Underwater noise
Technical report

Aflandshage Offshore
Wind Farm

WAHA01-GEN-PRO-05-000015 HOFOR WIND A/S

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Contents

Summary

In connection with the environmental impact assessment for Aflandshage Offshore Wind Farm in Øresund between Denmark and Sweden, NIRAS has carried out underwater sound emission modelling. This, to inform the impact assessment of marine mammals and fish, of the noise emission resulting from foundation installation at the proposed wind turbine locations.

Underwater sound emission was calculated for two monopile foundation types (7 m and 9.5 m diameter) as well as for a pin pile foundation using three piles each of 1 m diameter. Sound emission was calculated from three worst case source positions, expected to result in the largest sound emission in general, and towards nearby Natura 2000 areas.

A 3D acoustic model was created in dBSea 2.2.5, utilizing detailed knowledge of bathymetry, seabed sediment composition, water column salinity, temperature and sound speed as well as a detailed source model. Using advanced underwater sound propagation algorithms, the sound emission from each scenario was calculated in 360 directions (1° resolution).

From the underwater sound emission models, it was possible to calculate mitigation requirements for each installation, in order to comply with Danish regulations for underwater sound emission from pile driving activities, (Energistyrelsen, 2016). Factoring in the required source mitigation, allowed for determining the impact distances for the species of interest. This included species specific thresholds for avoidance behaviour, temporary and permanent threshold shift, as well as injury.

The frequency weighted species specific noise levels, reflecting the hearing sensitivities (audiograms) of Harbour Porpoise (*Phocoena phocoena*) and earless seals, were also calculated. This, to allow for comparison of current Danish guidelines (Energistyrelsen, 2016) with NOAA (National Oceanic and Atmospheric Administration) (NOAA, April 2018), as the latter is expected to constitute the foundation of the planned revision of the Danish guidelines on the subject, in the near future.

It is concluded that all proposed scenarios require source mitigation measures in order to comply with current Danish authority guideline requirements for underwater noise emission. Mitigation requirements for 1 m diameter pin piles up to 3.6 dB, and for monopiles up to 20.7 dB were estimated through underwater noise modelling.

With the expected future guidelines utilizing frequency weighted metrics, corresponding mitigation requirements were found to be lower than with the current guidelines for all pile sizes and positions. Installation of pin piles were found to be possible without any source mitigation, whereas monopile installation would require mitigation of up to 6.6 dB for a 7 m monopile and up to 9.1 dB for a 9.5 m monopile.

For the current guidelines, Temporary Threshold shift (TTS) was found likely to occur for marine mammals present up to 15.5 km away from pile installations, with likely avoidance behaviour reaction occurring up to 16.3 km from pile installation when using maximum hammer energy. For the expected future guidelines, the corresponding impact distances were found to be up to 14.4 km for TTS.

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1 Introduction

This report documents underwater sound propagation modelling performed in connection with the environmental impact assessment for the installation of Aflandshage Offshore Wind Farm located in Øresund at the edge of Køge Bay, see Figure 1.1. The report only handles underwater sound propagation for pile driving.

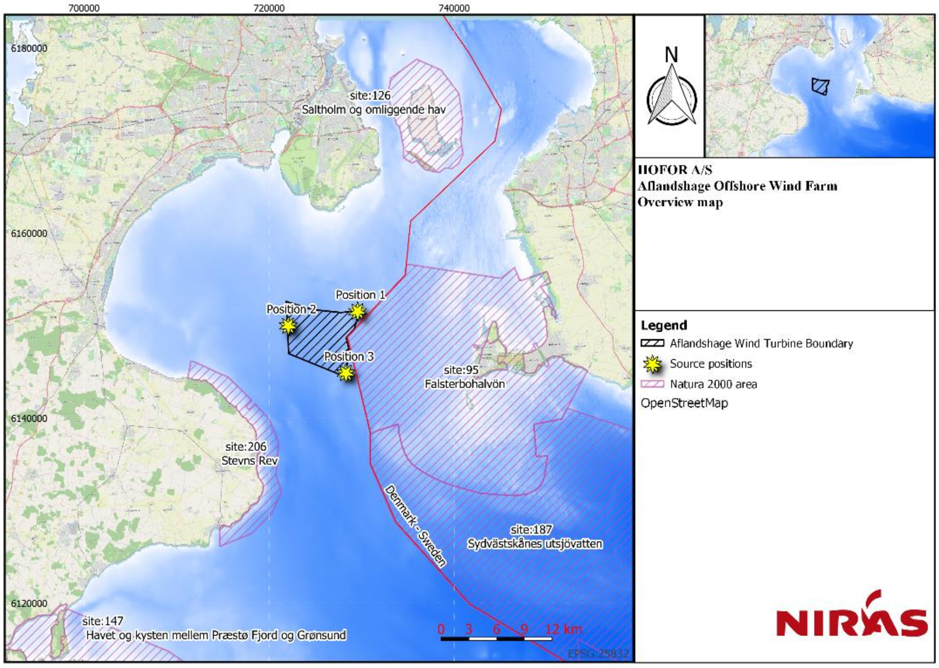


Figure 1.1: Overview of Aflandshage Offshore Wind Farm site (black) and surrounding Natura 2000 sites appointed for marine mammals (red).

The report also documents the required source mitigation necessary to comply with Danish guidelines for underwater noise emission (Energistyrelsen, 2016), and NOAA (National Oceanic and Atmospheric Administration) guidelines (NOAA, April 2018), as well as safe distances for thresholds relevant to the impact on marine mammals and fish. Furthermore, the report documents noise levels in species specific metrics related to the hearing ability of specific groups of marine mammals.

2 Purpose

The purpose of this report is to document which mitigation requirements are necessary to comply with Danish and NOAA guidelines for underwater noise, and to document underwater sound emission, weighted and unweighted, as a result of installation of wind turbine foundations, at the proposed offshore wind farm area.

3 Underwater noise impact criteria

The project must comply with current Danish authority guidelines on underwater noise emission from pile installation, as outlined in (Energistyrelsen, 2016). In addition to this, for the purpose of assessing the impact on marine mammals and fish, a number of threshold levels are determined.

3.1 Danish guideline mitigation requirements

In the Danish guidelines for underwater noise from pile driving activities (Energistyrelsen, 2016), it is stated that the so-called accumulated Sound Exposure Level (SEL_{C24h}) from each installation sequence must not exceed a threshold value of $190\ dB\ re\ 1\ \mu Pa^2 s$. The procedure for calculating SEL_{C24h} for a piling sequence is described in technical detail in (Energistyrelsen, 2016) and is conclusively expressed by the equation:

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

Where:

- 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
- SEL_{Max} is the source level at 1 m distance at 100% hammer energy
- X and A describe the sound propagation
- r_0 is the marine mammal distance to source at the onset of piling
- v_f is the fleeing speed of the marine mammal directly away from the source
- Δt_i is the time difference between onset of piling, and the i'th strike.

The guidelines specify standard values for the marine mammal starting distance (1.3 km given the use of pingers and seal scarers prior to piling) and a fleeing speed (1.5 m/s), while it dictates the need for the concession holder to determine the project specific source and sound propagation parameters.

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. From here on, the relationship between hammer energy level and pile strike number is referred to as the hammer curve.

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

Once all parameters have been estimated as accurately as possible, the SEL_C can be calculated. If the level exceeds the threshold $SEL_C = 190 dB\ re\ 1\ \mu Pa^2 s$ (porpoises permanent threshold shift), the source level must be mitigated accordingly.

The forecast is to be presented to the Danish Energy Agency for approval, and must be verified through measurements during the actual installation of the piles, as stated by the guidelines (Energistyrelsen, 2016).

"If the actual accumulated SEL does not exceed the threshold value, installation work can proceed as planned. If, on the other hand, the actual accumulated SEL exceeds the threshold value, then the Concessionaire must take measures to identify the causes of this deviation and perform corrective measures, including adjusting the installation method. When this work has been carried out, the next piles can be installed. In this situation, control measurements of underwater noise must also be performed for this next pile, and so forth, until the threshold value is complied with or the final pile in the installation round has been installed."

3.2 Marine mammal and fish noise impact criteria

Based on installation where guideline requirement for maximum allowed cumulative sound exposure level is complied with, through mitigation if necessary, the impact on marine mammals and fish is determined. This report purely concerns the technical aspects of underwater noise. For a more thorough explanation the different metrics, the reader is referred to the relevant technical background reports for marine mammals and fish.

3.2.1 Current Danish guideline threshold levels

Assessment of the noise impact on marine mammals, is currently based on unweighted SEL thresholds for marine mammal behavioral reaction, temporary threshold shift (TTS) and permanent threshold shift (PTS), as presented in Table 3.1. For fish, also the criteria for physical injury is used. For more information on the different thresholds, the reader is referred to the technical background reports for Marine Mammal as well as the specific impact assessment chapters of the EIA (Chapter 8.2 – Marine Mammals and Chapter 8.3 – Fish).

Table 3.1: Unweighted threshold criteria for marine mammals and fish. (Energistyrelsen, 2016; Tougaard, 2016)

Species	Fleeing Speed [m/s]	Impact Criteria	Matric	Threshold value [dB]
Harbour Porpoise	1.5	PTS	$SEL_{C,24h}$	190
		TTS		175
		Behaviour	SEL_{SS}	145
Phocid Pinniped		PTS	$SEL_{C,24h}$	200
		TTS		176
		Behaviour	SEL_{SS}	145
Cod	0.38	TTS	$SEL_{C,24h}$	185
		Injury		204
	0.9	TTS		185
		Injury		204
Herring	1.04	TTS		185
		Injury		204
Larvae and eggs	0	Injury		207

3.2.2 Revision of guideline threshold levels

Due to developments in the Danish community on marine bioacoustics, it is now believed that a shift in best practice will happen in the near future, with regards to marine mammal impact thresholds. A large study from the American National Oceanographic and Atmospheric Administration (NOAA), (NOAA, April 2018) is expected to form the basis for the revision of the Danish guidelines, where weighted thresholds are used. Whether or not the threshold levels will be the same as the NOAA guidelines or not is still not clear.

This will mean that instead of having an unweighted assessment, as Danish guidelines currently consist of, a more species specific weighting will be utilized, effectively taking the frequency specific hearing sensitivities of each species into account, when estimating the impact of a given noise source. The species specific weighted threshold criteria, can be seen below in Table 3.2. Thus, in the present report, calculation of noise impact on marine mammals are also conducted according to the NOAA guidelines, where weighted thresholds are used.

Table 3.2: Species specific weighted threshold criteria for marine mammals, (NOAA, April 2018)

Species	Fleeing Speed [m/s]	Impact Criteria	Matric	Threshold value [dB]
Harbour Porpoise	1.5	PTS	$SEL_{C,24h,VHF}$	155
		TTS		140
Phocid Pinniped		PTS	$SEL_{C,24h,PW}$	185
		TTS		170

3.2.3 Noise emission into Swedish territory

As the project area is close to Sweden and noise emission will carry over into Swedish waters, it is relevant to also consider the regulation of underwater noise in Sweden. Sweden, unlike Denmark, however, does not have established regulation, but evaluates underwater noise on a per project basis. In recent years, frequency weighted metrics, as those presented in Table 3.2, have been used for underwater noise modelling, (Mikaelsen M. A., Kriegers Flak Sweden - Underwater noise monitoring, 2019), (Mikaelsen M. A., Store Middelgrund Sweden - Underwater noise monitoring, 2020), and are considered to be a suitable representative for any evaluation of underwater noise inside Swedish waters.

4 Description of activities

The foundation method for the turbines is expected to be either monopile or gravitational (NIRAS, 2021). Of these, monopile foundations require pile driving activities for the installation and are expected to produce underwater sound levels that can potentially cause an impact on marine mammals and fish. In addition to monopile foundations, a scenario assuming a tripod foundation is also considered in the modelling[1]. The details of the different project scenarios are outlined in the technical project description (NIRAS, 2021).

Due to the high number of combinations possible within the project scope, it is not deemed feasible to carry out detailed underwater sound propagation modelling for all of them.

Underwater sound propagation modelling is therefore carried out for a number of representative scenarios, aiming to cover the most likely and most noisy combinations. For each of the scenarios, three source positions were chosen, representing

[1] Tripod foundations were part of the technical project description in the earlier stages of the project, and the underwater noise modelling carried out for this foundation is still included for reference.

the worst case positions inside the wind turbine boundary, with regards to maximum sound transmission and proximity to nearby Natura 2000 zones. The positions do not necessarily reflect actual wind turbine positions in any layout. Below, the worst-case scenarios selected for underwater sound propagation modelling are listed and described.

- Scenario 1: Installation of a tripod foundation with three 1 m diameter pin piles
- Scenario 2: Installation of a 7 m diameter monopile foundation
- Scenario 3: Installation of a 9.5 m diameter monopile foundation

A fourth likely scenario of an 8 m monopile foundation is furthermore evaluated, based on the underwater noise propagation modelling conducted for scenario 2 and 3.

Common for all scenarios, in accordance with Danish regulation (Energistyrelsen, 2016), prior to soft start, it is assumed that marine mammals are deterred to a minimum distance of 1300 m from the pile installation, by use of additional mitigation measures (pingers and seal scarers).

Based on NIRAS experience from earlier projects, (Mikaelsen M. A., 2015), (Mikaelsen M. A., Vesterhav Nord, Vesterhav Syd & Bornholm - Underwater noise monitoring, 2017), (Mikaelsen M. A., Walney Extension UK - Underwater noise monitoring, 2017), (Mikaelsen M. A., Kriegers Flak Sweden - Underwater noise monitoring, 2019), (Mikaelsen M. A., Store Middelgrund Sweden - Underwater noise monitoring, 2020) it was agreed with HOFOR to assume the following installation procedures for the underwater noise calculations.

4.1 Scenario 1: 1 m tripod foundations

In Scenario 1, turbines are installed using a tripod foundation. Where a monopile foundation consist of a single large diameter pile that carries the wind turbine, a tripod foundation is a steel support structure that is placed on the seabed. The structure has three legs, which are anchored to the deeper sediment layers through three smaller pin piles, one at the base of each leg. The pin pile diameter is significantly smaller than that of a monopile, typically below 1 m diameter.

- It is assumed that installation is carried out using an impact hammer with a maximum hammer energy of 2.000 kJ.
- It is assumed that the installation will require up to 2000 pile strikes for each of the three pin piles, totaling 6.000 pile strikes pr. foundation.
- Soft start will be employed using 150 pile strikes at 10% of maximum hammer energy, at a time interval of 2 seconds between each pile strike.
- Full hammer energy (100%) for the rest of the installation, with 1 pile strike every 2 seconds.
- All three piles are assumed installed with minimal inter pile downtime.

4.2 Scenario 2: 7 m monopile foundations

In Scenario 2, wind turbines with an individual effect of 5.5 – 6.5 MW are installed. The required foundation size for a monopile foundation to support this turbine size is listed as up to 7 m diameter.

- It is assumed that installation is carried out using an impact hammer with a maximum hammer energy of 3.500 kJ.
- It is assumed that the installation will require up to 7.000 pile strikes.

- Soft start will be employed using 150 pile strikes at 10% of maximum hammer energy, at a time interval of 4 seconds between each pile strike.
- Ramp up will follow the soft start with linear increase in hammer energy from 20% - 100% with a total of 300 pile strikes, at a time interval of 4 seconds between each pile strike.
- Full hammer energy (100%) is then used for the remainder of the 7.000 pile strikes, with 1 pile strike every 2 seconds.

4.3 Scenario 3: 9.5 m monopile foundations

In Scenario 3, wind turbines with an individual effect of 9,5-11 MW are installed, on a monopile foundation with a diameter of up to 9.5 m[2].

- It is assumed that installation is carried out using an impact hammer with a maximum hammer energy of 4.000 kJ.
- It is assumed that the installation will require up to 8.000 pile strikes.
- Soft start will be employed using 150 pile strikes at 10% of maximum hammer energy, at a time interval of 4 seconds between each pile strike.
- Ramp up will follow the soft start with linear increase in hammer energy from 20% - 100% with a total of 300 pile strikes, at a time interval of 4 seconds between each pile strike.
- Full hammer energy (100%) is then used for the remainder of the 8.000 pile strikes, with 1 pile strike every 2 seconds.

4.4 Pile driving source level

It was not possible to obtain a source level for the proposed pile driving scenarios, and it was therefore chosen to examine best available knowledge on the relationship between pile size and source level. The newest published knowledge on measured sound levels from pile driving activities in (Bellmann M. K., 2018), provides a graphic summary of measured source levels as a function of pile size. This is shown in Figure 4.1.

[2] For installation of a monopile with a diameter of 8 meter, the same installation scenario as for a monopile with a diameter of 9.5 meters is assumed. Underwater noise propagation modelling for the 8 meter monopile has not been undertaken, however the necessary noise mitigated for installation of the 8 meter monopile has been estimated, by interpolation from the results of the underwater noise modelling conducted for scenario 2 and 3.

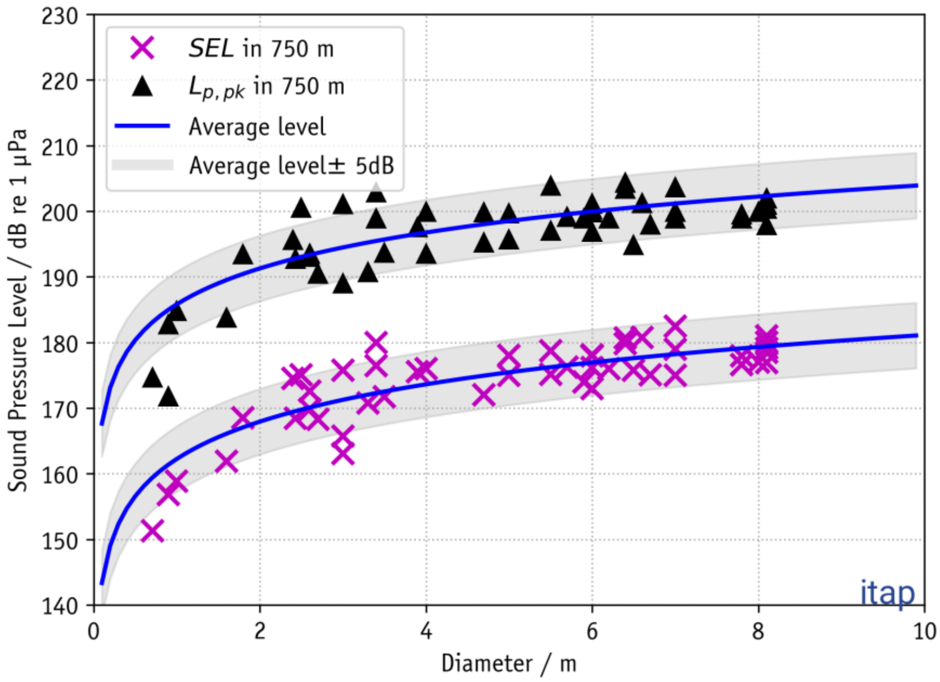


Figure 4.1: Relationship between measured SPL and SEL levels at 750 m distance, and pile size (Bellmann M. K., 2018).

The measurements are all normalized to 750 m distance from the pile, as this is the required measurement distance in German underwater noise regulation.

Examining Figure 4.1, the blue curve indicates the best fit of the measurement results. For the Sound Exposure Level (SEL) results, this relationship between pile size and measured level is approximately $\Delta SL = 19 * log10(\frac{D2}{D1})$, D1 and D2 being the diameter of 2 piles, and ΔSL being the dB difference in source level between the two.

