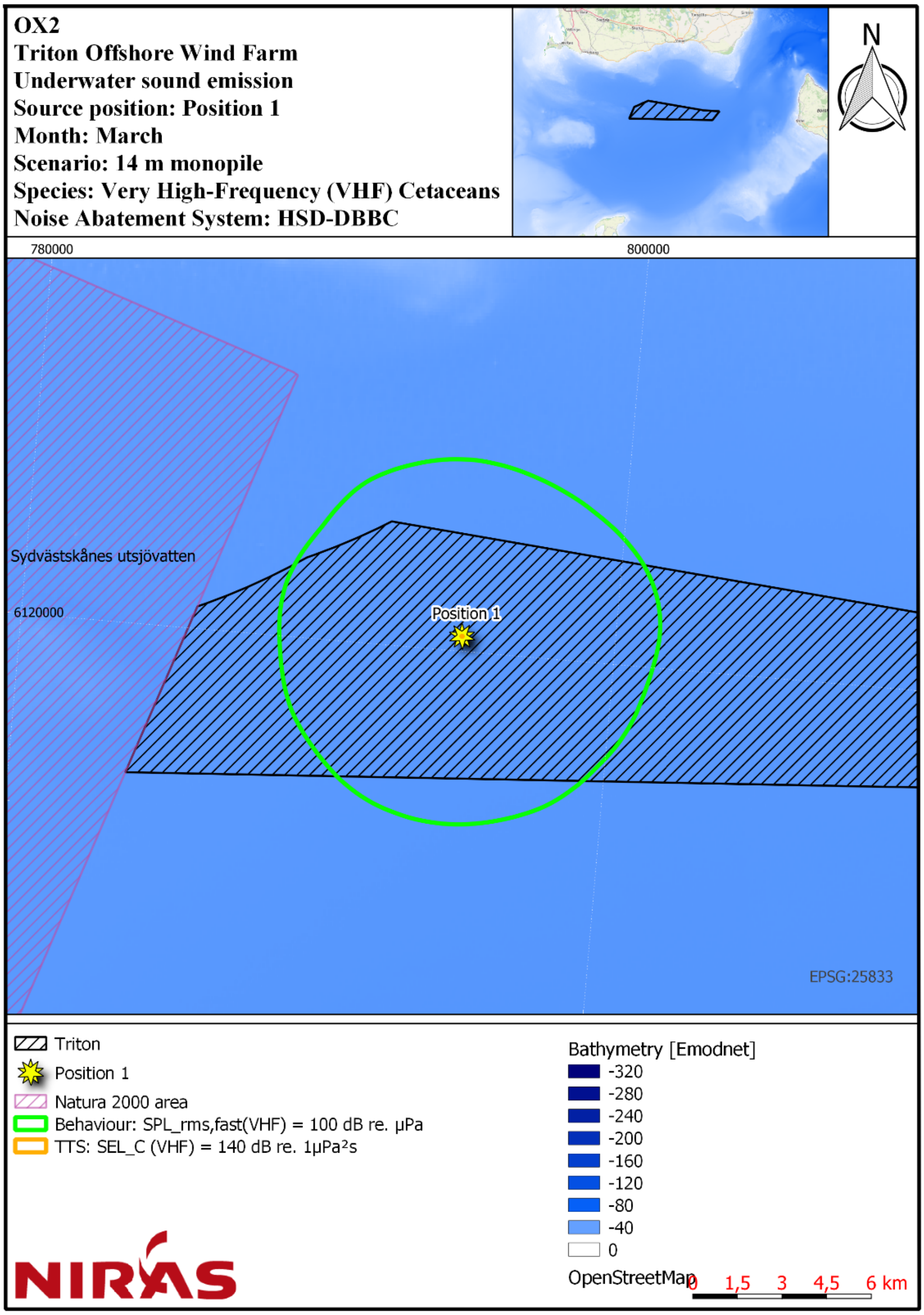


Figure A.3: Noise contour map for position 2, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of March.

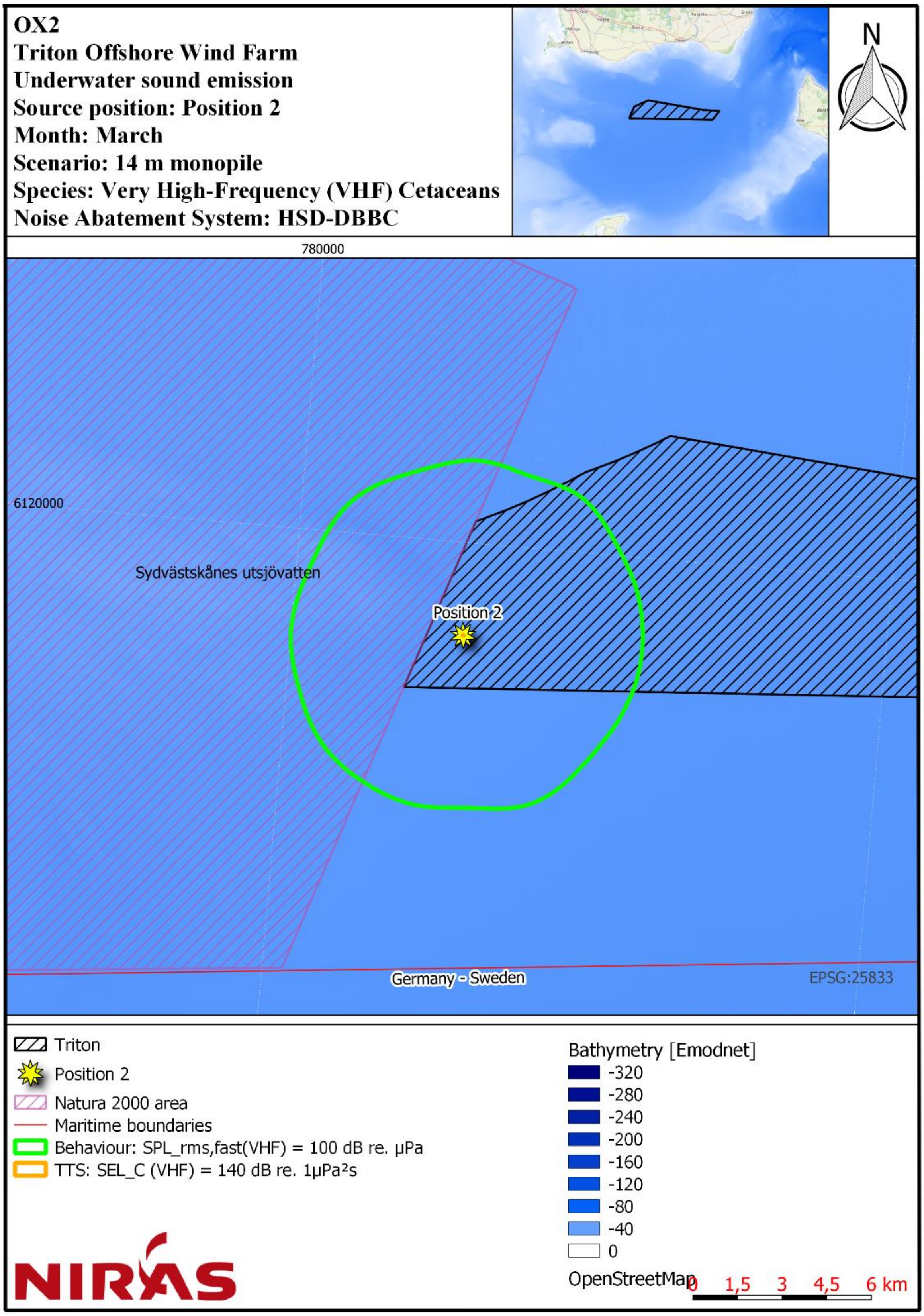


Figure A.4: Noise contour map for position 3, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of March.

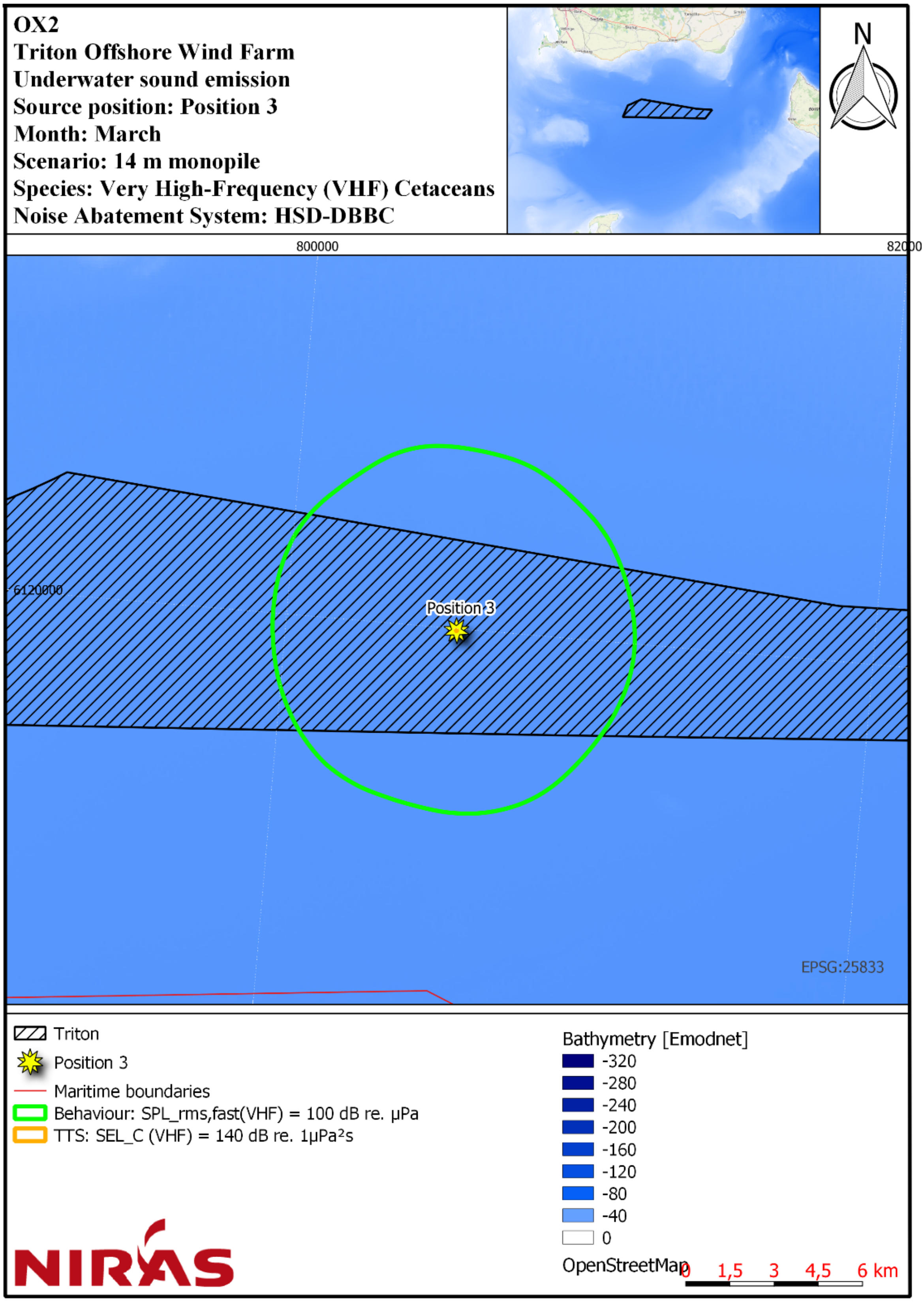
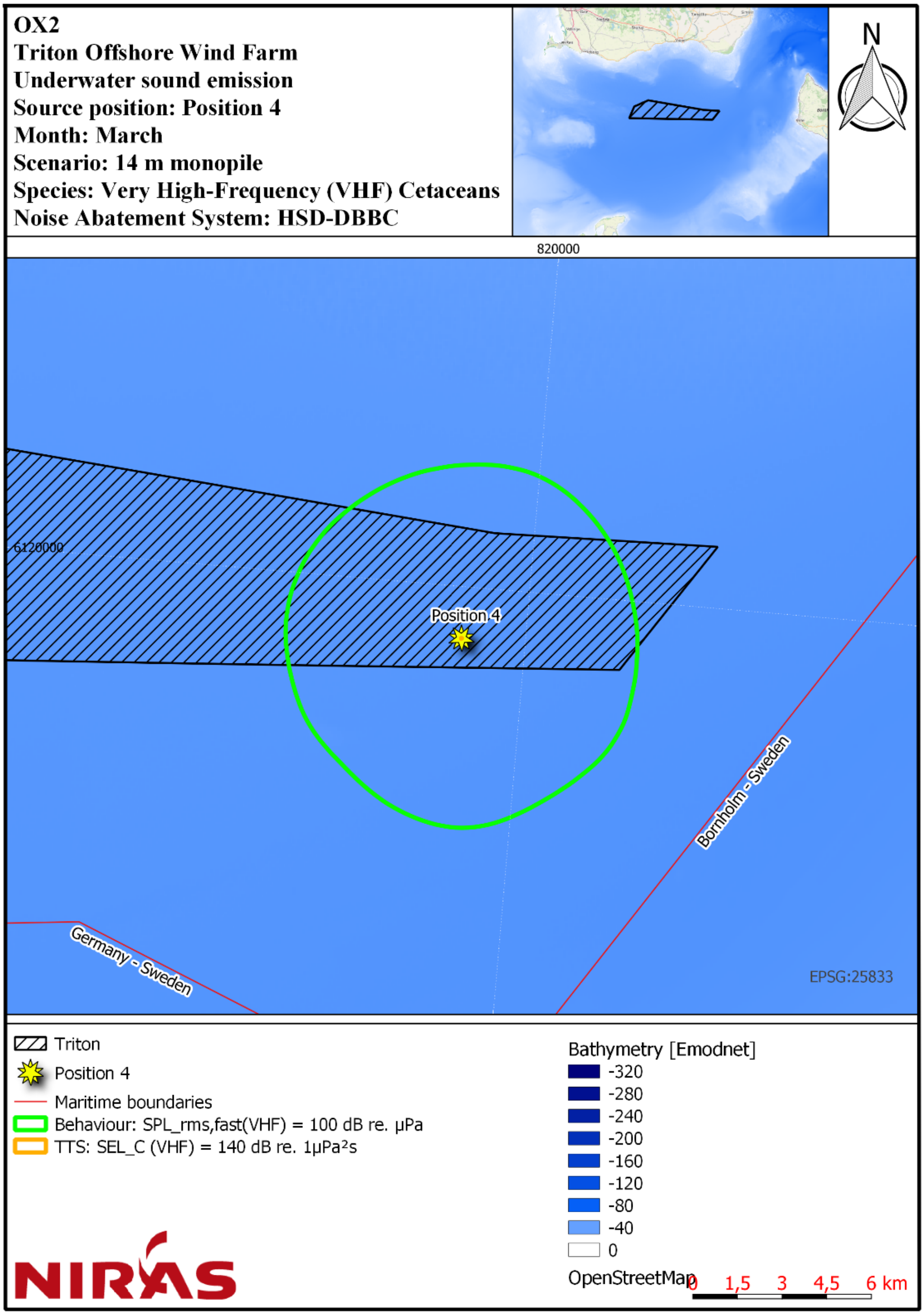