It should be noted however, that some variations for a certain pile size do occur, as indicated by the spread of datapoints, around the fitted lines. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate.

For the three underwater sound propagation scenarios, inspecting Figure 4.1 would indicate the following average Sound Exposure Levels (SEL), at 750 m:

- Scenario 1: 1 m diameter pin pile: $SEL_{MAX,750m} = 162.4\ dB\ re. 1\ \mu Pa^2 s$
- Scenario 2: 7 m diameter monopile: $SEL_{MAX,750m} = 178.5\ dB\ re. 1\ \mu Pa^2 s$
- Scenario 3: 9.5 m diameter monopile: $SEL_{MAX,750m} = 181.0\ dB\ re. 1\ \mu Pa^2 s$

Using Thiele's equation for sound propagation (Thiele R. , 2002) proposing a 4.5 dB increase in sound level pr. halving of distance, the resulting increase from 750 m distance to 1 m distance equals 43.1 dB.

Source Levels at 1 m would thus be:

- Scenario 1: 1 m diameter pin pile: $SEL_{MAX,1m} = 205.5\ dB\ re. 1\ \mu Pa^2 s$
- Scenario 2: 7 m diameter monopile: $SEL_{MAX,1m} = 221.6\ dB\ re. 1\ \mu Pa^2 s$
- Scenario 3: 9.5 m diameter monopile: $SEL_{MAX,1m} = 224.1\ dB\ re. 1\ \mu Pa^2 s$

For the fourth likely scenario of an 8 m diameter monopile, the source level would be $SEL_{MAX,1m} = 222.7\ dB\ re. 1\ \mu Pa^2 s$.

Due to the lack of a detailed drivability analysis for the wind farm, it has not been possible to assess whether or not a more or less conservative source level compared to the calculated average should be utilized. As the pile driving scenario parameters are all considered to be realistic worst case, it was decided to use the average source levels for underwater sound propagation calculation to avoid being overly cautious.

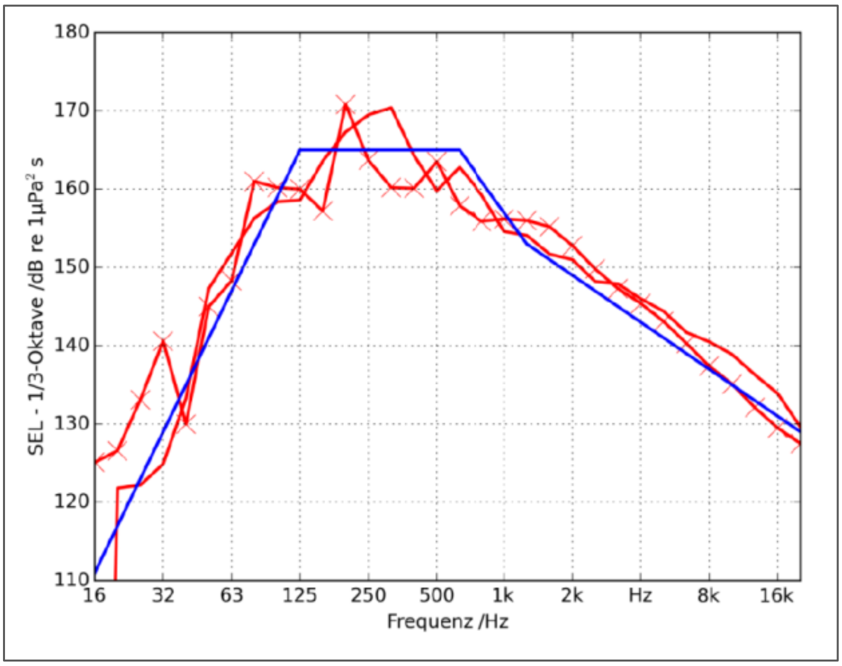
It is worth noting, that even the newest measurements are limited at 8.1 m monopiles, and that any extrapolation of source level of piles, beyond this size, is associated with uncertainty. In our opinion the data of Bellmann et al. (Bellmann M. K., 2018) presents the best available knowledge in the field to date, and it is therefore used to dictate the extrapolation of source level for the 9.5 m monopile.

4.4.1 Pile driving frequency spectrum

Having chosen unweighted source level $SEL_{MAX,1m}$ for the 1 m pin pile, 7 m, and 9.5 m diameter monopiles, the source frequency composition must be determined to accurately calculate the sound emission.

Due to the natural variations of measured frequency content between sites, piles, water depths, hammer energy levels and other factors, a generalized spectrum is used, as 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. In (Bellmann M. K., 2018) it is proposed to use the idealized pile spectra, as presented in Figure 4.2 (blue).

Figure 4.2: Idealized pile driving frequency spectrum (blue). Source: (Bellmann M. K., 2018).



It is however deemed necessary to perform a frequency shift of the idealized spectra based on the pile diameter. The general rule is that smaller diameter piles will have their maximum levels at a higher frequency, than those of larger diameter. For the 1 m pin piles the idealized spectra is used as presented in Figure 4.2, while the 7 and 9.5 m monopiles use a downward 1/3 octave shifted frequency spectrum. For the monopiles, this means an upper plateau located at 100 Hz – 500 Hz compared to 125 Hz – 630 Hz for the pin pile.

5 Sound propagation modelling method

This chapter will first give a brief overview of underwater sound propagation 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 ends with documentation of the sound propagation modelling results in both graphic representations, and with calculations of the sound propagation parameters required for the calculation of SEL_C, VHF- and PW-weighting.

5.1 Underwater sound propagation theory

This section is based on (Jensen, Kuperman, Porter, & Schmidt, 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, Kuperman, Porter, & Schmidt, 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.

Snell's law states that:

$$\frac{\cos(\theta)}{c} = constant$$

Where:
θ is the ray angle []
c is the speed of sound $[m/s]$.

This relationship implies that sound bends toward regions of low sound speed (Jensen, Kuperman, Porter, & Schmidt, 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.

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.

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.

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, the sound energy will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by:

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

Where f is the frequency of the wave in kHz (Jensen, Kuperman, Porter, & Schmidt, 2011). This infers that increasing frequency also leads to increased absorption.

5.2 Underwater noise modelling software

NIRAS uses the underwater noise modelling software: dBSea version 2.2.5 (build 293), developed by Marshall Day Acoustics.

The software uses bathymetry, sediment and sound speed input data to build a 3D acoustic model of the environment. This, combined with accurate sound propagation models, such as dBSeaPE, a Parabolic Equation algorithm and dBSeaRay, a Ray Theory algorithm, make for accurate prediction of the sound propagation.

For this project, the following dBSea setup was used.

- Calculations carried out in 1/3 octave bands to reflect the hearing of marine mammals
- The dBSeaPE-algorithm was used for the entire calculated spectrum (12,5 Hz-32kHz)
  - dBSeaRay was omitted from the calculations, due to the relatively large difference in water depth (from 50 to 2 m), resulting in unnatural dispersion estimates resulting from the ray-based algorithm limitations.
- Calculation in 100 x 1 m grid (distance x depth interval)
- Calculation of 360 transects, providing a 1° resolution.

5.3 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.

5.3.1 Bathymetry

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

The bathymetry used in these calculations were acquired through the website of the Danish national geological surveys (GEUS, 2020). The data set was compiled in 1997 (updated in 2005-2006), and is composed from elevation lines, collected by multiple different geological survey agencies such as Farvandsvæsenet and Baltic Sea Research Institute. In general, the water depth is around 15-20 m within the project boundary, see Figure 5.1.

The area around the two planned wind farms is dominated by the eastern coast of Sjælland, Denmark, and the western coast of Skåne, Sweden. Within the strait of Øresund is a couple of smaller islands, and the overall meanderings of the Danish and Swedish coastal lines. All of these features will influence the spread of noise in the area.

Aflandshage is positioned at the eastern edge of Køge Bay, which will limit the spread of noise in that direction. The spread of noise is therefore mostly expected to be in the southern direction, out of the Øresund strait, towards the Baltic Sea.

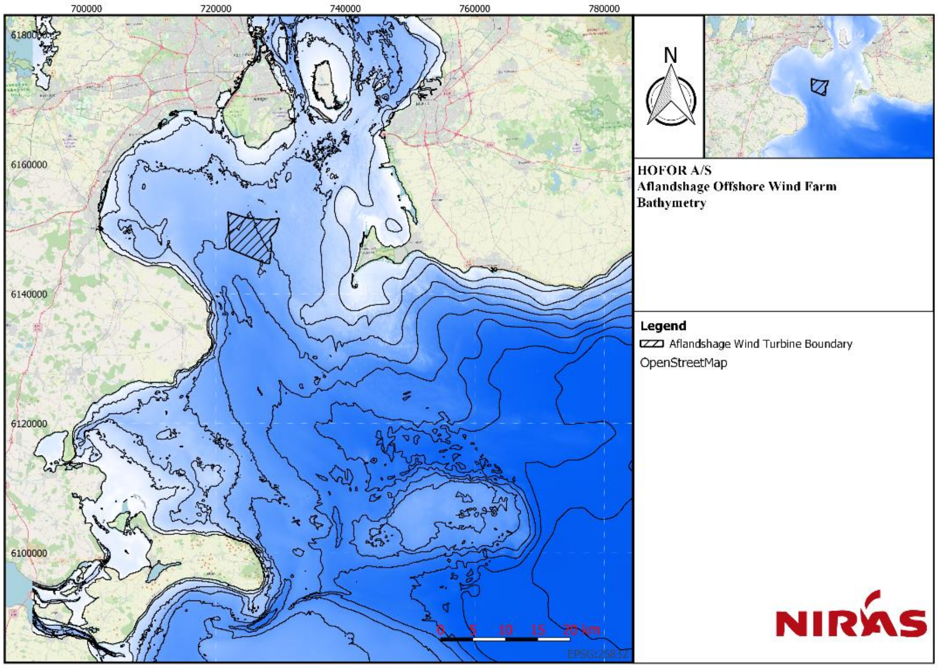


Figure 5.1: Bathymetry map for Aflandshage project area and surroundings. Also shown with numbering (1-3) are the chosen positions for sound emission modelling.

5.3.2 Seabed sediment composition

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.

For this project, the seabed substrate map from https://www.emodnet-geology.eu/ was studied in QGIS along with the GEUS "Pre-Quaternary surface topography of Denmark" map from www.geus.dk, and the book "Danmarks Geologi" chapter 4 to determine the sediment types and thicknesses for the site and surroundings. Additionally, geological modelling and sediment composition estimates, conducted and reported by GEO for the two sites, have also been used (GEO, 2019).

From the investigations, it was determined that the site and surroundings mostly have a top layer of mud and sand of varying thickness on average 5 meters. Patches of gravel, mixed boulders and other mixed sediments also occur. The lower half of the layer is however modelled using a more densely packed sediment type to account for the increased pressure on the lower sediment. Below this, is the chalk layer with thickness up to 1.5 km.

5.3.3 Sound Speed Profile

The sound propagation depends not only on bathymetry and sediment but also 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. No detailed time schedule has been proposed for the installation of turbine foundations, and it was therefore investigated what the typical salinity, temperature and sound speed profiles are expected to be for the different months of the year.

NIRAS examined 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) 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 has been extracted for all months, and are shown below in Figure 5.2, where the extracted sound speed profiles are shown at the available positions. Note that the gridded layout of the sound speed profiles indicates their respective position geographically. Empty plots thus illustrate where landmass is present, and a sound speed profile therefore is not available.

Underwater sound propagation modelling is carried out only for the month with most favourable condition for sound emission, and as described in section 5.1, this would typically be a month where upward refraction is evident. Examining Figure 5.2, this would indicate March as the worst case month in all locations, with January and February coming in second. For clarity, the sound speed profiles for each position for the month of march are shown in Figure 5.3.

Figure 5.2: Sound speed profiles for all 12 months for project area and surrounding waters, based on temperature and salinity data from World Ocean Atlas 2018 v2 (NOAA, 2019)

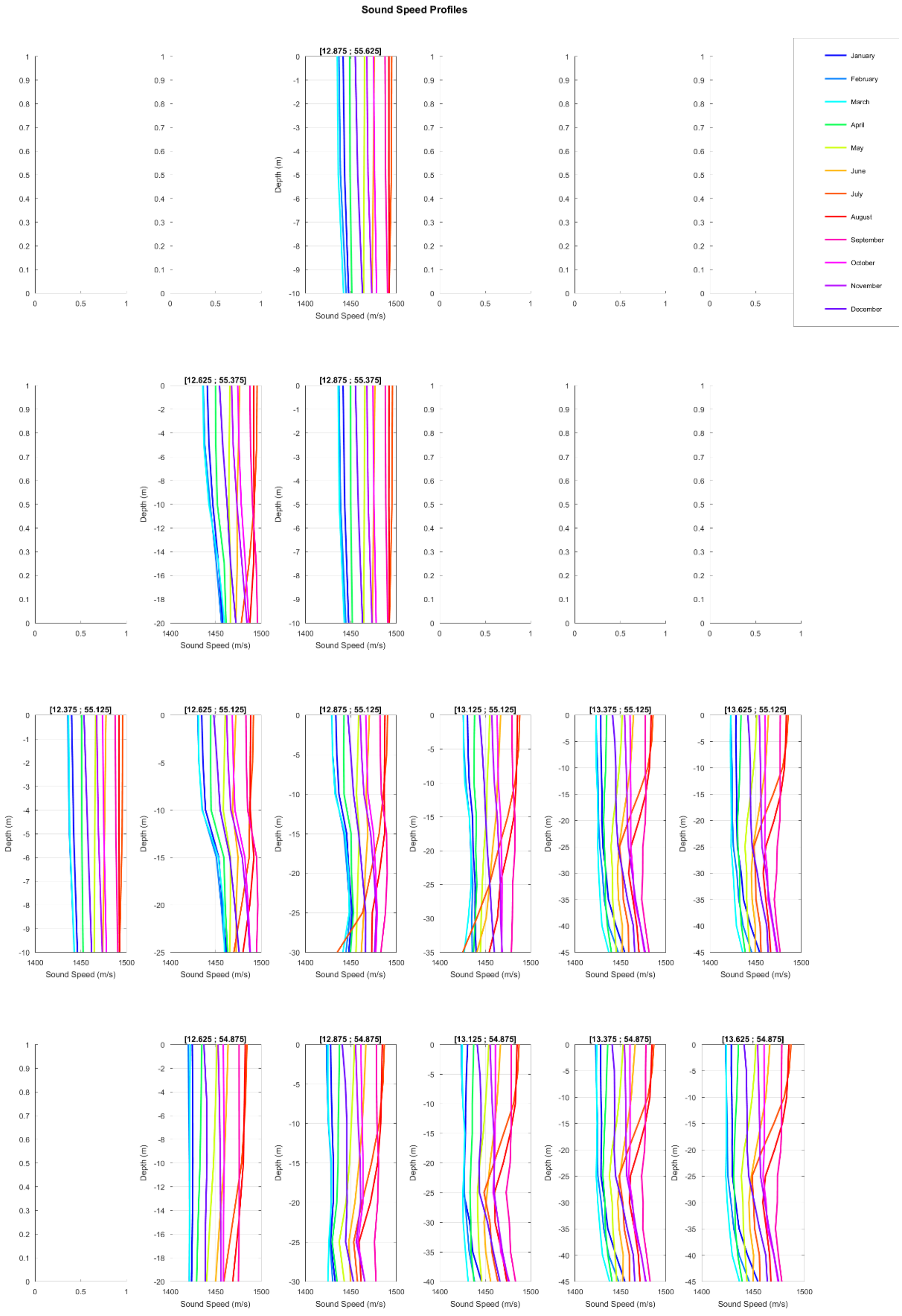
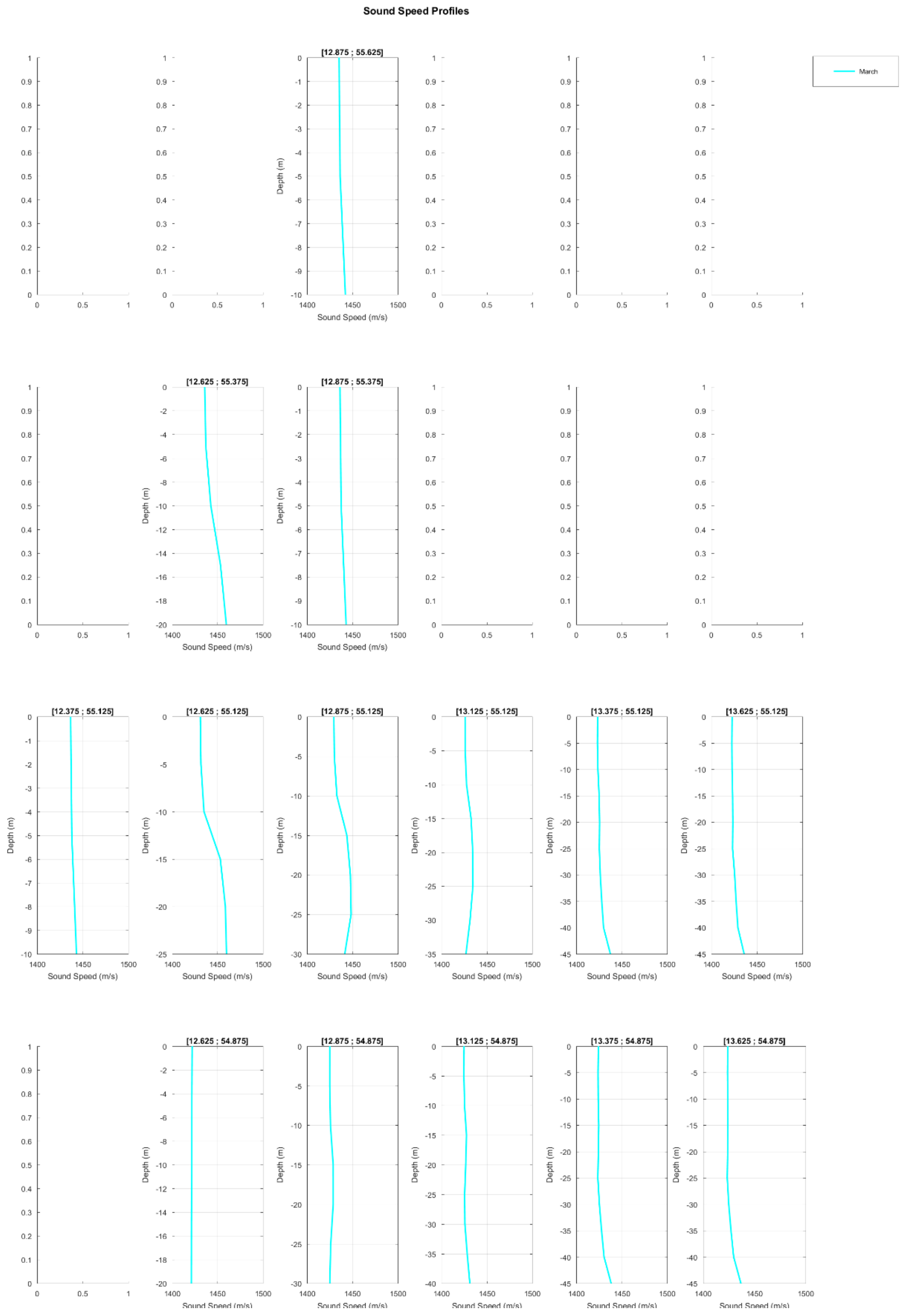


Figure 5.3: Sound speed profiles for March for the project area and surrounding waters, based on temperature and salinity data from World Ocean Atlas 2018 v2 (NOAA, 2019).