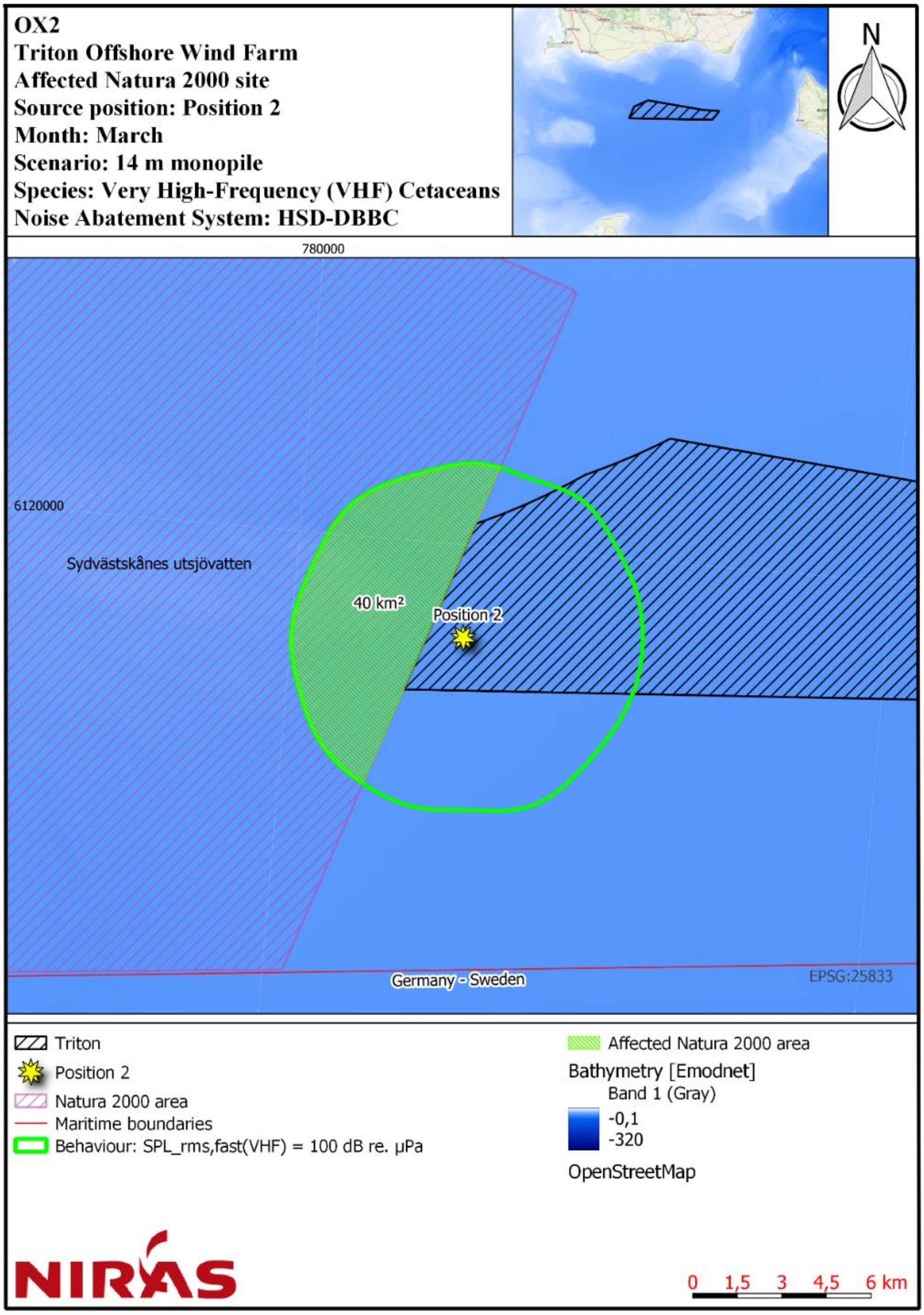