6 Results

Sound propagation for unmitigated sources is modelled in a 1° resolution (360 transects), and for a 100 x 1 m grid (distance x depth interval). By examining the transmission loss for each transect, the mitigation requirement is calculated for each of them, as outlined in section 3.1, by calculating the SEL_{c24h} and comparing this to the guideline threshold value of 190 dB re 1 μPa^{2}s. For the expected revised guideline thresholds, the mitigation requirement is calculated individually from the $SEL_{c24h,VHF}$ (harbour porpoise) and $SEL_{c24h,PW}$ (seals) by comparing individually to the 155 dB re 1 μPa^{2}s and 185 dB re 1 μPa^{2}s thresholds respectively.

Due to the method of incorporating fleeing behaviour in the model, errors (too long impact distances) tend to occur for transects that reach a landmass within a very short distance. Impact distances are generally listed as the maximum impact distance, whereas noise maps show the impact distance in all directions. To reflect the differences in impact distances with angle, a supporting measure in the form of affected area in km^2 is given, as this more accurately reflects the actual impact.

This process is carried out for all installation locations and all foundation types, as described in section 4, and the results are presented in section 6.1.

Given the calculated source level mitigation requirements, these are, where necessary, applied to the sources and resulting mitigated sound level contours for TTS, PTS and behaviour are calculated and illustrated, see section 6.2 to serve as input for the impact assessment.

6.1 Source level mitigation requirements

Mitigation requirements for the sources are presented graphically through colour coded maps for each of the scenarios. The mitigation requirements are shown for each transect to outline the differences in mitigation requirement. The mitigation requirements are also summarized in tables where a common color scale shared for both unweighted and frequency weighted has been used, to visually illustrate the differences for the current and expected future guideline requirements. Green colors indicate a lower requirement, where red colors indicate higher requirements.

6.1.1 Unweighted source level mitigation requirements

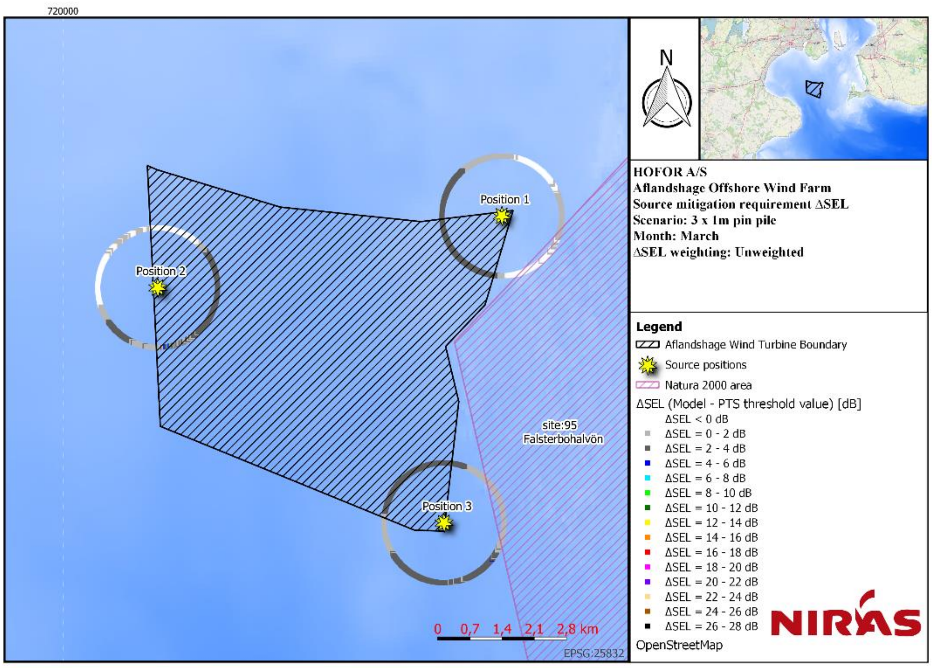
Mitigation requirements, as per current Danish guidelines, per pile location are shown in Table 6.1 as the worst case. From this, it is observed that mitigation requirements for 1 m pin piles is up to 3.6 dB, while the 7 m and 9.5 m monopile require significantly higher mitigation levels, that is up to 18.2 dB for a 7 m monopile, and the 20.7 dB for a 9.5 m monopile. For the 8 m monopile, the mitigation requirement would be 1.1 dB higher than the levels reported for the 7 m monopile and will therefore be 19.3 dB.

Table 6.1: Calculated mitigation requirement (worst case), current Danish guidelines.

Foundation type	Position	Cumulative Sound Exposure Level, SEL_{C24h} [dB re. 1 µPa²s]	Mitigation Requirement $\Delta SEL = SEL_{C24h} - 190$ [dB re. 1 µPa²s]
3 x 1m pin pile (@2000kJ – 3 x 2000 strikes)	1	193.2	3.2
	2	193.0	3.0
	3	193.6	3.6
1 x 7m monopile (@3500kJ – 7000 strikes)	1	208.1	18.1
	2	207.7	17.7
	3	208.2	18.2
1 x 9.5m monopile (@4000kJ – 8000 strikes)	1	210.6	20.6
	2	210.3	20.3
	3	210.7	20.7
*: Negative value means no mitigation is required in order to comply with guideline Threshold			

The results (for 3 m pin piles and 7 and 9.5 m monopiles) are also illustrated graphically for all transects individually in Figure 6.1 - Figure 6.3, where the per-transect mitigation requirement is shown in color coding to show how the requirements vary with transect direction. For larger versions of the maps, see Appendix A.

Figure 6.1: Illustration of mitigation requirements for 3x1 m pile installation, current guidelines.



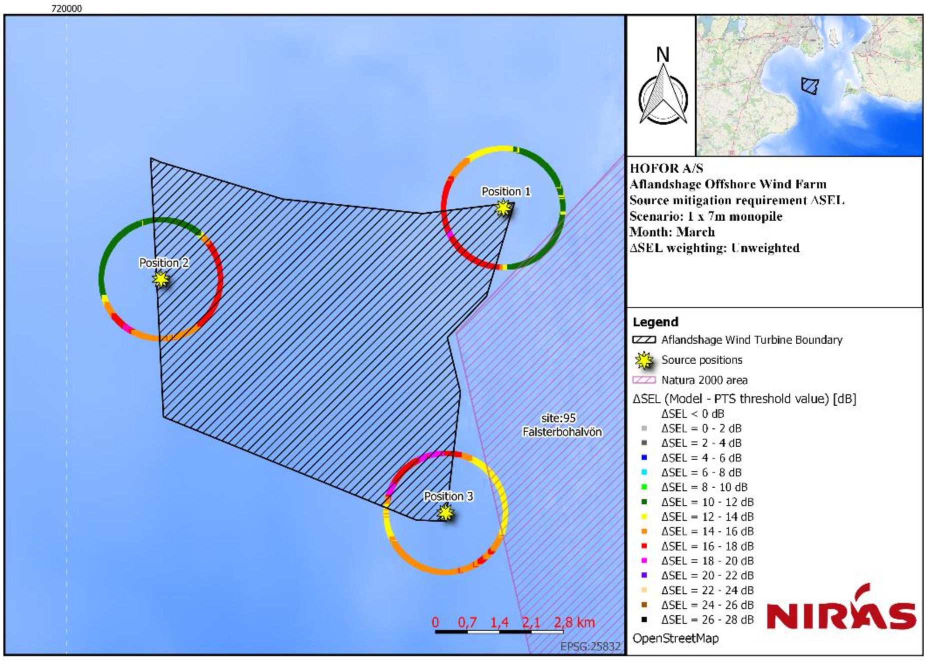


Figure 6.2: Illustration of mitigation requirements for 7 m monopile installation, current guidelines.

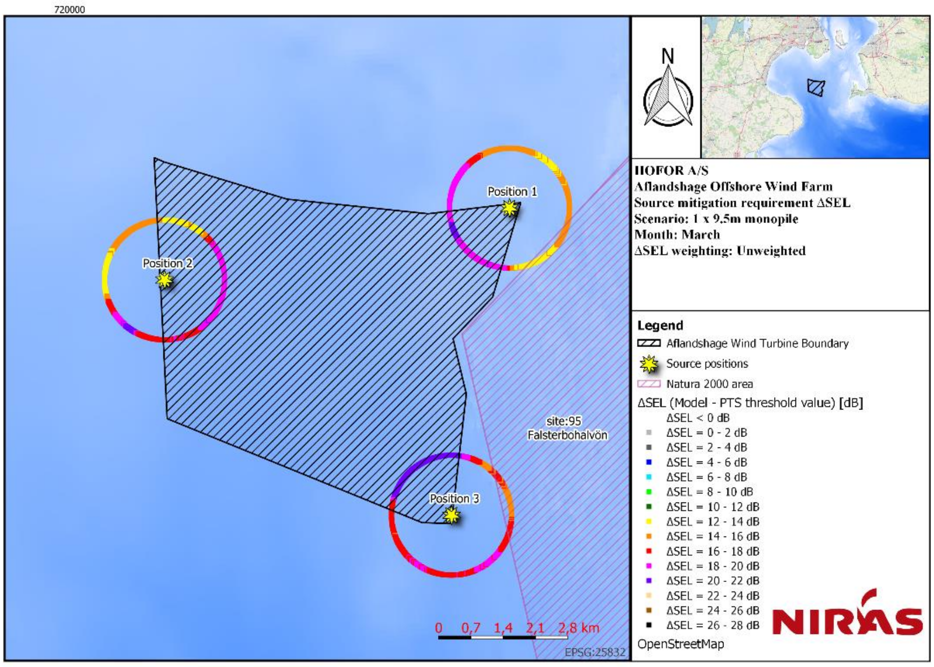


Figure 6.3: Illustration of mitigation requirements for 9.5 m monopile installation, current guidelines.

6.1.2 Weighted source level mitigation requirements

The mitigation requirements, as per expected future Danish guidelines, per pile location are shown in Table 6.2 as the worst case. From this, it is observed that there is no mitigation requirement for the 1 m pile installation, as the SEL_{C24h} does not exceed threshold value for PTS. This for both harbour porpoise and pinnipeds. For the 7 m monopile the mitigation requirements are up to 6.6 dB, while they are up to 9.1 dB for the 9.5 m monopile. For the 8 m monopile, the mitigation requirement would be 1.1 dB higher than the levels reported for the 7 m monopile and will therefore be 7.7 dB.

Table 6.2: Calculated mitigation requirement (worst case), expected future Danish guidelines. Negative values indicate that received SEL_{C24h} does not exceed threshold value for PTS and mitigation is therefore not required.

Foundation type	Position	Cumulative Sound Exposure Level, $SEL_{C24h,VHF}$ [dB re. 1 µPa²s]	Mitigation Requirement $\Delta SEL = SEL_{C24h,VHF} - 155$ [dB re. 1 µPa²s]	Cumulative Sound Exposure Level, $SEL_{C24h,PW}$ [dB re. 1 µPa²s]	Mitigation Requirement $\Delta SEL = SEL_{C24h,VHF} - 185$ [dB re. 1 µPa²s]
3 x 1m pin pile (@2000kJ 3 x 2000 strikes)	1	148.7	-6.3	179.0	-6.0
	2	148.7	-6.3	178.7	-6.3
	3	148.6	-6.4	179.1	-5.9
1 x 7m monopile (@3500kJ 7000 strikes)	1	160.5	5.5	191.5	6.5
	2	160.5	5.5	191.1	6.1
	3	160.3	5.3	191.6	6.6
1 x 9.5m monopile (@4000kJ 8000 strikes)	1	163.0	8.0	194.1	9.1
	2	163.0	8.0	193.7	8.7
	3	162.8	7.8	194.1	9.1
*: Negative value means no mitigation is required in order to comply with guideline Threshold					

Due to the large number of maps, the graphic results for all transects individually are shown in Appendix B, where the per-transect mitigation requirement is shown in color coding to show how the requirements vary with direction. The highest mitigation requirements as presented in Table 6.2, for pinnipeds in water (PW) are however shown below in Figure 6.4 - Figure 6.6 for the different pile sizes.

Figure 6.4: Illustration of mitigation requirements for 3x1 m pile installation, expected future guidelines.

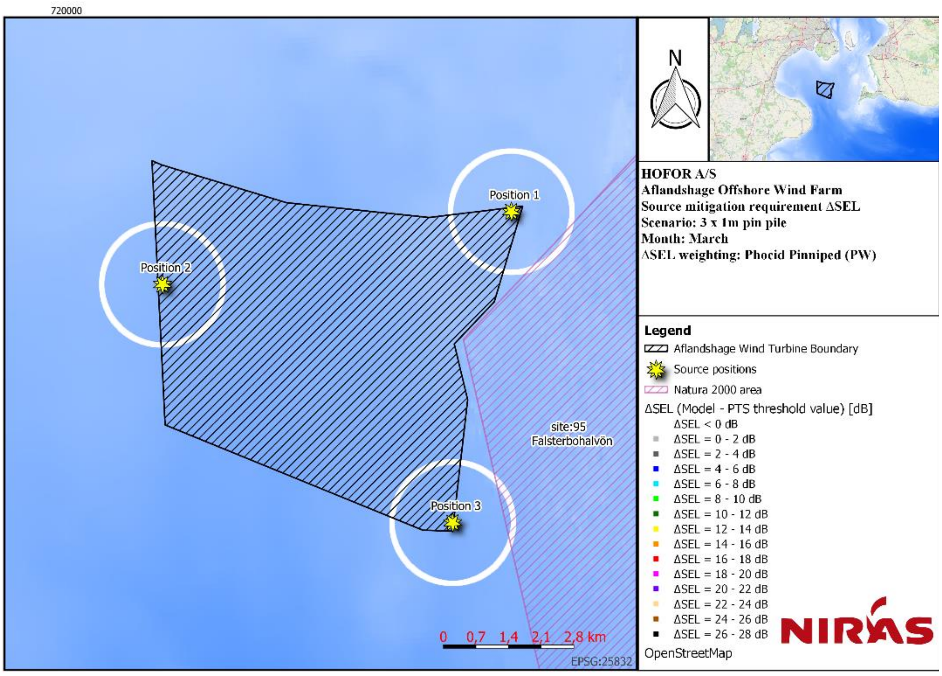
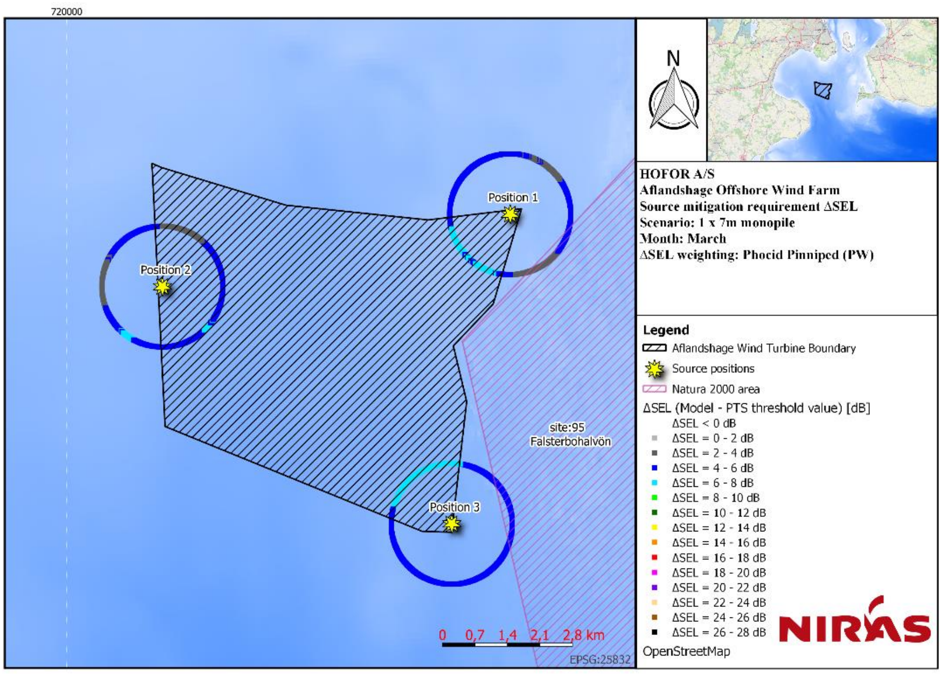


Figure 6.5: Illustration of mitigation requirements for 7 m monopile installation, expected future guidelines.



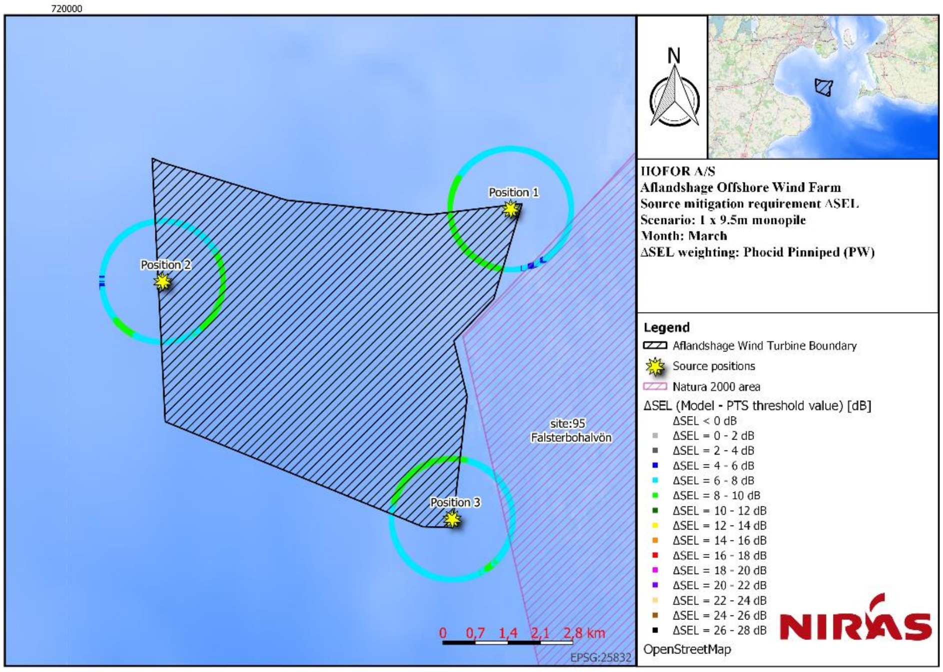


Figure 6.6: Illustration of mitigation requirements for 9.5 m monopile installation, expected future guidelines.

6.1.3 Source mitigation methods

As found through sound propagation modelling, source mitigation measures must be applied in order to comply with current Danish guidelines for pile installation, (Energistyrelsen, 2016), for all pile installation scenarios. For expected future guidelines, source mitigation measures are also required for monopile installations. In the below, a brief description of different Noise Abatement Systems (NAS) are described, along with current best available knowledge on achievable source mitigation.

The most frequently applied technique uses bubble curtains. Normally air is pumped into a hose system at the bottom of the sea. These hoses are perforated and air bubbles leak. The air bubbles form a curtain over the entire water column. The noise is reduced considerably as the sound waves decrease when passing from water to air (and vice versa) or they are reflected. The techniques with which bubble curtains are applied vary greatly. Generally, bubble curtains can be divided in two groups, the Little Bubble Curtain (LBC) and the Big Bubble Curtain (BBC). The Little Bubble Curtain surrounds the pile directly whereas the Big Bubble Curtain is deployed on the sea floor completely surrounding the entire construction site.