Figure A.5: Noise contour map for position 4, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of March.



Appendix 3 – Affected Natura 2000 area, March, HSD-DBBC

Figure A.6: Noise contour map for position 2, showing impact distance for behaviour with VHF-weighting together with the affected Natura 2000 area when HSD-DBBC NAS is applied in March.



Appendix 4– Underwater sound emission, June, BBC

Figure A.7: Noise contour map for position 1, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of June.

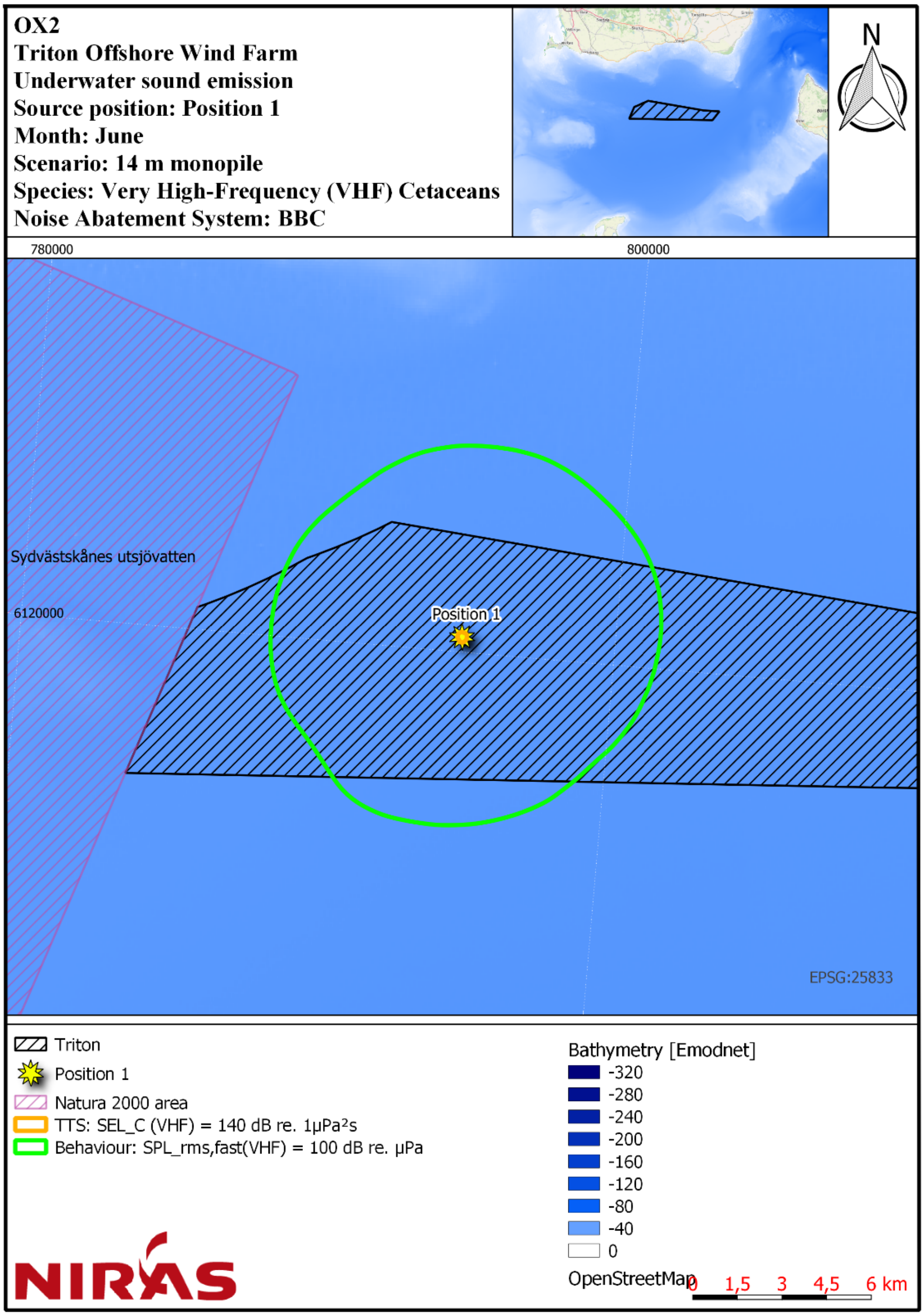


Figure A.8: Noise contour map for position 2, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of June.

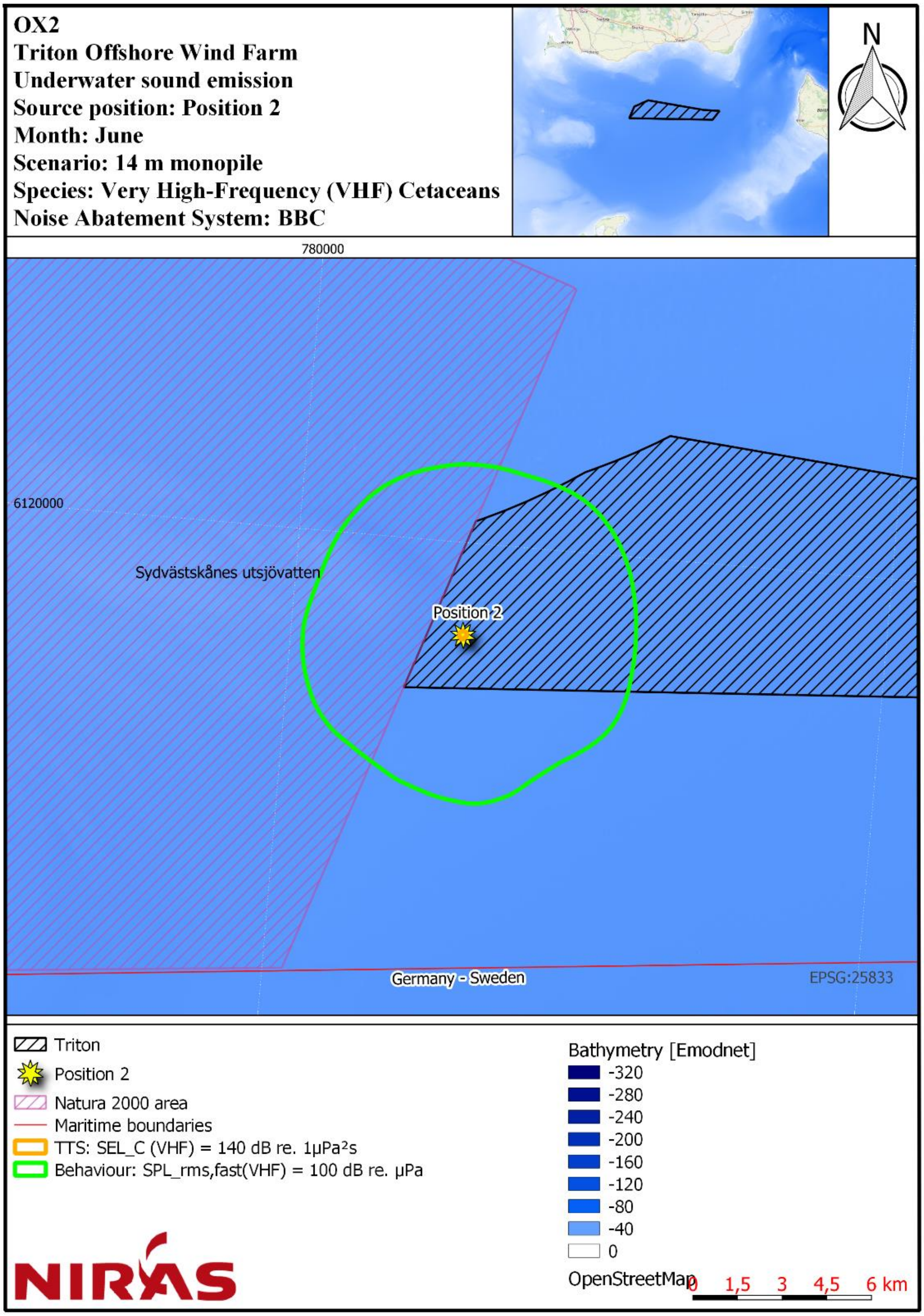


Figure A.9: Noise contour map for position 3, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of June.