For the Little Bubble Curtain one problem is to keep the bubbles close to the pile. If bubbles drift away the curtain is not complete and the noise escapes from the holes with no significant reduction. Therefore, several adaptations were developed. Several layers of curtain can be applied, or bubbles can be technically confined to the pile. However, some of the noise cannot be reduced as it spreads via a seismic pathway. During impulse pile driving the earth is shaken and this emits noise from the sea floor beyond the bubble curtain. The Little Bubble Curtain was tested during the construction of BARD Offshore I. Here noise reductions of 9-13 dB were achieved. The reduction of noise increased with increasing noise frequency (Bellmann et al. 2014), (Bellmann, et al., August 2020).

Big Bubble Curtains can mitigate some of the noise of the seismic pathway. The seismic noise is partly emitted already after a few meters into the water. This is already between the pile and the Big Bubble Curtain and can therefore be mitigated by the latter one. Also important in this technique is that the Big Bubble Curtain surrounds 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. Here a noise reduction of on average 11 dB was achieved with the best configuration. This project tested different configurations. The success depended on three parameters: sizes of holes in the hosepipe (determines bubble sizes), distance apart of holes (determines density of bubble curtain) and the amount of air used. The best configuration was found to be with relatively small holes, a short distance apart and using a substantial amount of air (Diederichs et al. 2014).

The effect of a Big Bubble Curtain can be increased if a second Bubble Curtain is installed 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.

To prevent particularly sensitive areas from being affected a linear bubble curtain is occasionally applied. This is installed supplementary to other noise mitigation systems in order to reduce noise escaping a one specific direction.

Another group of noise mitigation systems are Pile Sleeves. These are systems that are put over the pile itself and contain different kinds of insulators. They are therefore in some ways similar to the Little Bubble Curtain as this also surrounds the pile directly. The noise mitigation relies mainly on the absorption effects of the different insulators. As both systems are very similar and are both deployed directly around the pile, they can also be combined. In one practical application, an air-filled double wall is installed and between this wall and the pile a bubble curtain is applied (IHC Noise Mitigation System). This system was used for example at the German wind park Riffgat. Noise mitigation was assumed to be around 16-18 dB (Verfuß 2014).

Another system (BEKA-shells) also uses a system of several walls. Here bubble curtains are also included. The size of bubbles varies. Different sizes of bubbles can mitigate noises of different frequencies. Additionally, industrially developed damper material is used as an additionally layer. The complete system can also be lowered onto the sea bottom in order to mitigate the noise escaping via the seismic pathway (Koschinski & Lüdemann 2013).

The Hydro Sound Damper (HSD) is a pile sleeve in which air-filled balloons or robust foam elements have been inserted. Preliminary tests suggest that this pile sleeve technique could reduce the sound by 7-13 dB. The highest efficiency was obtained in the frequency range of 200-500 Hz (Remmers & Bellmann 2013).

Cofferdams are a special type of Pile Sleeve. They also surround the pile. Here the interspace between pile and wall is dewatered. Thus the piling process takes place practically in an aerial environment and noise is mitigated at interfaces between air, metal and water. The sleeves are deemed to reduce noise by around 20 dB. This was also demonstrated in Århus Bugt (Verfuß, 2014). However, tests further offshore and in connection with the construction of wind parks have yet to be carried out (Verfuß, 2014).

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 6.7.

It must, however, be noted that the reported broadband mitigation, ΔSEL is given for a flat frequency spectrum. 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 4.4.1 page 12, is far from a flat octave band spectra, and the listed values therefore are comparable to the calculated mitigation requirements.

In Figure 6.8, the attenuation achieved with the different NAS, are instead given in 1/3 octave bands, thus allowing for calculation of comparable mitigation levels. For the spectra used for the 7 m, 8 m and 9.5 m monopiles, the application of a DBBC NAS (dark blue curve on Figure 6.8) would for instance have an unweighted mitigation effect of $\Delta SEL \cong 28\ dB$, while the frequency weighted metrics PW and VHF would see a mitigation effect of $\Delta SEL_{PW} \cong 34\ dB$ and $\Delta SEL_{VHF} \cong 19\ dB$ respectively.

From this, theoretically, the calculated source mitigation requirements found in sections 6.1.1 and 6.1.2 should be achievable with currently available Noise Abatement Systems. It should however be noted, as also emphasized in (Bellmann, et al., August 2020), that they are always site-specifically adapted and finetuned to provide the optimal mitigation. The presented levels are a result of such processes. Whether or not any arbitrary project will be able to achieve the same mitigation levels as presented, depend on many factors, including bathymetry, sediment composition and local currents, being the most significant ones.

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 solutions become available.

Figure 6.7: Achieved source mitigation levels on completed projects using different NMS, (Bellmann, et al., August 2020)

Table 4: *Achieved noise reduction of single Noise Abatement Systems and combinations of secondary Noise Abatement Systems in their respective optimized system configuration depending on different, technical-constructive and site-specific framework conditions. All basic underwater noise measurement data were collected in the North Sea with currents of up to 0.75 m/s and a sandy soil.*

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)	$13 \leq 15 \leq 17$ dB IHC-NMS8000 $15 \leq 16 \leq 17$ dB	> 450 > 65
2	HSD (water depth up to 40 m)	$10 \leq 11 \leq 12$ 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)	$17 \leq 19 \leq 23$	> 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)	$19 \leq 21 \leq 22$	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	$15 \leq 16 \leq 20$	> 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 6.8: Frequency dependent noise reduction for Noise Mitigation solutions, (Bellmann, et al., August 2020).

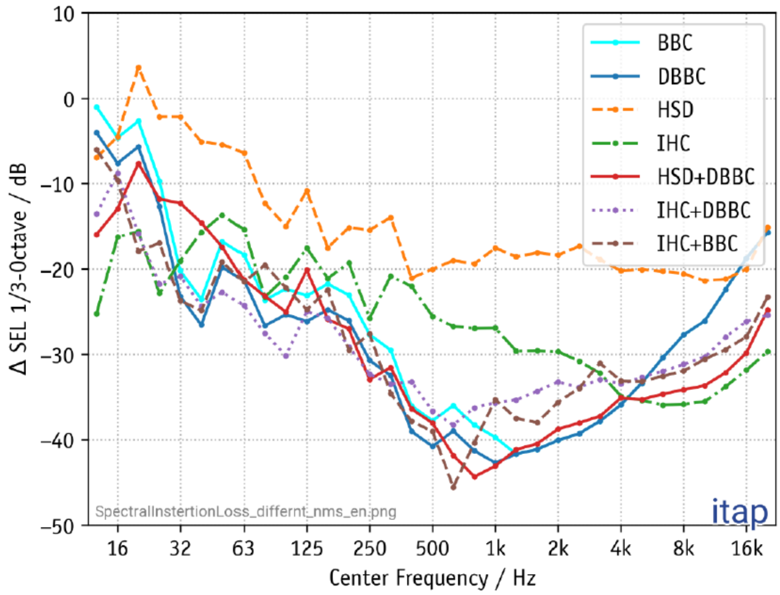


Figure 32: *Resulting noise reduction (transition loss) of the applied Noise Abatement Systems – IHC-Noise Mitigation Screen (NMS8000), Hydro Sound Damper (HSD) and optimized single/double Big Bubble Curtain (BBC/DBBC), averaged over all applications within the German EEZ of the North Sea. Note: The presentation of the insertion loss differs from the specification of the DIN SPEC 45653 to that extent, that not the difference from reference- and test measurement, but from test- and reference measurement is displayed. Negative values thus mark a high noise reduction.*

6.2 Impact ranges and areas

Applying the required source level mitigation to each of the foundation installation scenarios, allows for determining the impact distances for each of the threshold values described in section 3.2.

6.2.1 Unweighted impact ranges and areas

The worst case safe starting distance for each of the unweighted threshold values was calculated, and is shown in Table 6.3.

Table 6.3: Threshold impact distances for foundation installation, using mitigated source levels

Species	Fleeing Speed [m/s]	Impact Criteria	Matric	Threshold value [dB]	Threshold Distance [km], worst case								
					Position 1			Position 2			Position 3		
					9.5m mono pile	7m mono pile	3x1m pin pile	9.5m mono pile	7m mono pile	3x1m pin pile	9.5m mono pile	7m mono pile	3x1m pin pile
Harbour Porpoise	1.5	PTS	$SEL_{C,24h}$	190	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
		TTS		175	15.5	15.4	15.3	12.2	12.2	12.1	10.9	10.9	11.0
		Behaviour	SEL_{ss}	145	16.3	16.3	15.7	14.3	14.3	13.2	13.1	13	12.3
Harbour seal		PTS	$SEL_{C,24h}$	200	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
		TTS		176	15.0	15.0	14.9	11.5	11.5	11.4	10.3	10.3	10.5
		Behaviour	SEL_{ss}	145	16.3	16.3	15.7	14.3	14.3	13.2	13.1	13	12.3
Cod	0.38	TTS	$SEL_{C,24h}$	185	13.9	13.9	11.1	10.6	10.6	9.1	9.9	9.9	9.1
		Injury		204	< 0.05	< 0.05	0.07	0.17	0.17	0.2	0.05	0.04	< 0.05
	0.9	TTS		185	10.8	10.8	8.1	7.7	7.7	6.9	7.6	7.6	6.7
		Injury		204	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Herring	1.04	TTS		185	10.0	10.0	7.4	7.1	7.1	6.5	7.1	7.1	6.1
		Injury		204	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Larvae and eggs	0	Injury		207	1.3	1.3	0.9	1.55	1.55	1.05	1.3	1.3	0.78
Where a "-" indicates a distance below 10 m													

As shown in Table 6.3, impact distances vary based on pile installation position, and on foundation type and size. In effect, the smaller diameter the pile, the shorter the threshold distances. Exceptions from this can occur as a result of the difference in frequency spectrum between the pin piles and monopiles, leading to slightly higher impact ranges for the smaller piles.

In addition to the worst case distances presented in Table 6.3, the threshold distances for each transect were calculated in every scenario. The resulting distances are illustrated graphically in Figure 6.9 - Figure 6.14 for TTS threshold, and in Figure

6.15 - Figure 6.17 avoidance behaviour. The noise contour maps are also attached in large size in Appendix C.

Figure 6.9: TTS impact distance for harbour porpoise, position 1 (with mitigation), unweighted

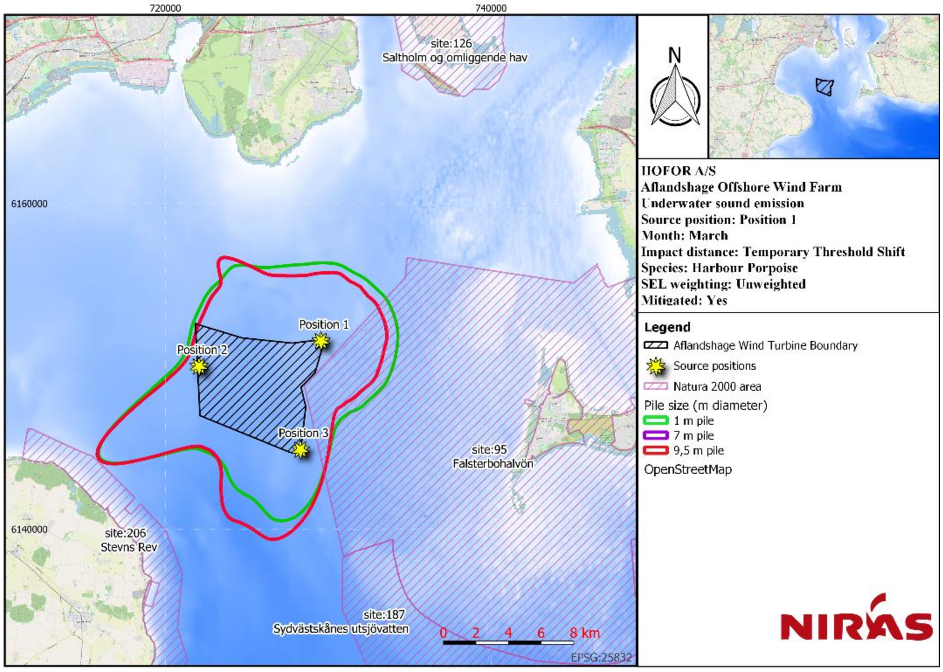
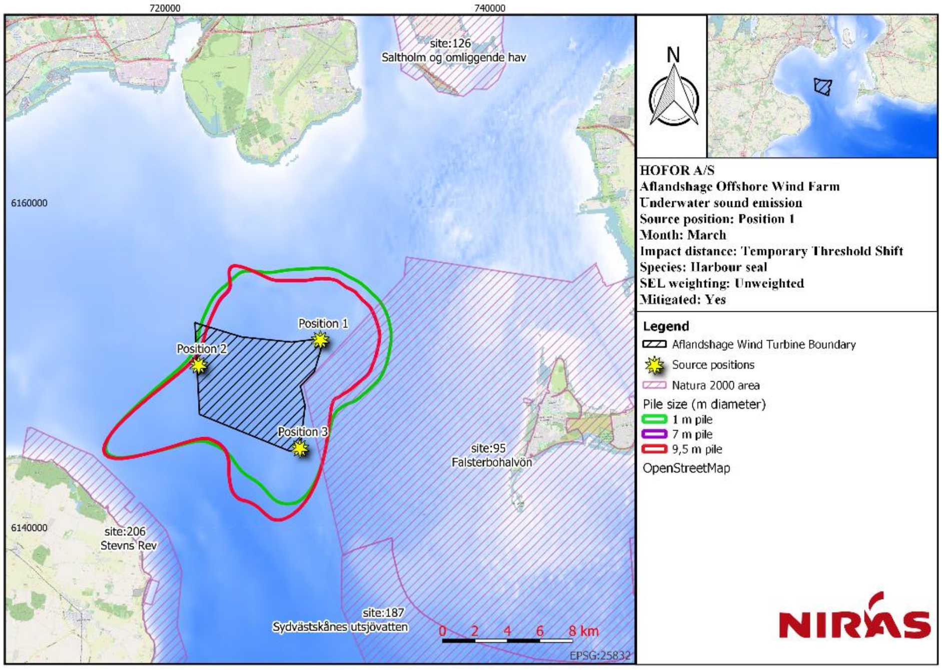


Figure 6.10 TTS impact distance for harbour seal, position 1 (with mitigation), unweighted



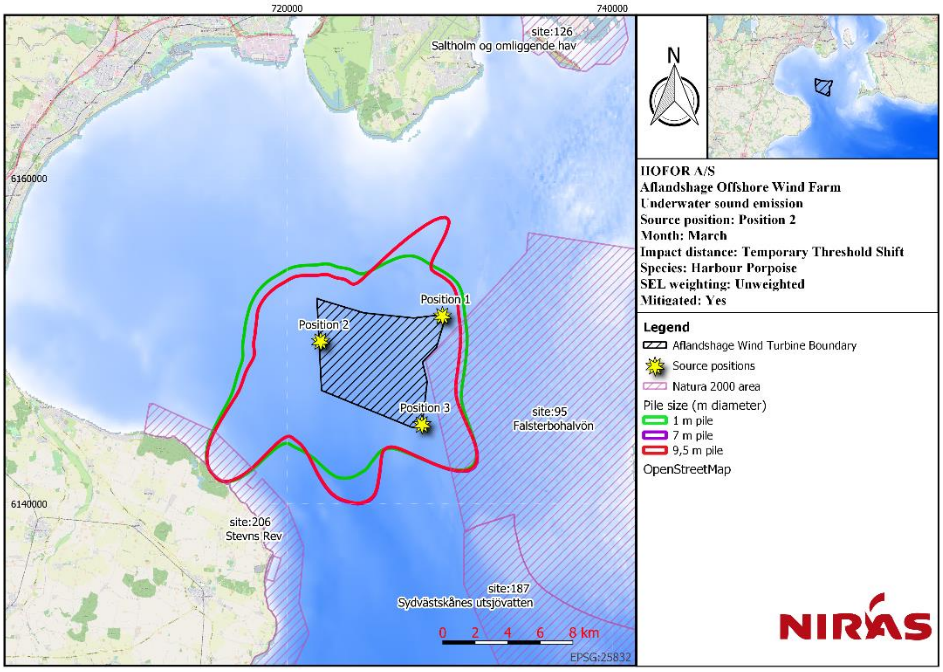


Figure 6.11: TTS impact distance for harbour porpoise, position 2 (with mitigation), unweighted.

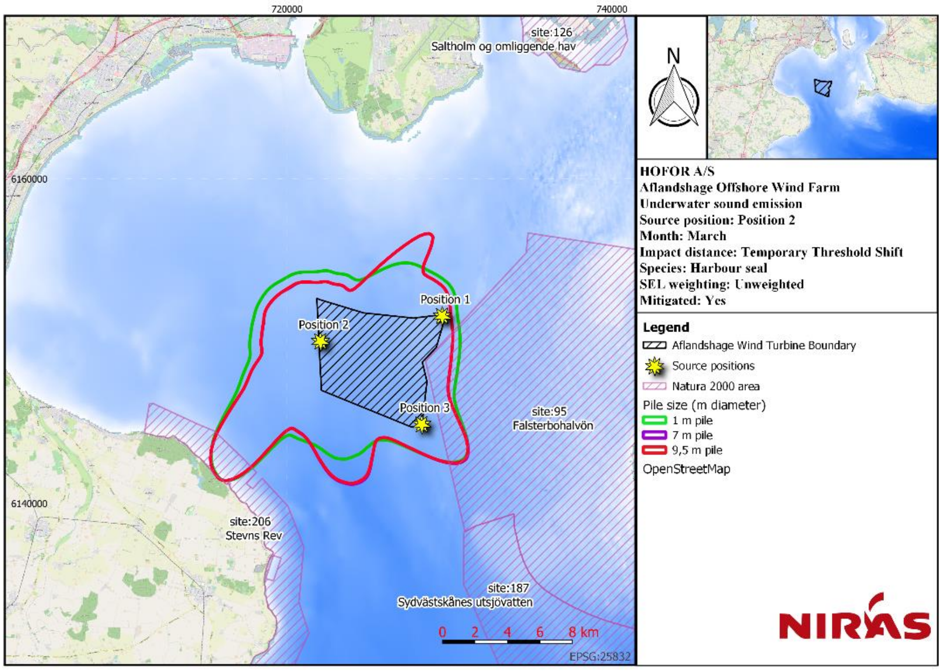


Figure 6.12: TTS impact distance for harbour seal, position 2 (with mitigation), unweighted.

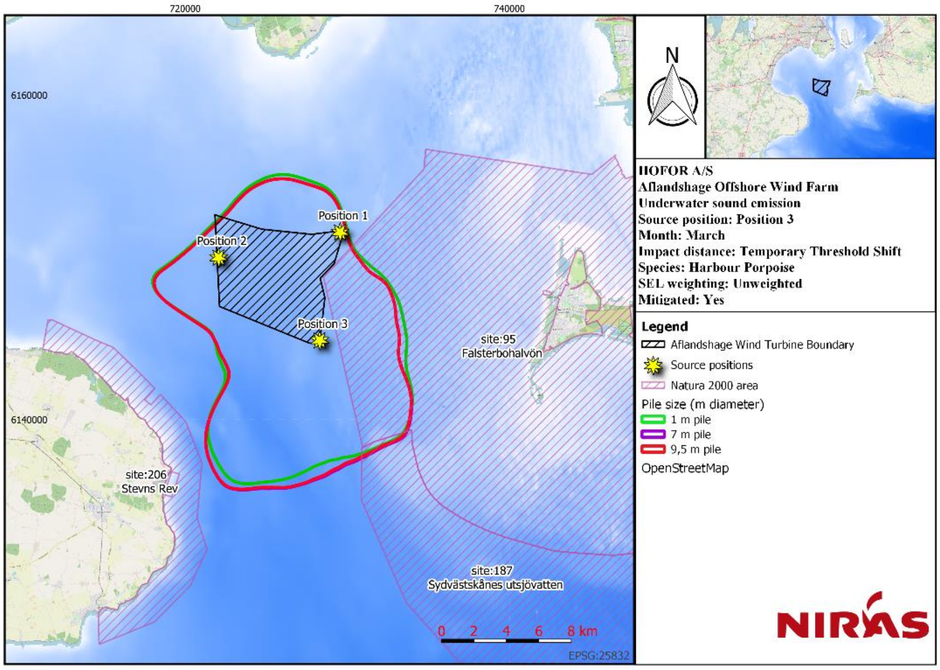


Figure 6.13: TTS impact distance for harbour porpoise, position 3 (with mitigation), unweighted.

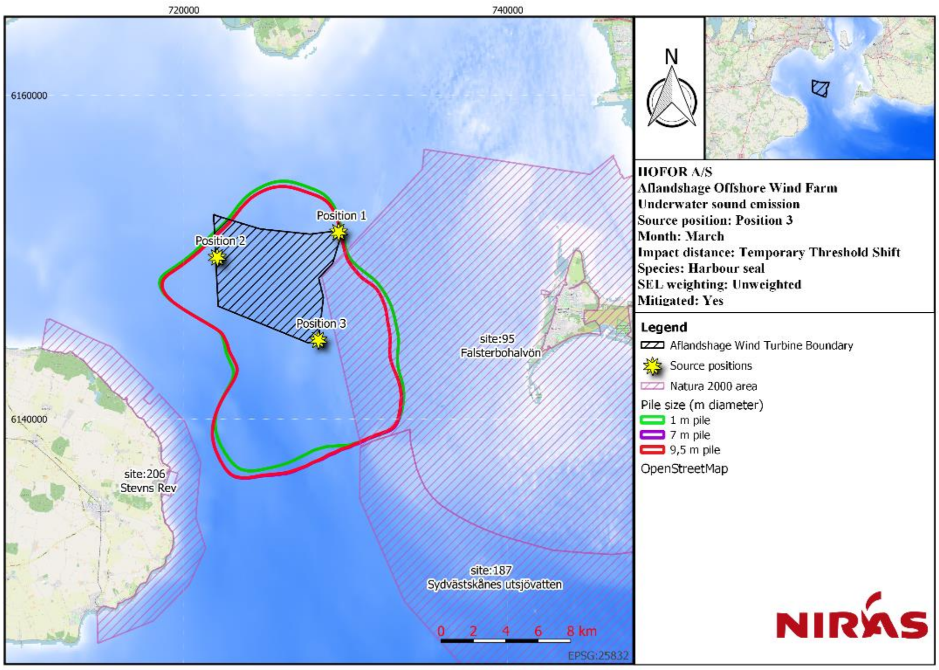


Figure 6.14: TTS impact distance for harbour seal, position 3 (with mitigation), unweighted.

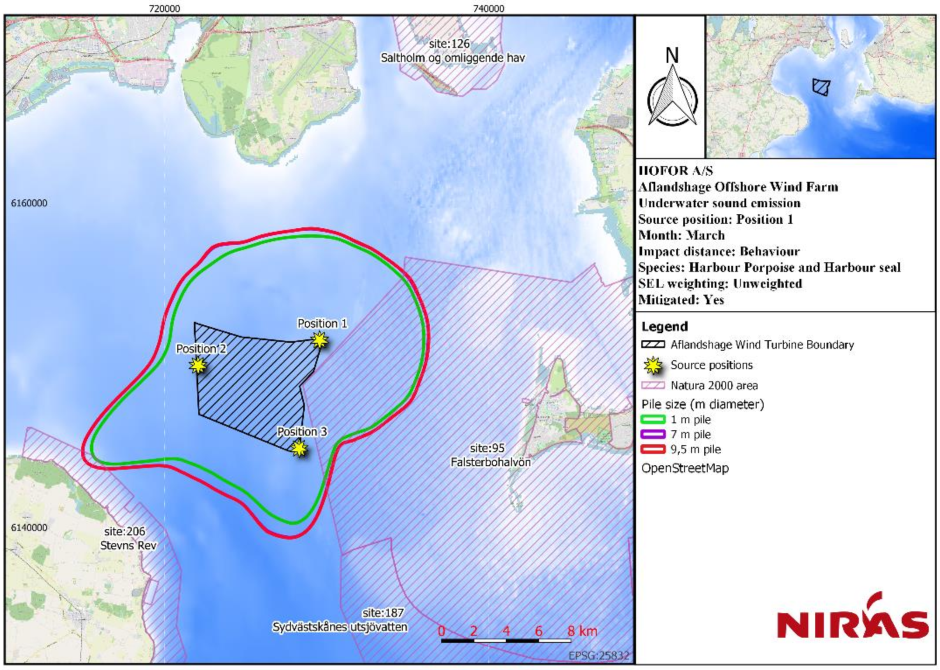


Figure 6.15 Avoidance behaviour distance for harbour porpoise and harbour seal, position 1 (with mitigation), unweighted.

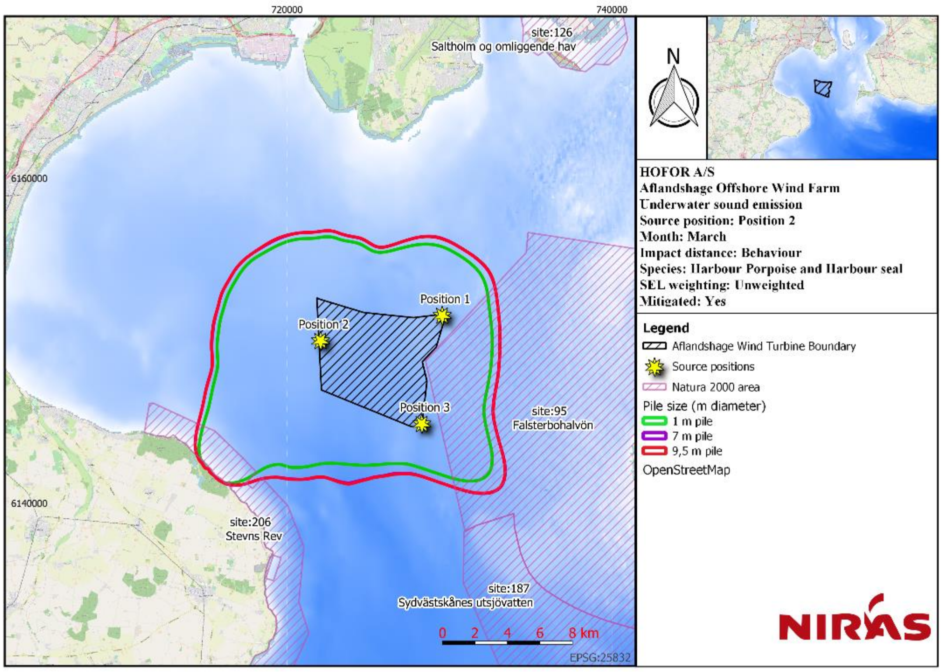


Figure 6.16: Avoidance behaviour distance for harbour porpoise and harbour seal, position 2 (with mitigation), unweighted.

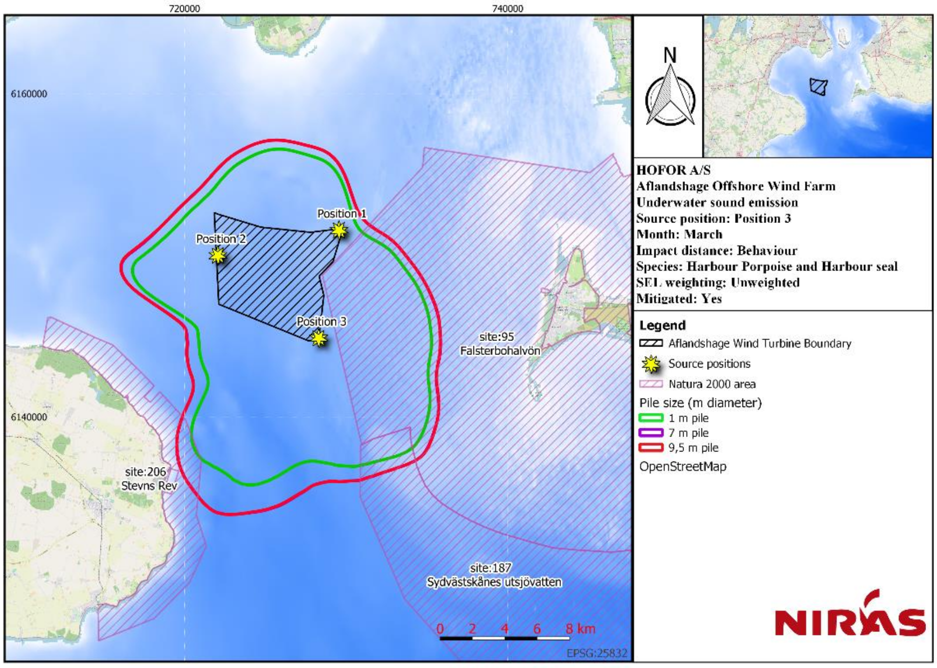


Figure 6.17: Avoidance behaviour distance for harbour porpoise and harbour seal, position 3 (with mitigation), unweighted.

It is seen that the distance varies greatly based on the direction of the transect, however for the different pile sizes the resulting affected areas are very similar in shape and size. This is because each source is mitigated to comply with the same threshold level (190 dB re 1 μPa^{2}s, PTS threshold for harbour porpoises) and the mitigated source levels are therefore almost identical for the different piles. As a result thereof, the impacted area for each threshold is not adequately represented by the worst case impact distances given in Table 6.3. In Table 6.4, the affected areas are listed for each of the scenarios, as the sum area over all transects in km^2, and in Table 6.5, as the affected areas inside nearby Natura 2000 marine mammal protection zones.

Table 6.4: Total affected area [km²] for TTS and avoidance behaviour

Unweighted: Total		Affected area TTS [km²]			Affected area Behaviour [km²]		
Marine Mammal Species	Position	9.5m mono-pile	7m mono-pile	3x1m pin pile	9.5m mono-pile	7m mono-pile	3x1m pin pile
Harbour porpoise	1	161	160	165	247	246	220
	2	169	169	170	257	257	228
	3	198	198	197	307	306	254
Harbour seal	1	137	136	143	247	246	220
	2	144	144	149	257	257	228
	3	167	167	169	307	306	254

Table 6.5: Affected areas [km²] for TTS and avoidance behaviour inside nearby Natura 2000 sites.

Unweighted: Site 126		Affected area TTS [km²]			Affected area Behaviour [km²]		
Marine Mammal Species	Position	9.5m mono-pile	7m mono-pile	3x1m pin pile	9.5m mono-pile	7m mono-pile	3x1m pin pile
Harbour porpoise	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0
Harbour seal	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	0	0	0

Unweighted: Site 95		Affected area TTS [km²]			Affected area Behaviour [km²]		
Marine Mammal Species	Position	9.5m mono-pile	7m mono-pile	3x1m pin pile	9.5m mono-pile	7m mono-pile	3x1m pin pile
Harbour porpoise	1	19	19	26	49	49	45
	2	14	14	16	40	40	31
	3	39	39	42	70	70	61
Harbour seal	1	16	16	21	49	49	45
	2	9	9	11	40	40	31
	3	32	32	36	70	70	61

Unweighted: Site 187		Affected area TTS [km^2]			Affected area Behaviour [km^2]		
Marine Mammal Species	Position	9.5m mono-pile	7m mono-pile	3x1m pin pile	9.5m mono-pile	7m mono-pile	3x1m pin pile
Harbour porpoise	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	1	1	1	7	7	5
Harbour seal	1	0	0	0	0	0	0
	2	0	0	0	0	0	0
	3	0	0	0	7	7	5

Unweighted: Site 206		Affected area TTS [km^2]			Affected area Behaviour [km^2]		
Marine Mammal Species	Position	9.5m mono-pile	7m mono-pile	3x1m pin pile	9.5m mono-pile	7m mono-pile	3x1m pin pile
Harbour porpoise	1	0	0	0	1	1	0
	2	5	5	5	7	7	7
	3	0	0	0	4	4	0
Harbour seal	1	0	0	0	1	1	0
	2	4	4	4	7	7	7
	3	0	0	0	4	4	0

6.2.2 Frequency weighted impact ranges and areas

The worst case safe starting distance for each of the frequency weighted threshold values was calculated and is shown in Table 6.6.

Table 6.6: Threshold impact distances for foundation installation, using mitigated source levels.

Species	Fleeing Speed [m/s]	Impact Criteria	Matric	Threshold value [dB]	Threshold Distance [km], worst case								
					Position 1			Position 2			Position 3		
					9.5m mono pile	7m mono pile	3x1m pin pile	9.5m mono pile	7m mono pile	3x1m pin pile	9.5m mono pile	7m mono pile	3x1m pin pile
Harbour Porpoise	1.5	PTS	$SEL_{C,24h}$	155	1,3	1,3	< 0,05	1,3	1,3	< 0,05	1,3	1,3	< 0,05
		TTS		140	13,7	13,7	6,7	13,2	13,2	7,1	13,8	13,8	6,5
Harbour seal		PTS	$SEL_{C,24h}$	185	1,3	1,3	0,1	1,3	1,3	0,11	1,3	1,3	0,06
		TTS		170	14,4	14,4	6,9	11,8	11,8	6,1	10,7	10,7	6,4

As shown in Table 6.6, impact distances are identical for the 7 m and 9.5 m monopiles, while the distances are significantly shorter for the 1 m pin piles.

In addition to the worst case distances presented in Table 6.6, the threshold distances for each transect were calculated in every scenario. An Illustration of the noise maps is shown in Figure 6.18 for TTS for pinnipeds (PW). The rest of the maps are found in Appendix D. From the noise maps, it is seen that the distance varies based on the direction of the transect. As a result thereof, the impacted area for each threshold is not adequately represented by the worst case impact distances given in Table 6.6. In Table 6.7, the affected areas are listed for each of the scenarios, as the sum area over all transects, and in Table 6.8, as the affected areas inside nearby Natura 2000 marine mammal protection zones.

Figure 6.18: TTS impact distance for harbour seal, position 1 (with mitigation), PW-weighting.

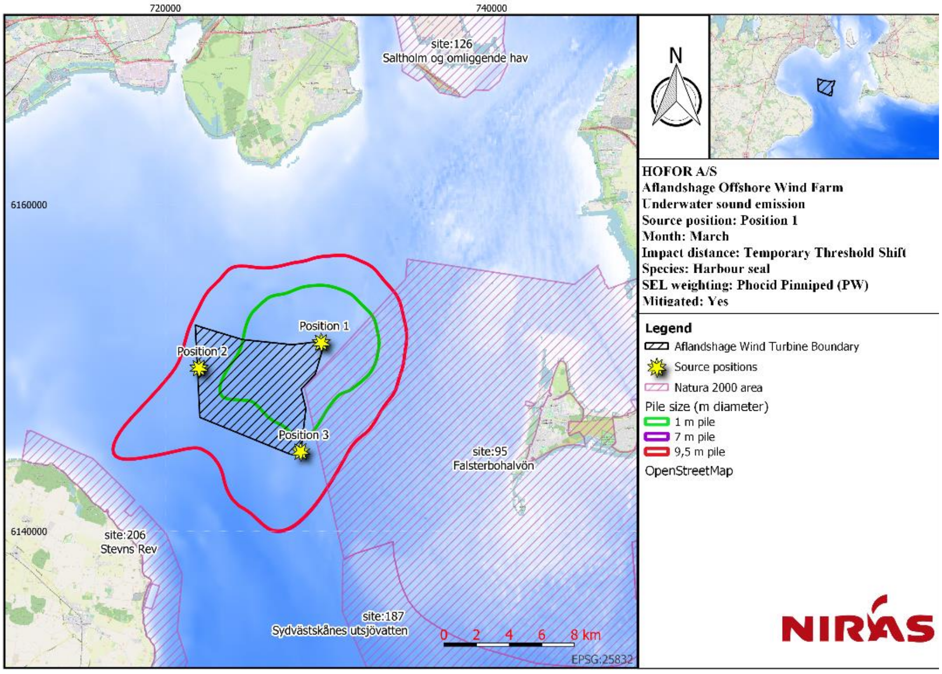


Table 6.7: Total affected areas [km²] for frequency-weighted TTS.

Frequency weighted: Total		Affected area TTS [km²]		
Marine Mammal Species	Position	9.5m monopile	7m monopile	3x1m pin pile
Harbour porpoise	1	448	448	105
	2	464	464	112
	3	445	445	103
Harbour seal	1	181	181	59
	2	198	198	60
	3	221	221	65

Table 6.8: Affected areas [km²] for frequency-weighted TTS inside nearby Natura 2000 sites.

Frequency weighted: site 126		Affected area TTS [km²]		
Marine Mammal Species	Position	9.5m monopile	7m monopile	3x1m pin pile
Harbour porpoise	1	0	0	0
	2	0	0	0
	3	0	0	0
Harbour seal	1	0	0	0
	2	0	0	0
	3	0	0	0

Frequency weighted: site 95		Affected area TTS [km²]		
Marine Mammal Species	Position	9.5m monopile	7m monopile	3x1m pin pile
Harbour porpoise	1	138	138	33
	2	43	43	0
	3	133	133	33
Harbour seal	1	36	36	13
	2	14	14	0
	3	47	47	16

Frequency weighted: site 187		Affected area TTS [km²]		
Marine Mammal Species	Position	9.5m monopile	7m monopile	3x1m pin pile
Harbour porpoise	1	0	0	0
	2	0	0	0
	3	18	18	0
Harbour seal	1	0	0	0
	2	0	0	0
	3	3	3	0

Frequency weighted: site 206		Affected area TTS [km^2]		
Marine Mammal Species	Position	9.5m monopile	7m monopile	3x1m pin pile
Harbour porpoise	1	0	0	0
	2	21	21	0
	3	18	18	0
Harbour seal	1	0	0	0
	2	2	2	0
	3	0	0	0

7 Conclusion

It is concluded that all proposed scenarios require source mitigation measures in order to comply with current Danish authority guideline requirements for underwater noise emission. Mitigation requirements for 1 m diameter pin piles up to 3.6 dB, and for monopiles up to 20.7 dB were documented through underwater noise modelling.

Literature on achievable mitigation for existing Noise Abatement Systems was examined, and found to indicate that the calculated mitigation requirements are all theoretically achievable using already established Noise Abatement Systems, as measured at other offshore wind farms.

With the expected future guidelines utilizing frequency weighted metrics, corresponding mitigation requirements were found to be lower than with the current guidelines for all pile sizes and positions. Installation of pin piles were found to be possible without any source mitigation, whereas monopile installation would require mitigation of up to 9.1 dB. Caution should however be taken with these figures, as the future guidelines have not yet been designed, and evaluation method and criteria could therefore change.