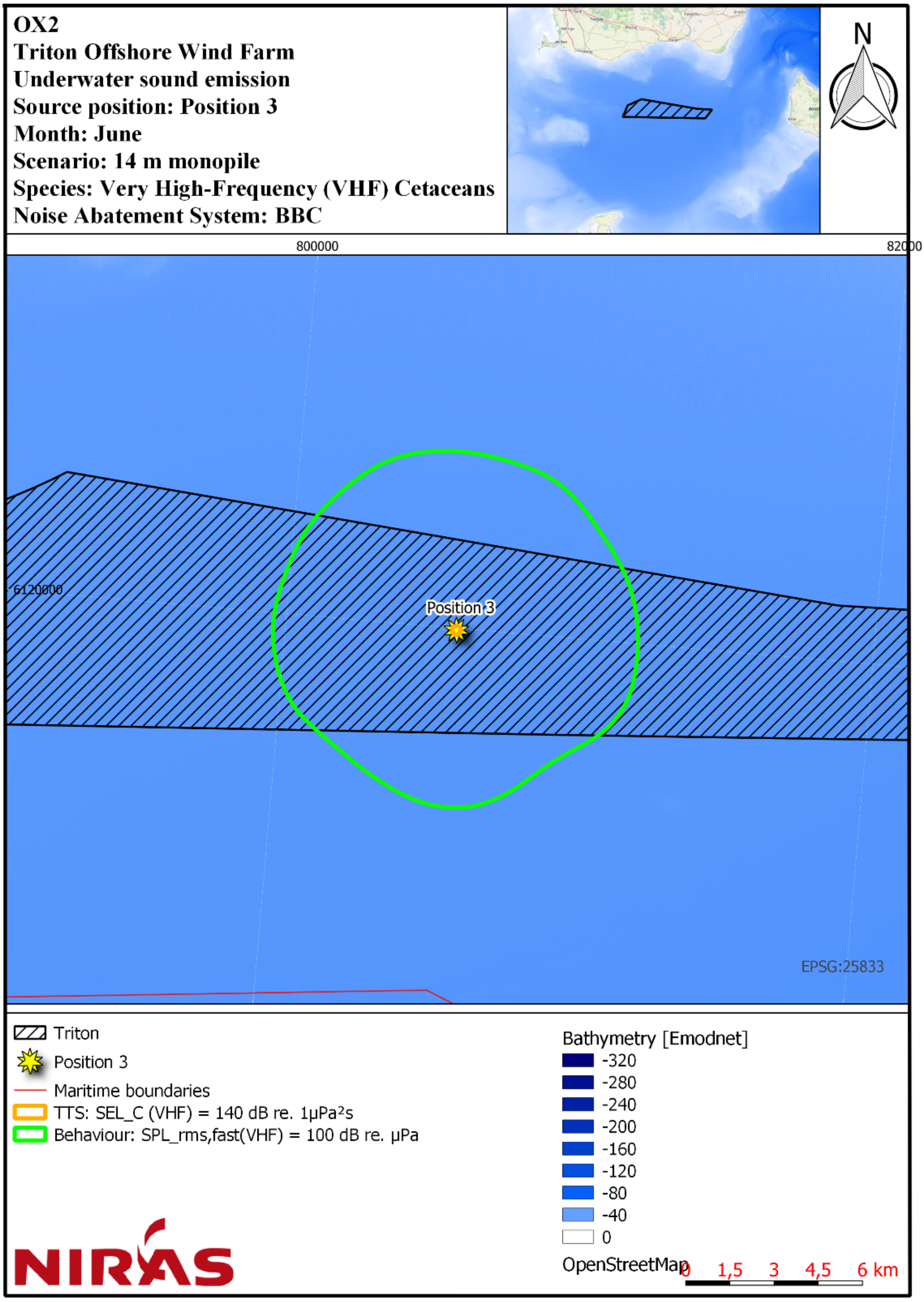
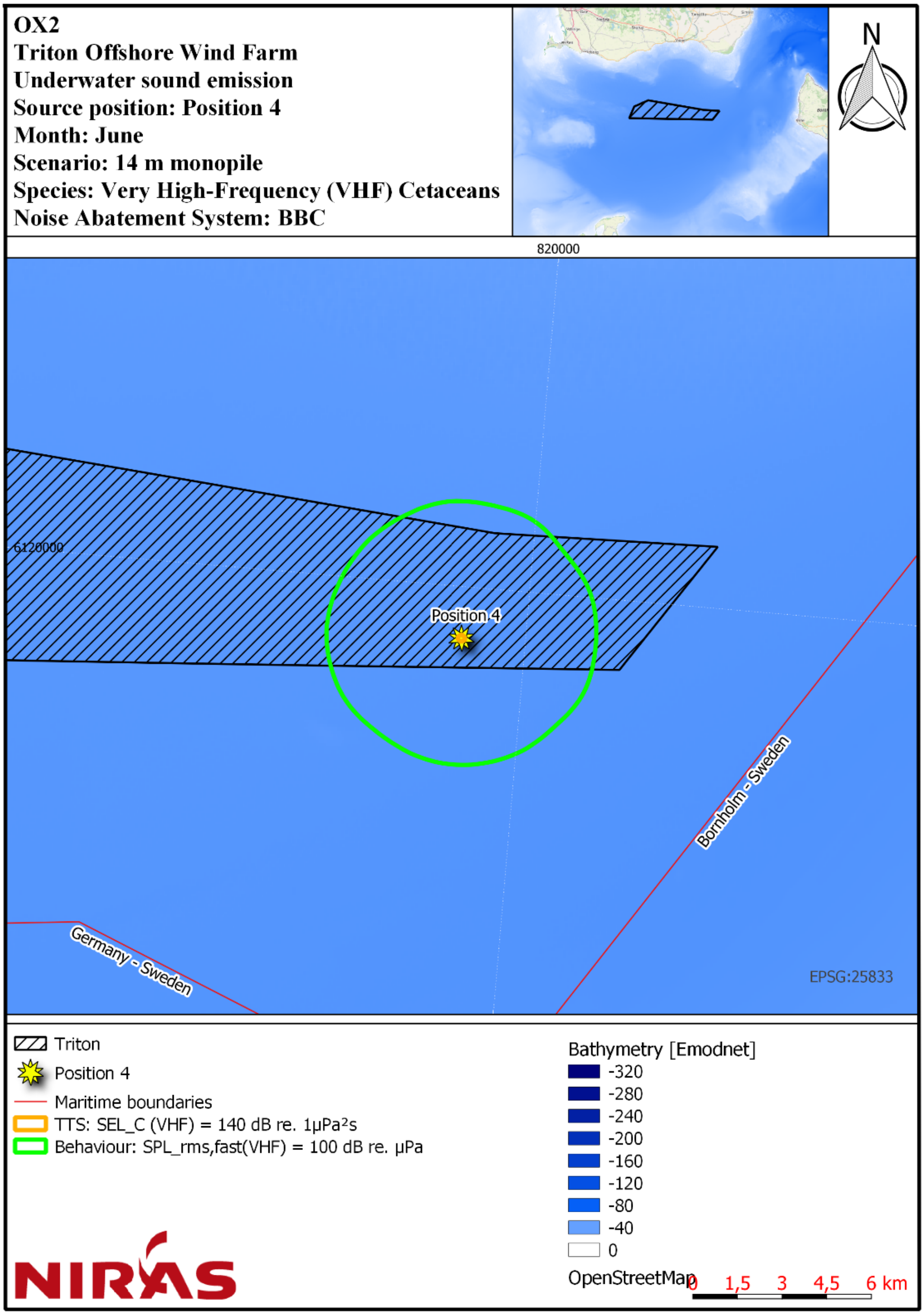