For the current guidelines, Temporary Threshold shift (TTS) was found likely to occur for marine mammals present up to 15.5 km away from pile installations, with likely avoidance behaviour reaction occurring up to 16.3 km from pile installation when using maximum hammer energy. For the expected future guidelines, the corresponding impact distances were found to be up to 14.4 km for TTS.

8 References

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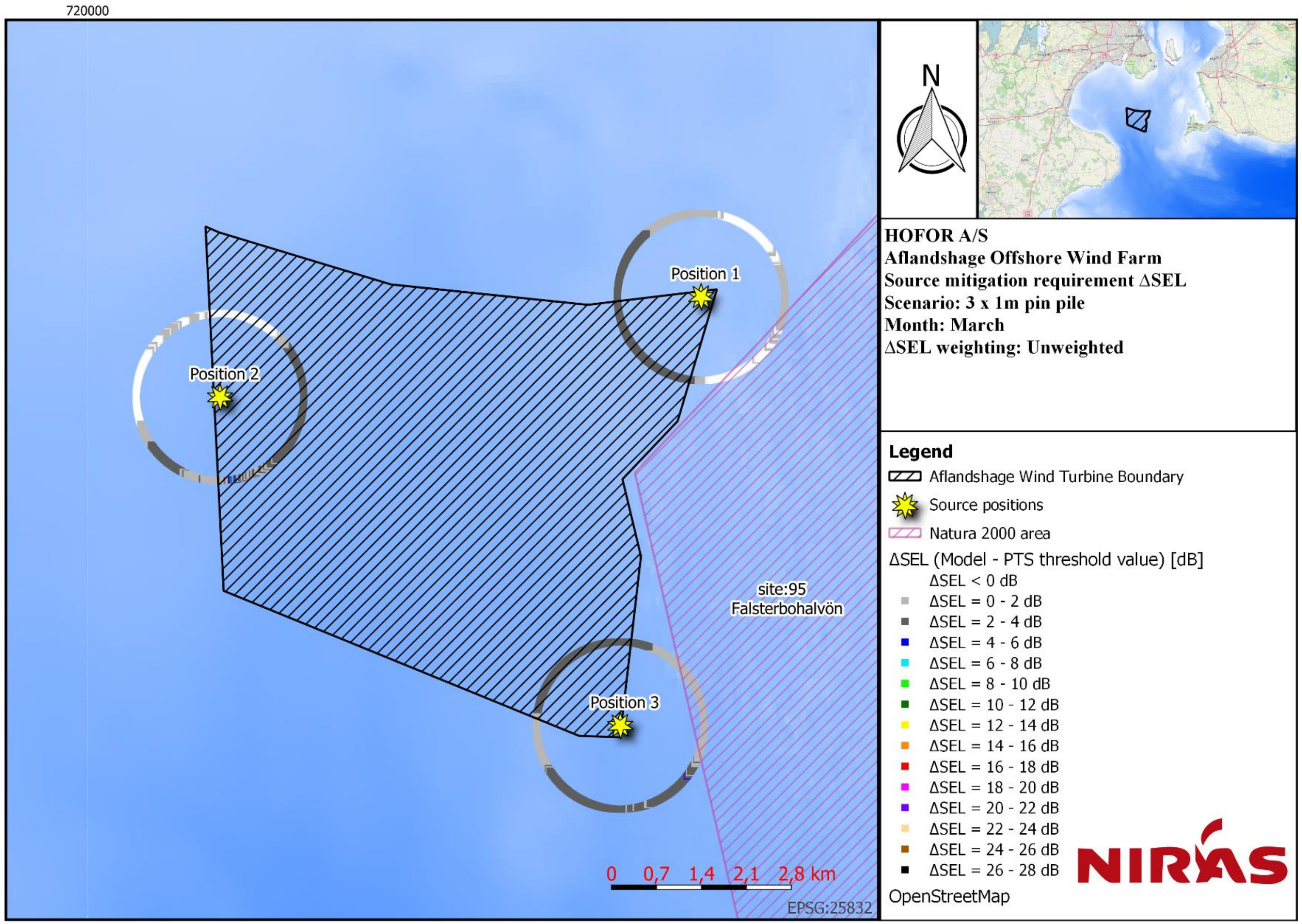
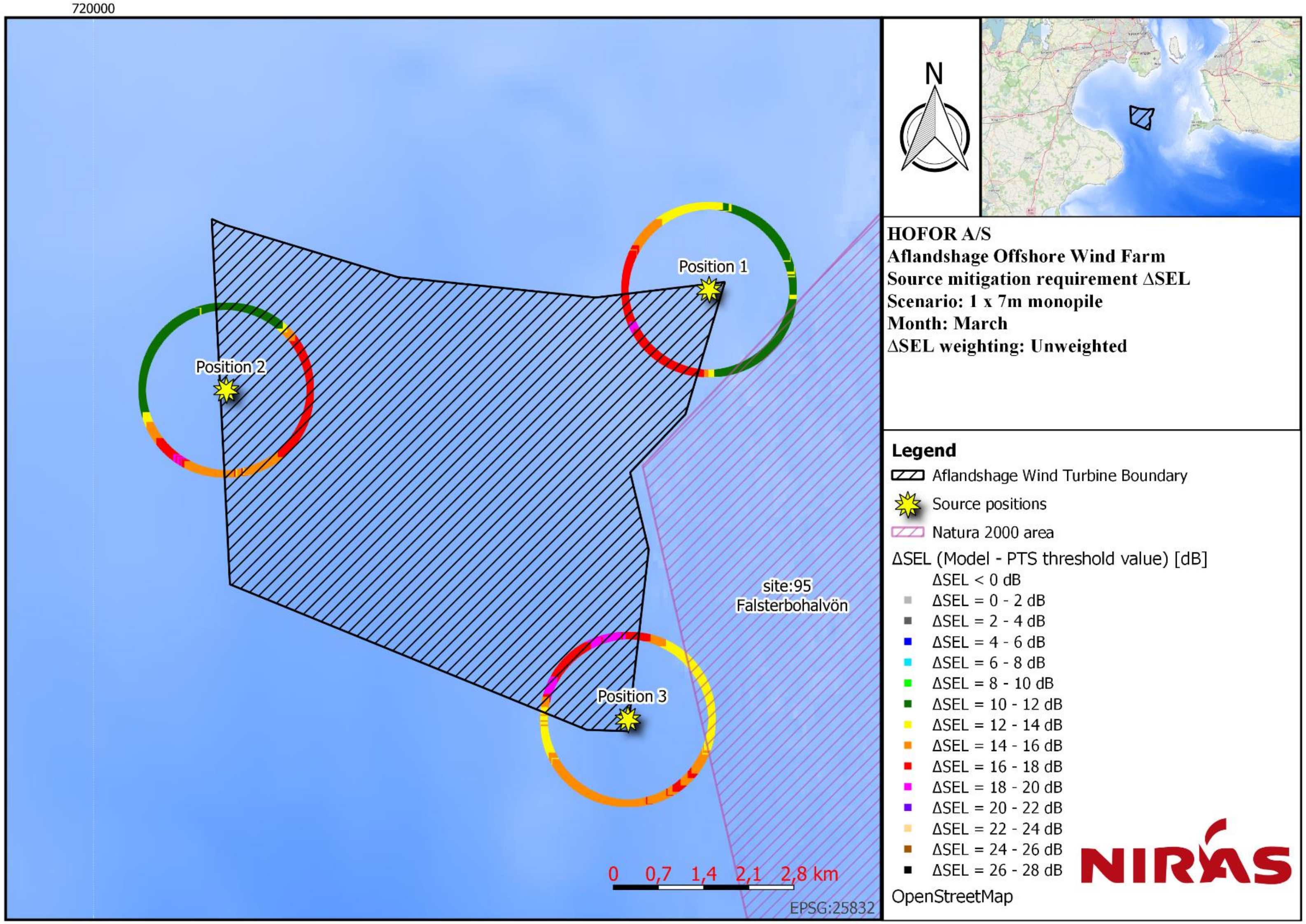
Appendix A: Source Mitigation requirements, current Danish guidelines

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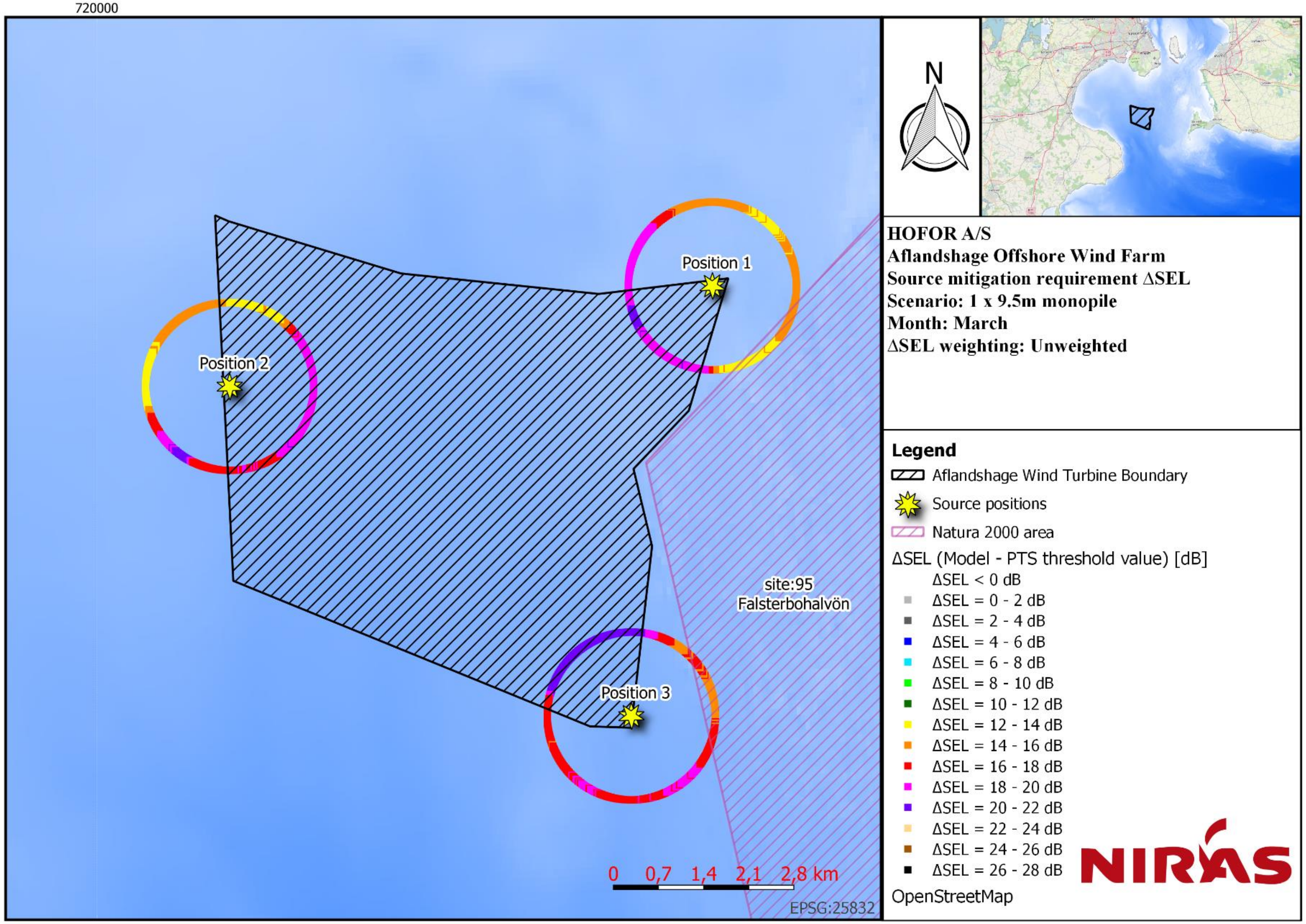
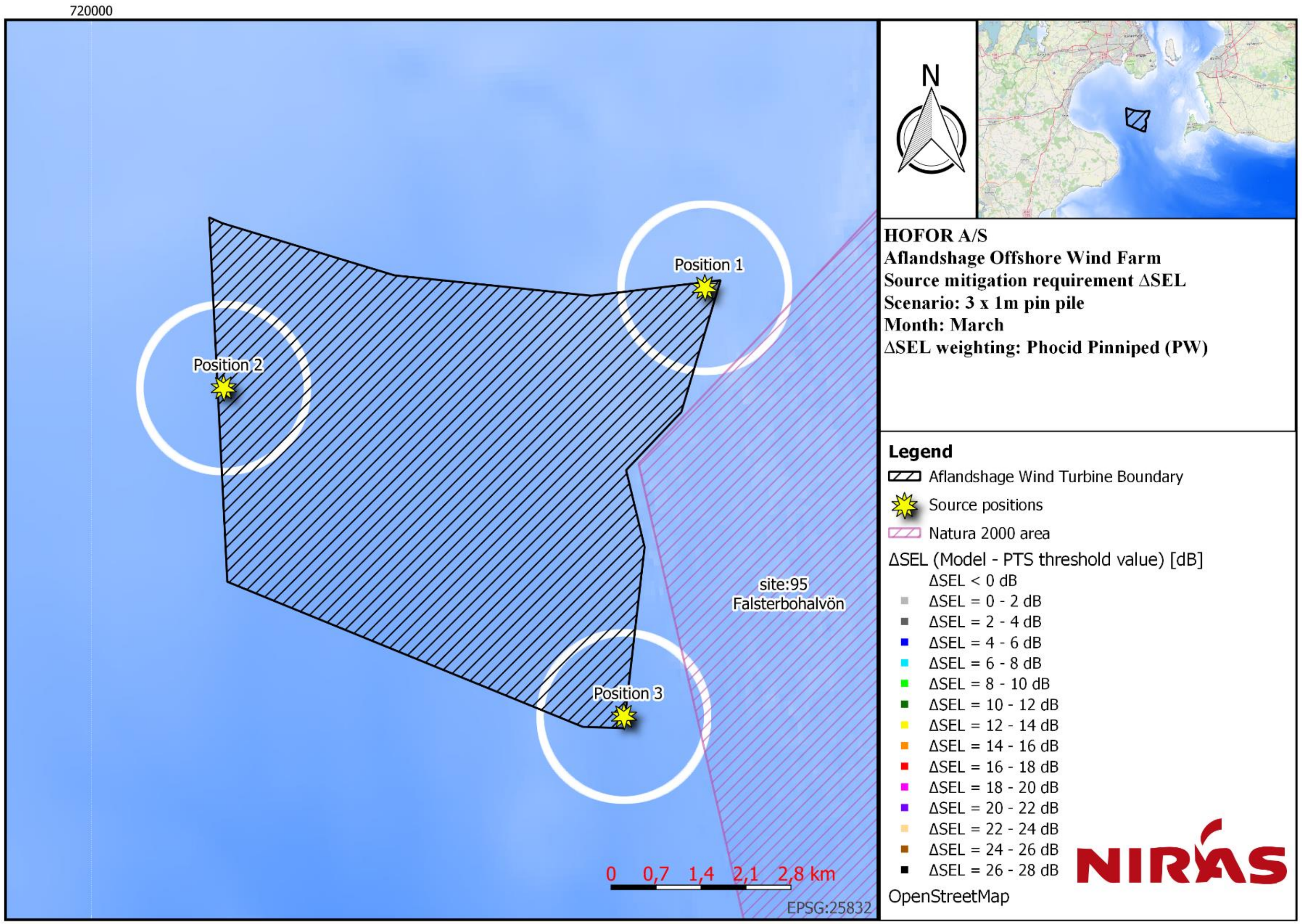
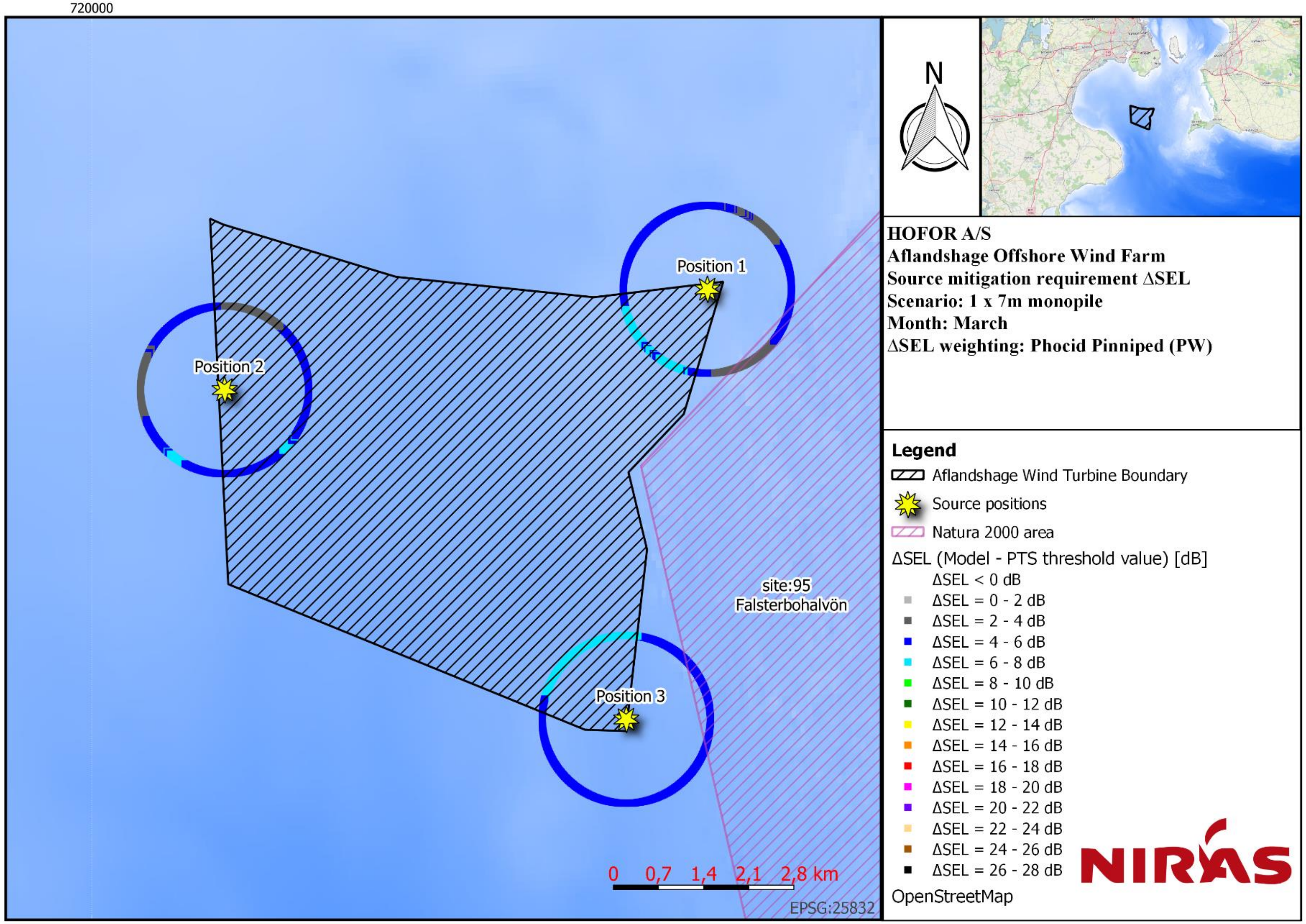
HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 7m monopile
Month: March
ΔSEL weighting: Unweighted
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
0 0,7 1,4 2,1 2,8 km
EPSG:25832
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
ΔSEL < 0 dB
ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
ΔSEL = 6 - 8 dB
ΔSEL = 8 - 10 dB
ΔSEL = 10 - 12 dB
ΔSEL = 12 - 14 dB
ΔSEL = 14 - 16 dB
ΔSEL = 16 - 18 dB
ΔSEL = 18 - 20 dB
ΔSEL = 20 - 22 dB
ΔSEL = 22 - 24 dB
ΔSEL = 24 - 26 dB
ΔSEL = 26 - 28 dB
OpenStreetMap
NIRAS


720000
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 9.5m monopile
Month: March
ΔSEL weighting: Unweighted
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
0 0,7 1,4 2,1 2,8 km
EPSG:25832
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
ΔSEL < 0 dB
ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
ΔSEL = 6 - 8 dB
ΔSEL = 8 - 10 dB
ΔSEL = 10 - 12 dB
ΔSEL = 12 - 14 dB
ΔSEL = 14 - 16 dB
ΔSEL = 16 - 18 dB
ΔSEL = 18 - 20 dB
ΔSEL = 20 - 22 dB
ΔSEL = 22 - 24 dB
ΔSEL = 24 - 26 dB
ΔSEL = 26 - 28 dB
OpenStreetMap
NIRAS

Appendix B: Source Mitigation requirements, expected future guidelines

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HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 7m monopile
Month: March
ΔSEL weighting: Phocid Pinniped (PW)
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
0 0,7 1,4 2,1 2,8 km
EPSG:25832
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
ΔSEL < 0 dB
ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
ΔSEL = 6 - 8 dB
ΔSEL = 8 - 10 dB
ΔSEL = 10 - 12 dB
ΔSEL = 12 - 14 dB
ΔSEL = 14 - 16 dB
ΔSEL = 16 - 18 dB
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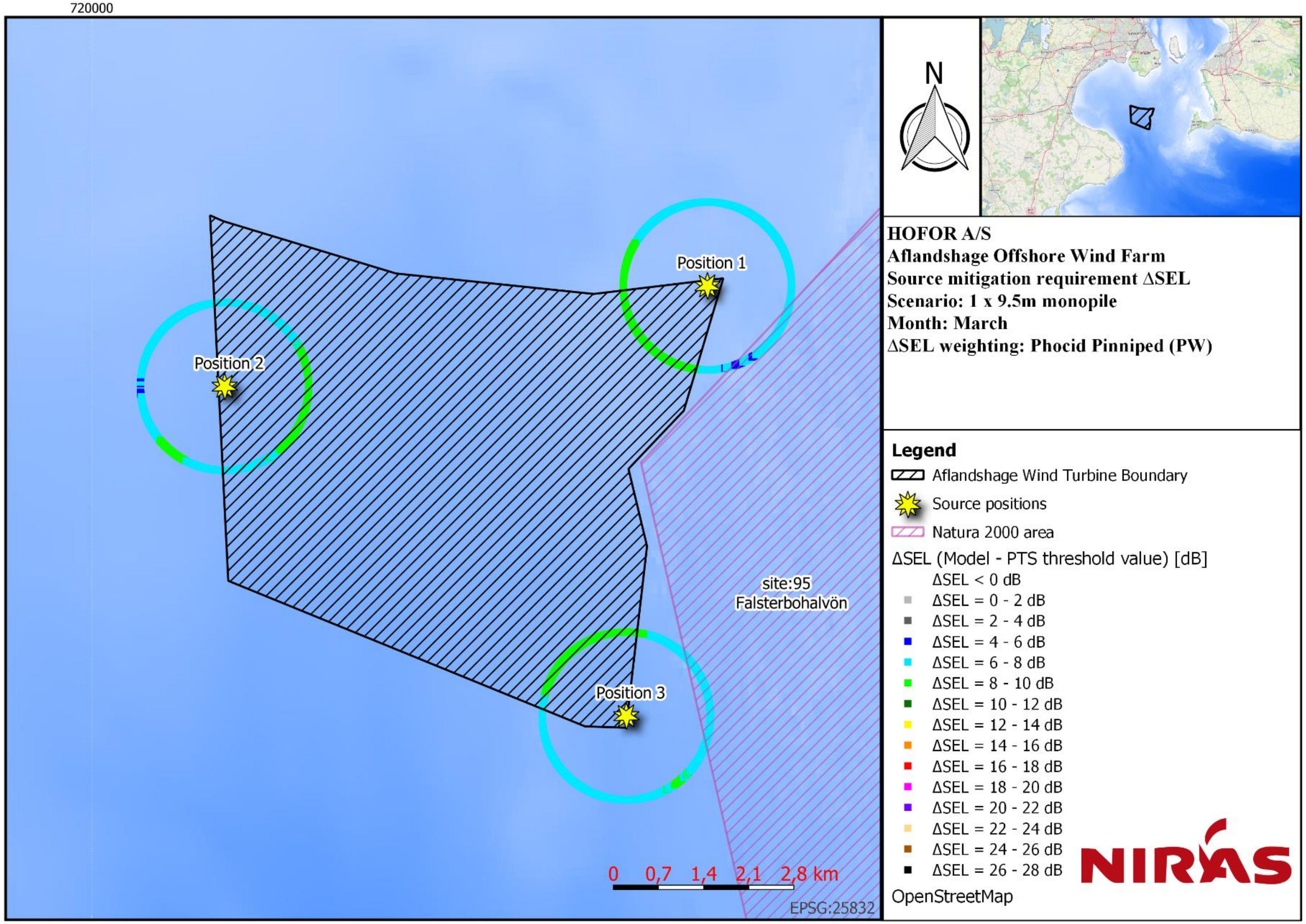
ΔSEL = 20 - 22 dB
ΔSEL = 22 - 24 dB
ΔSEL = 24 - 26 dB
ΔSEL = 26 - 28 dB
OpenStreetMap
NIRAS



HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 9.5m monopile
Month: March
ΔSEL weighting: Phocid Pinniped (PW)

Legend

- Aflandshage Wind Turbine Boundary
- Source positions
- Natura 2000 area

ΔSEL (Model - PTS threshold value) [dB]

- ΔSEL < 0 dB
- ΔSEL = 0 - 2 dB
- ΔSEL = 2 - 4 dB
- ΔSEL = 4 - 6 dB
- ΔSEL = 6 - 8 dB
- ΔSEL = 8 - 10 dB
- ΔSEL = 10 - 12 dB
- ΔSEL = 12 - 14 dB
- ΔSEL = 14 - 16 dB
- ΔSEL = 16 - 18 dB
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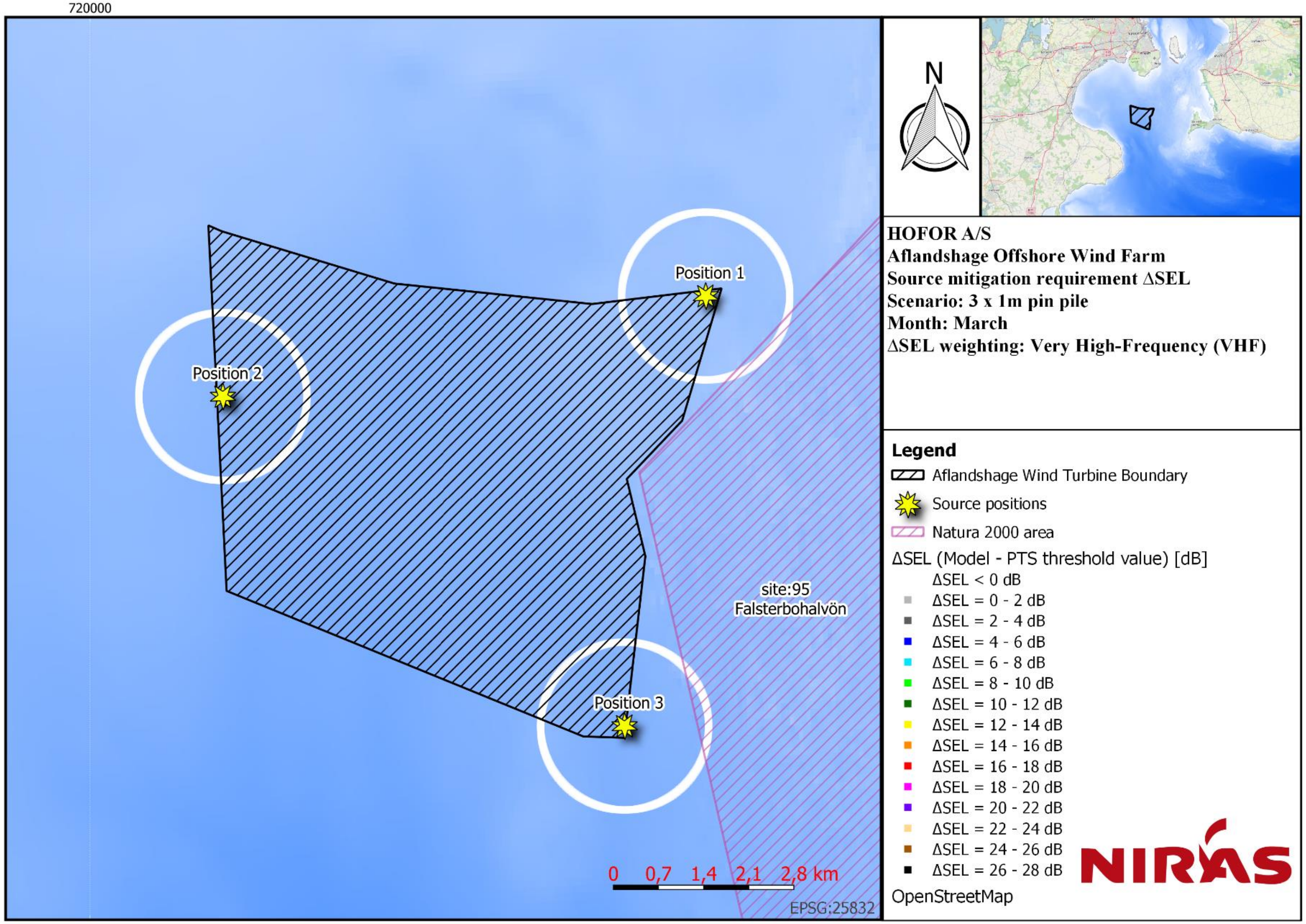
- ΔSEL = 22 - 24 dB
- ΔSEL = 24 - 26 dB
- ΔSEL = 26 - 28 dB