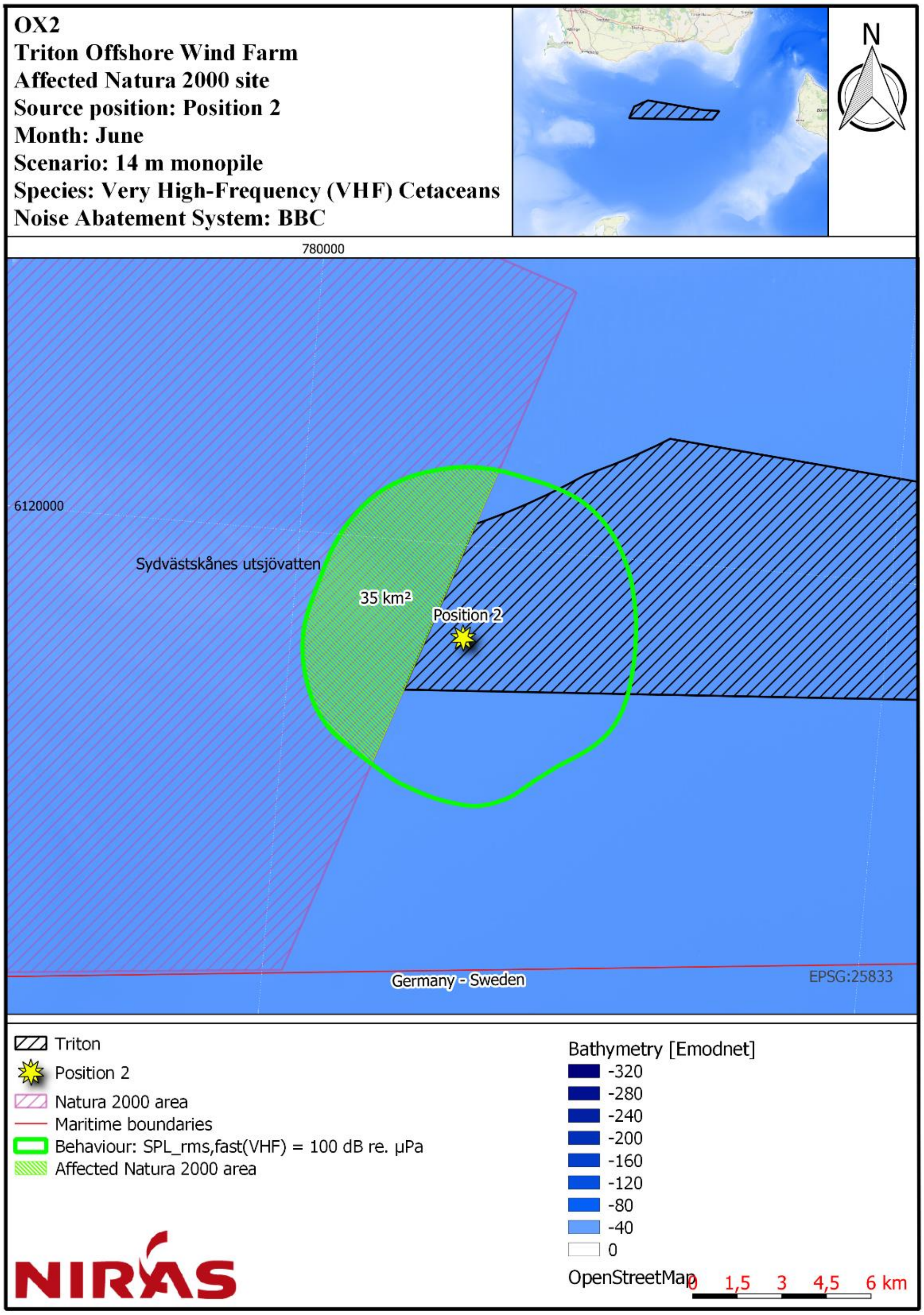


Figure A.10: Noise contour map for position 4, showing impact distances for TTS and behaviour with VHF-weighting and applied BBC NAS for the month of June.



Appendix 5 – Affected Natura 2000 area, June, BBC

Figure A.11: Noise contour map for position 2, showing impact distance for behaviour with VHF-weighting together with the affected Natura 2000 area when BBC NAS is applied in the month of June.



Appendix 6 - Underwater sound emission, June, HSD-DBBC

Figure A.12: Noise contour map for position 1, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of June.

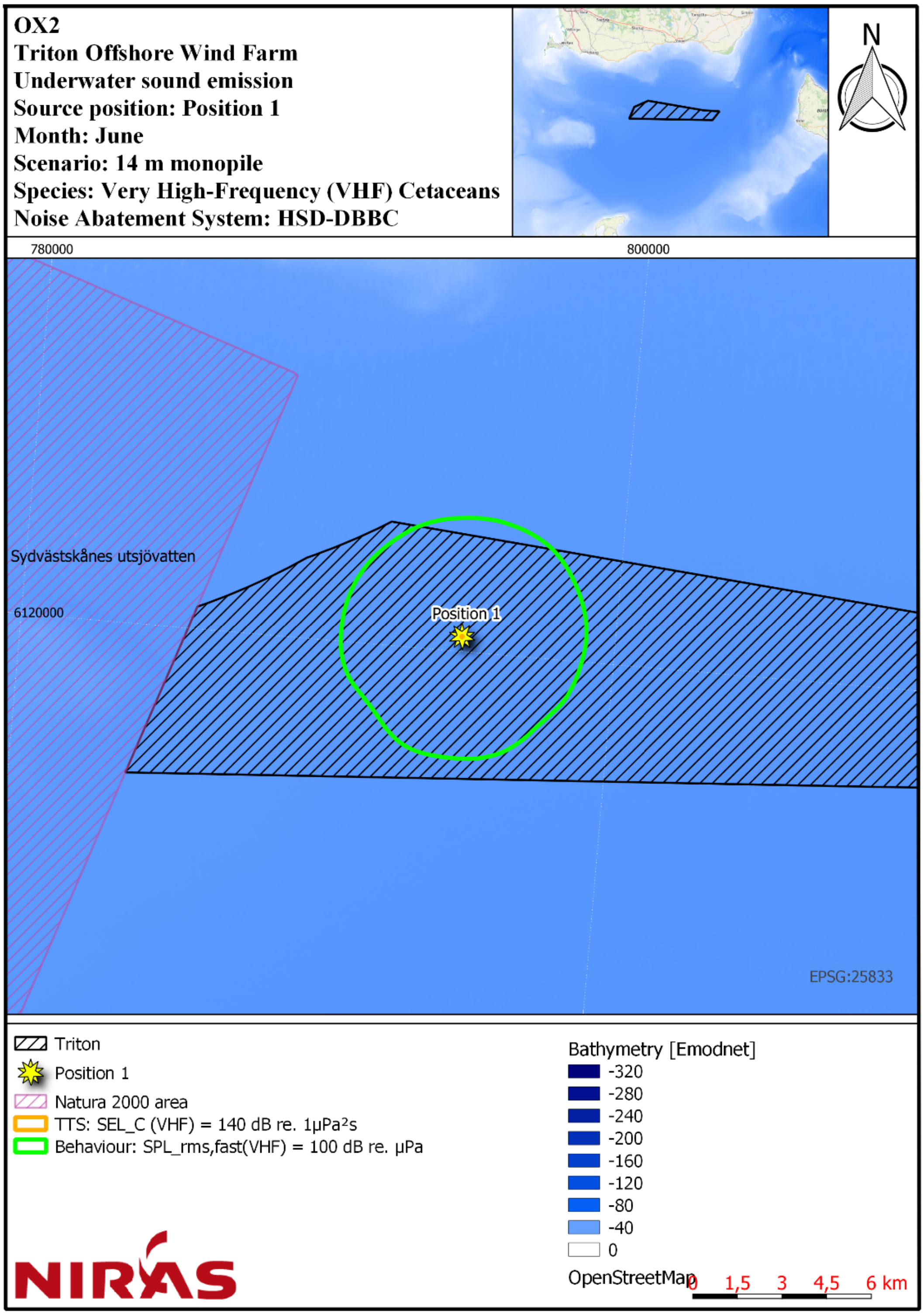


Figure A.13: Noise contour map for position 2, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of June.

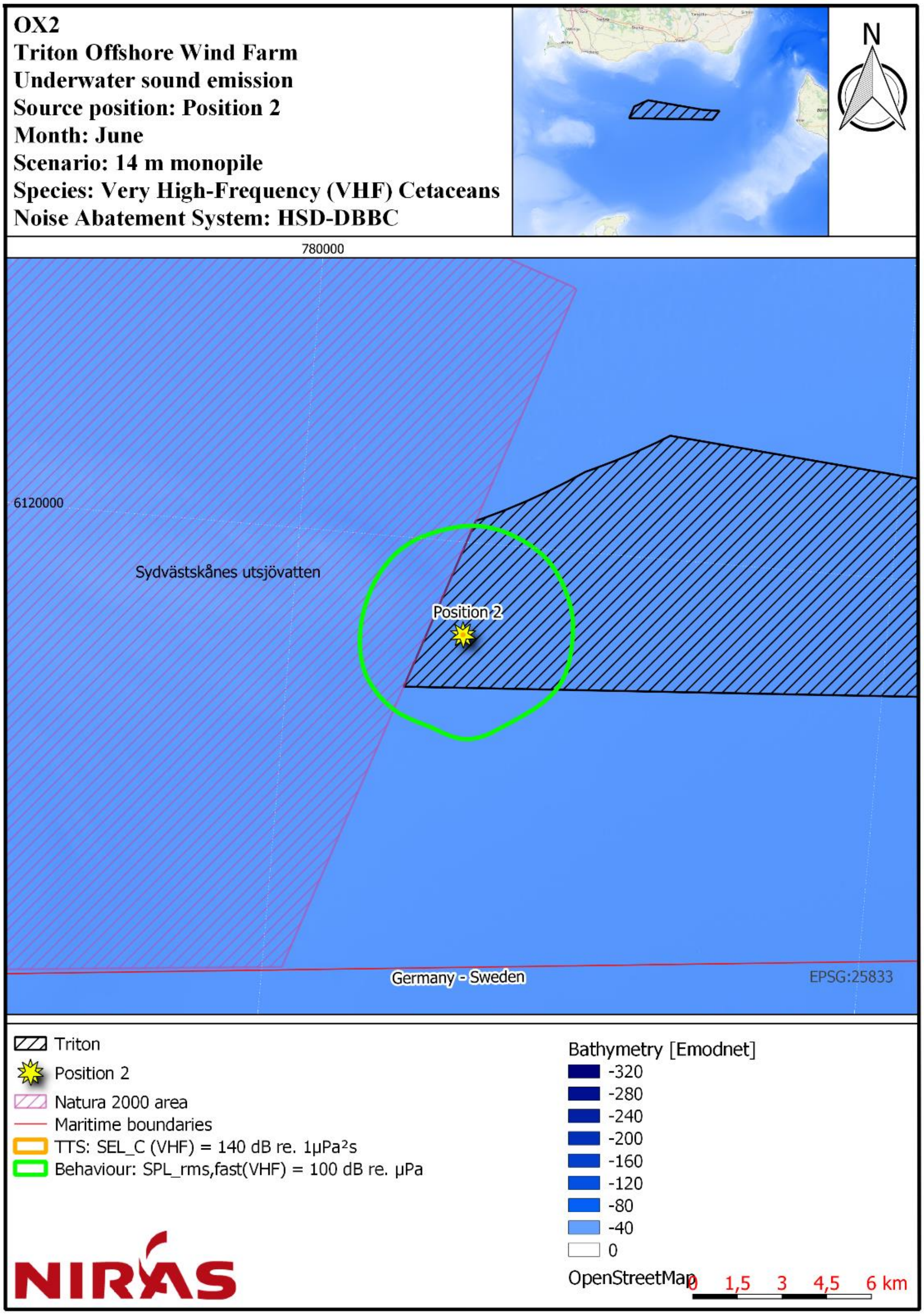


Figure A.14: Noise contour map for position 3, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of June.

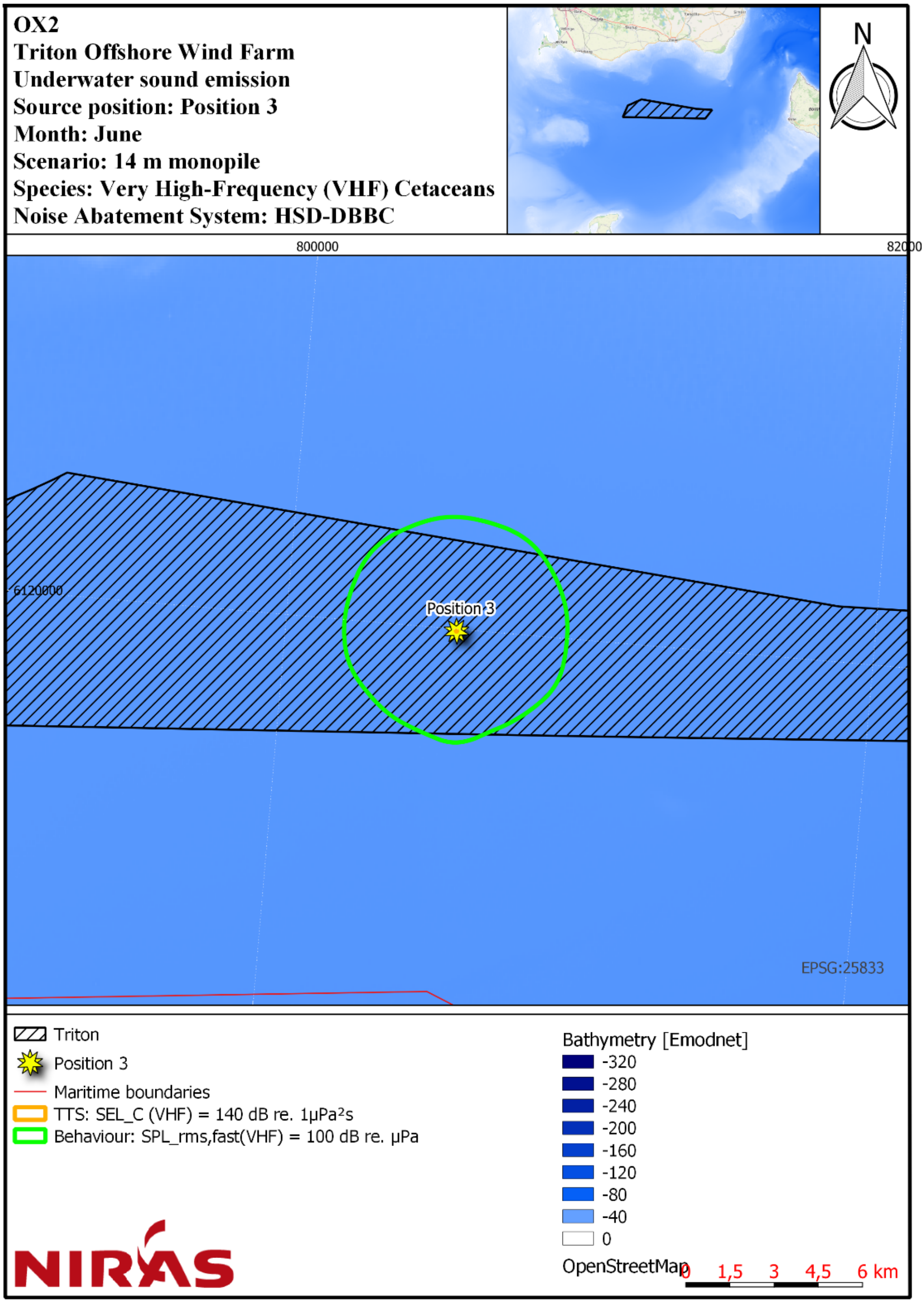
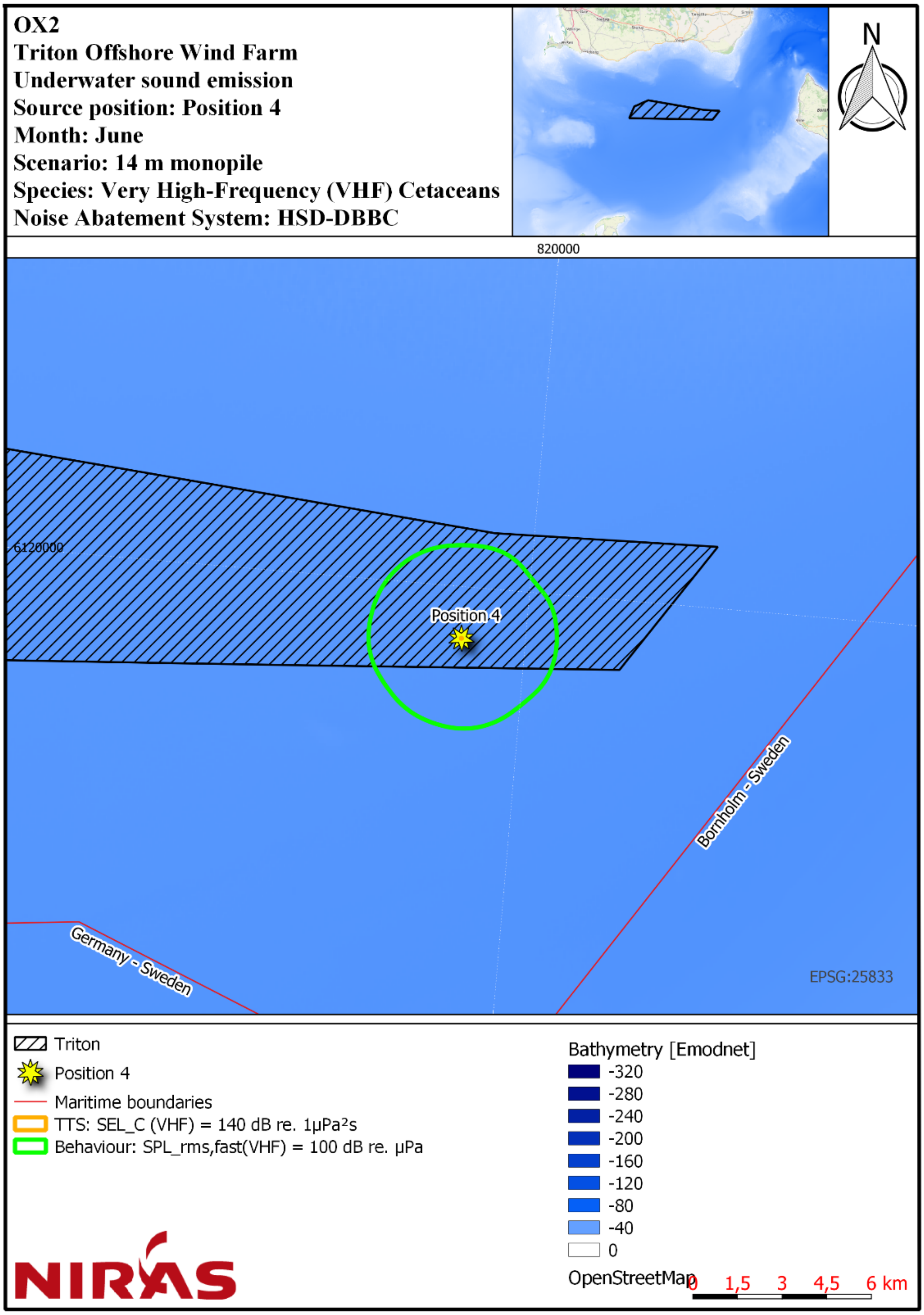


Figure A.15: Noise contour map for position 4, showing impact distances for TTS and behaviour with VHF-weighting and applied HSD-DBBC NAS for the month of June.



Appendix 7 – Affected Natura 2000 area, June, HSD-DBBC

Figure A.16: Noise contour map for position 2, showing impact distance for behaviour with VHF-weighting together with the affected Natura 2000 area when HSD-DBBC NAS is applied in the month of June.