OpenStreetMap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Position 2
Position 3
site:95
Falsterbohalvön
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EPSG:25832
HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 3 x 1m pin pile
Month: March
ΔSEL weighting: Very High-Frequency (VHF)
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
ΔSEL < 0 dB
ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
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ΔSEL = 16 - 18 dB
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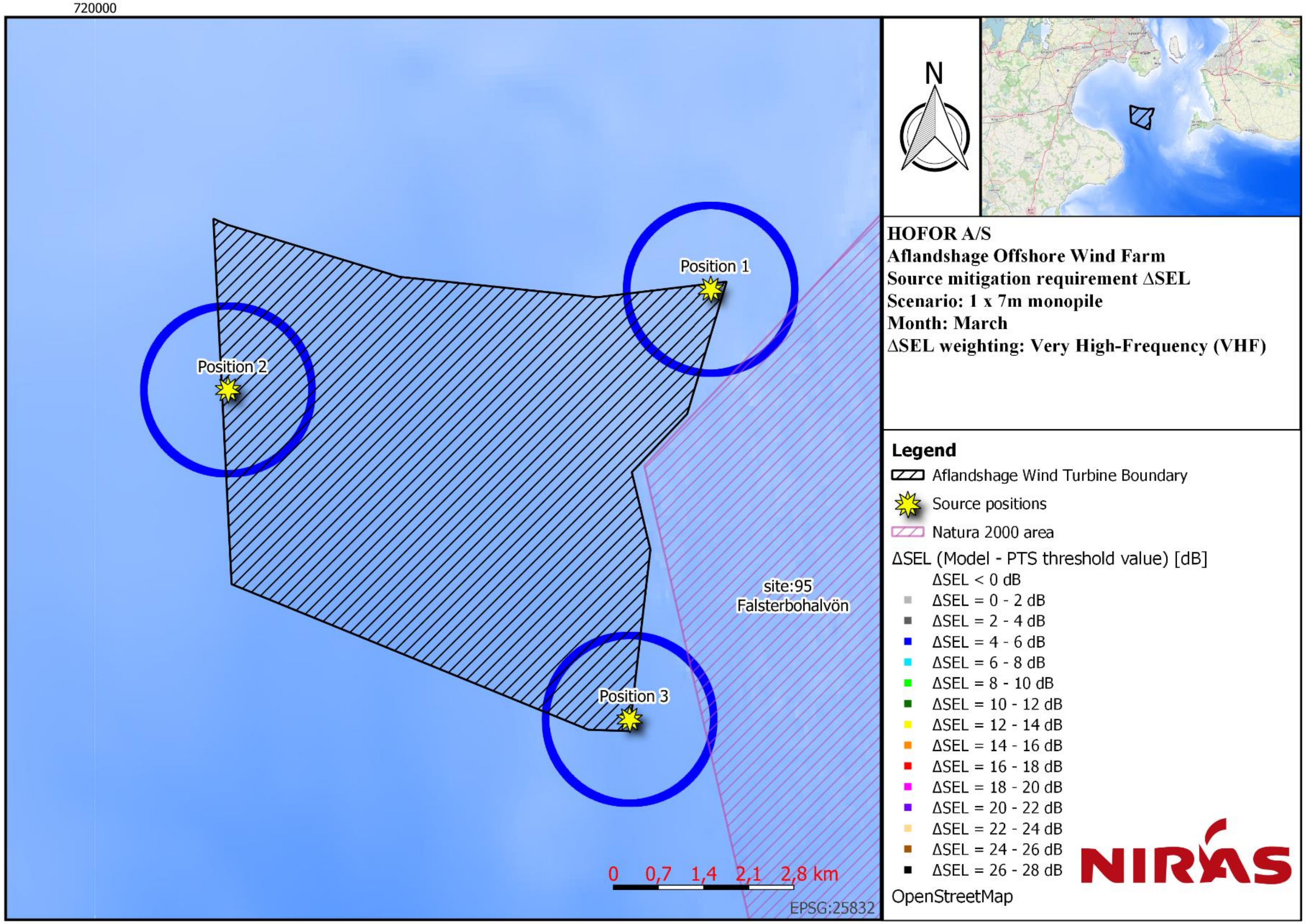
OpenStreetMap
NIRAS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EPSG:25832
HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 7m monopile
Month: March
ΔSEL weighting: Very High-Frequency (VHF)
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
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ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
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ΔSEL = 14 - 16 dB
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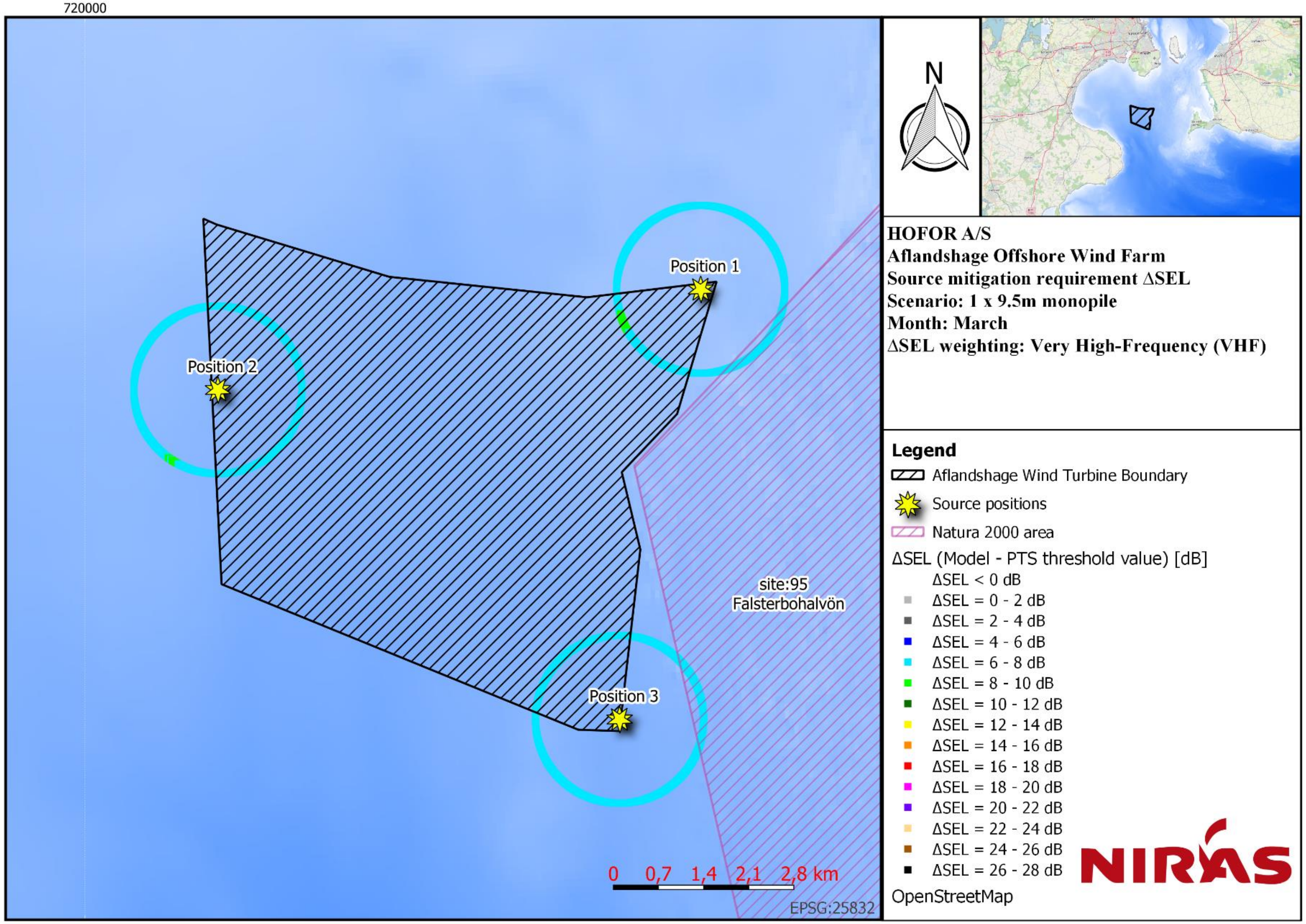
ΔSEL = 26 - 28 dB
OpenStreetMap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Position 1
Position 2
Position 3
site:95
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0 0,7 1,4 2,1 2,8 km
EPSG:25832
HOFOR A/S
Aflandshage Offshore Wind Farm
Source mitigation requirement ΔSEL
Scenario: 1 x 9.5m monopile
Month: March
ΔSEL weighting: Very High-Frequency (VHF)
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
ΔSEL (Model - PTS threshold value) [dB]
ΔSEL < 0 dB
ΔSEL = 0 - 2 dB
ΔSEL = 2 - 4 dB
ΔSEL = 4 - 6 dB
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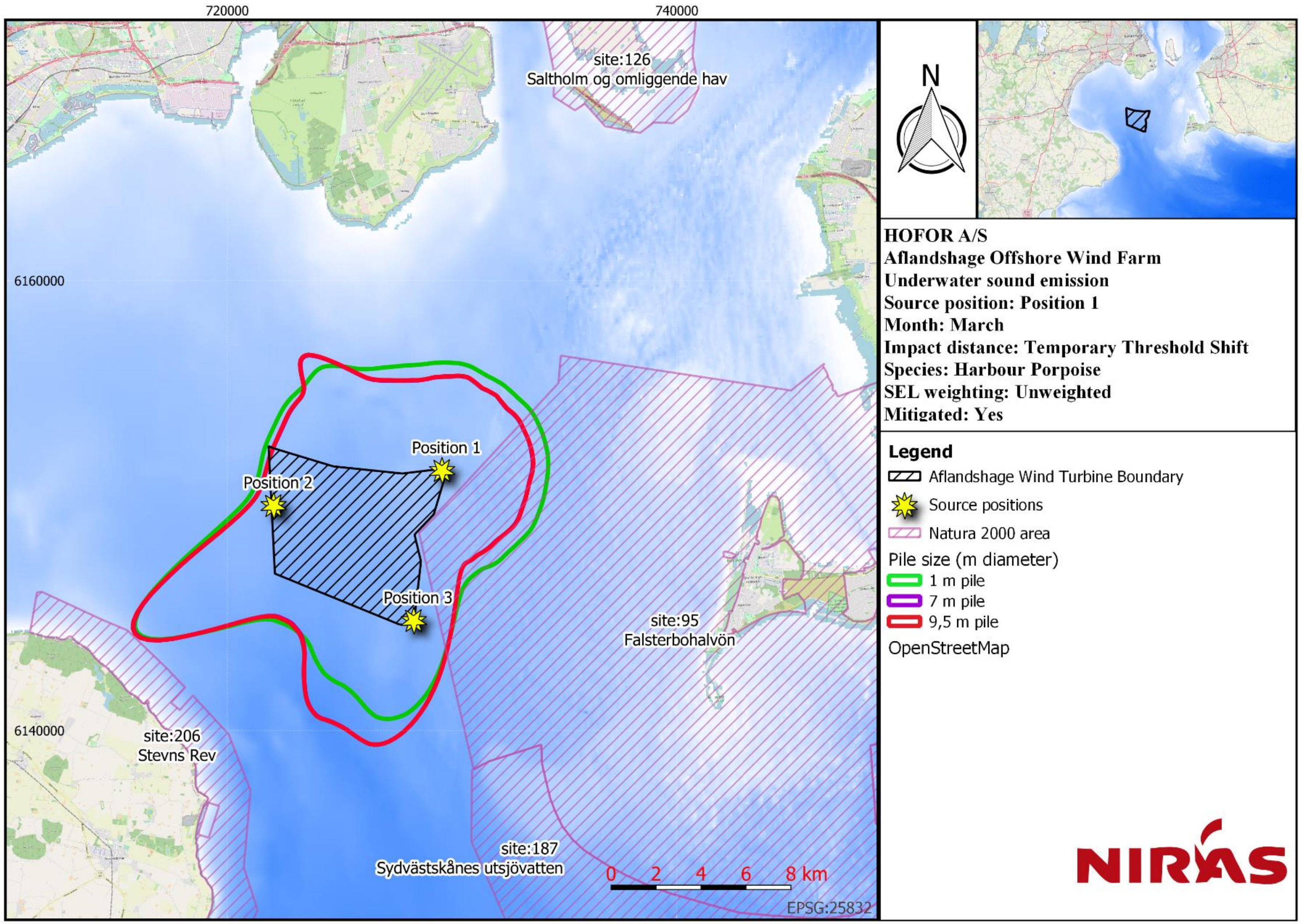
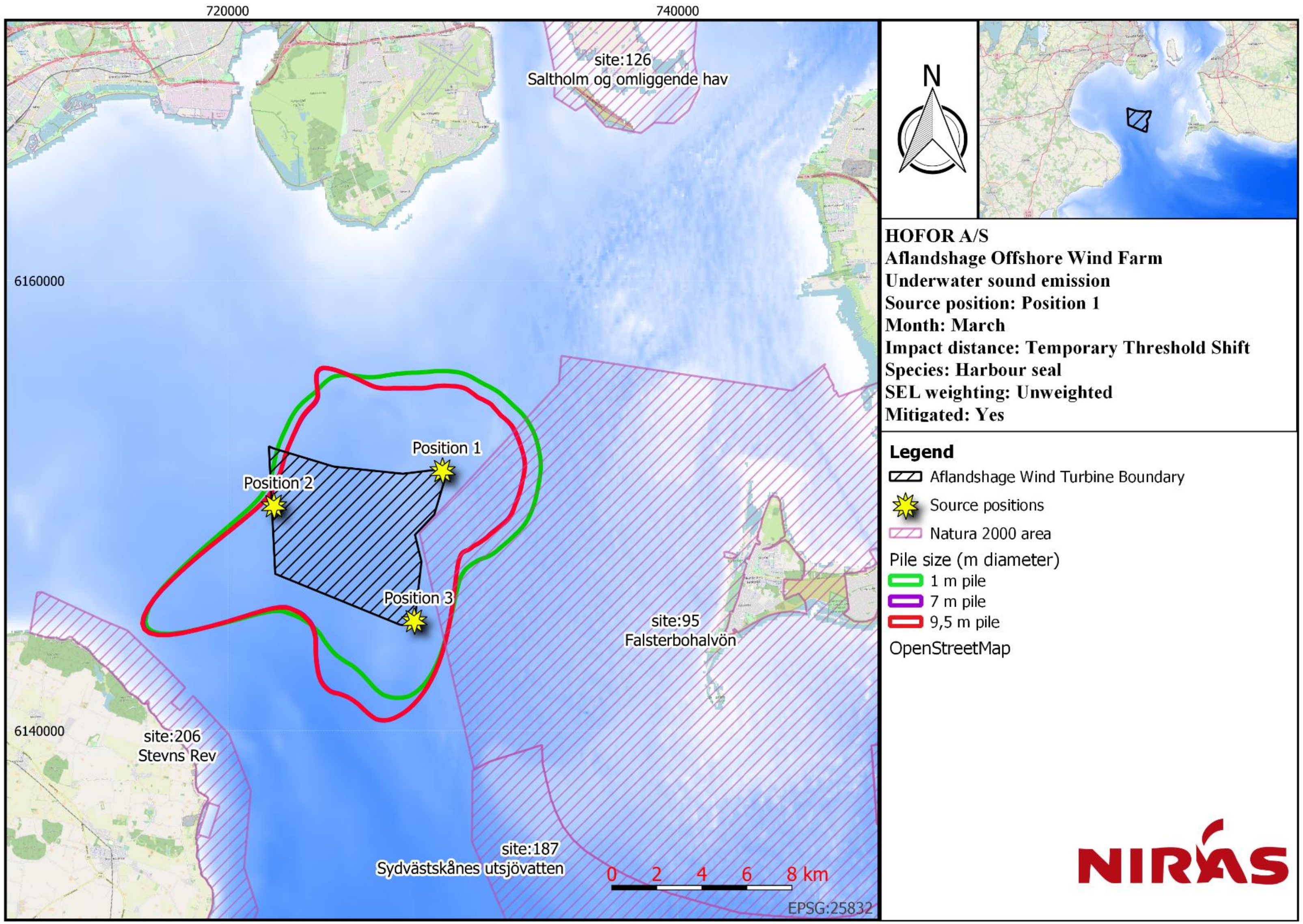
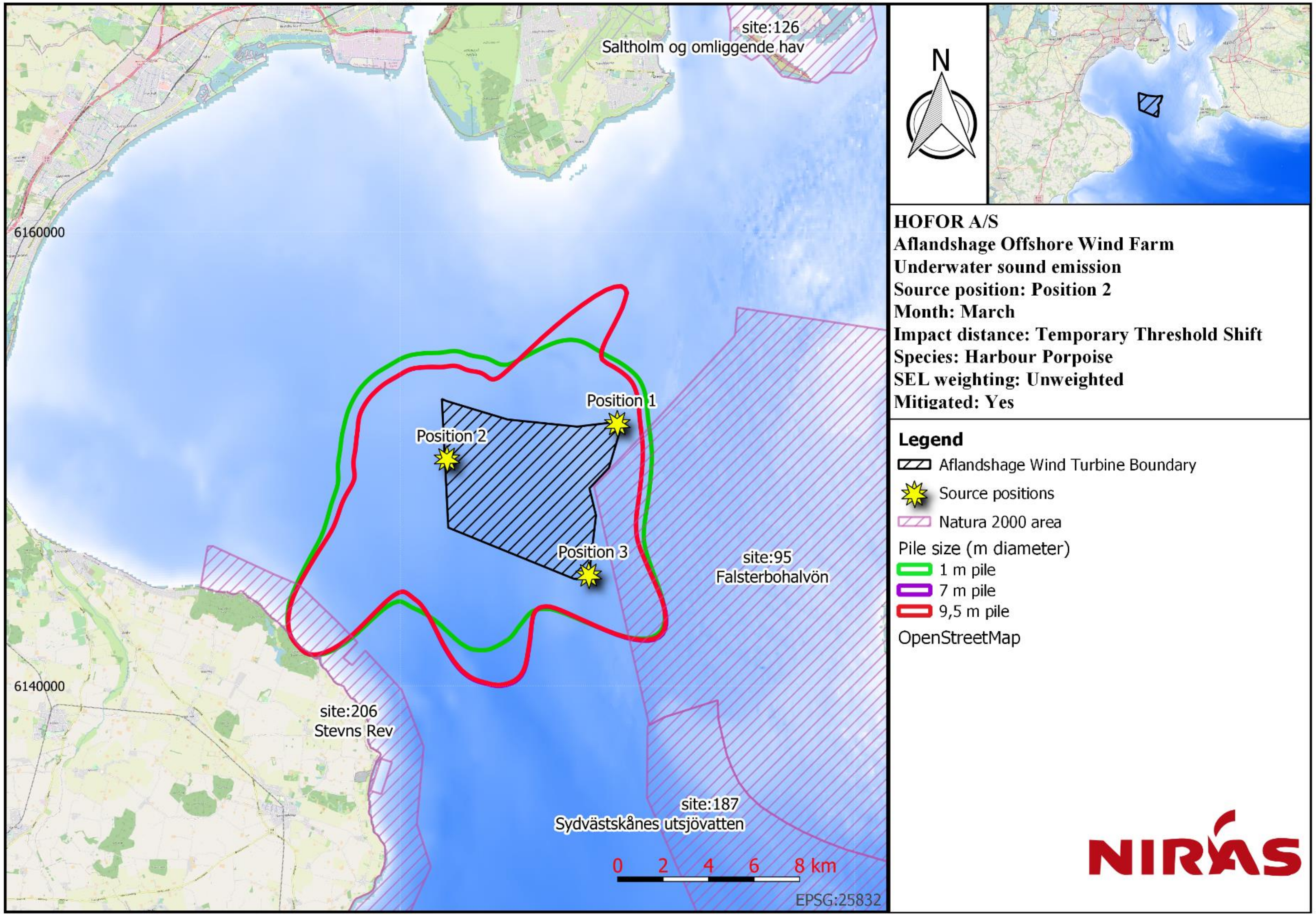
ΔSEL = 8 - 10 dB
ΔSEL = 10 - 12 dB
ΔSEL = 12 - 14 dB
ΔSEL = 14 - 16 dB
ΔSEL = 16 - 18 dB
ΔSEL = 18 - 20 dB
ΔSEL = 20 - 22 dB
ΔSEL = 22 - 24 dB
ΔSEL = 24 - 26 dB
ΔSEL = 26 - 28 dB
OpenStreetMap

Appendix C: Noise Contours with mitigation, current Danish guidelines




720000
740000
6160000
6140000
site:126
Saltholm og omliggende hav
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 1
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour seal
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
NIRAS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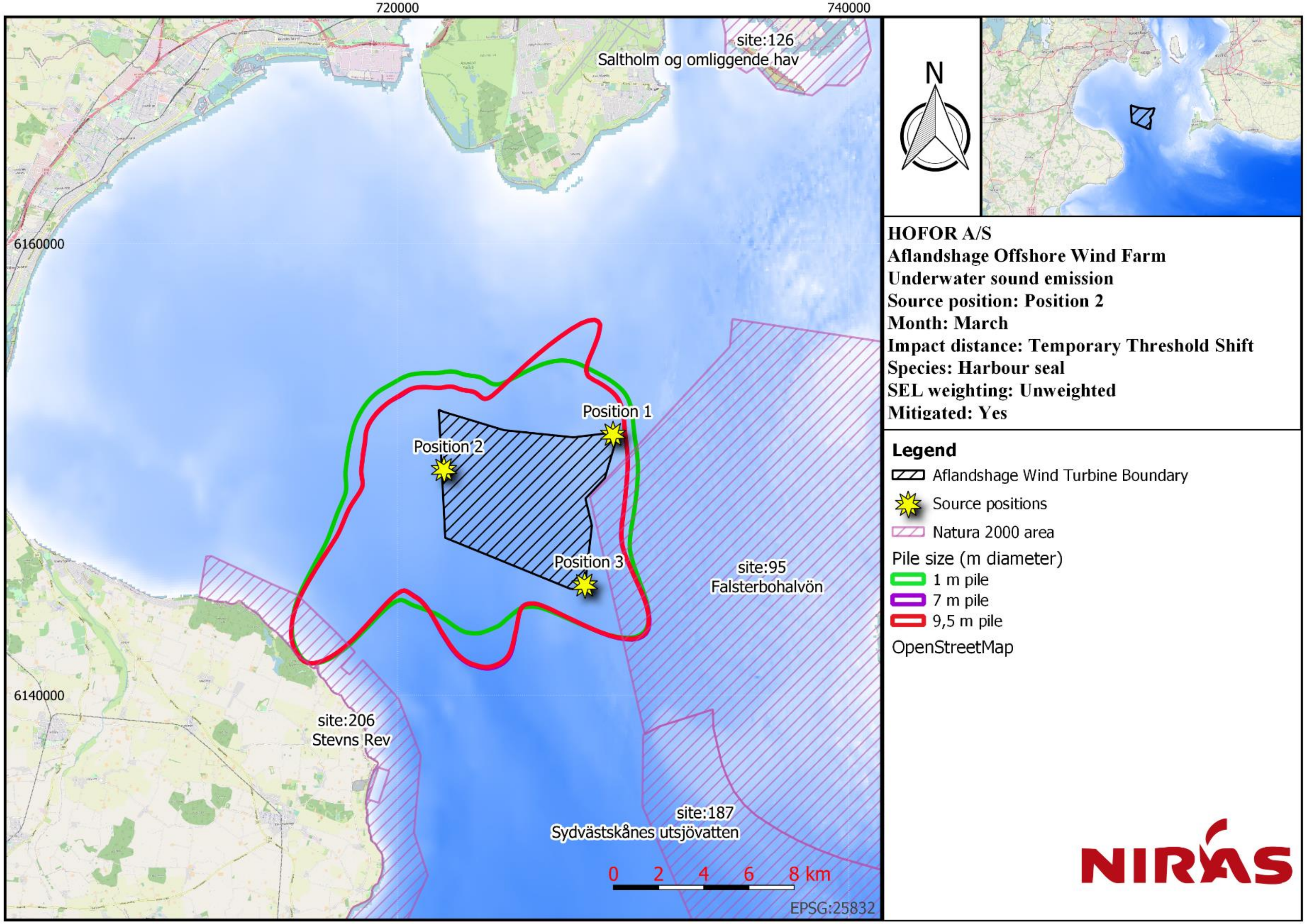
740000
6160000
6140000
site:126
Saltholm og omliggende hav
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 2
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour Porpoise
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
NIRAS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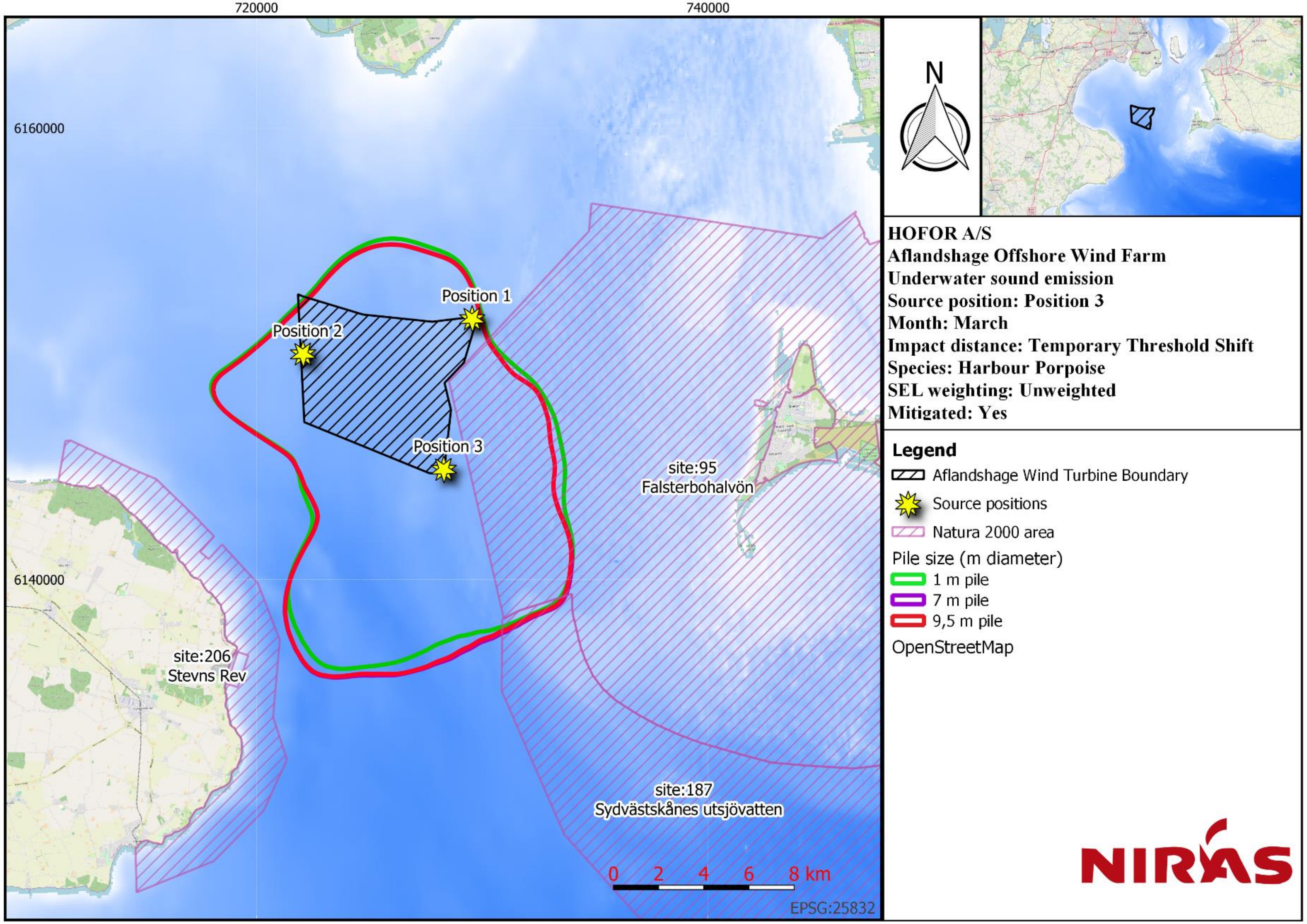
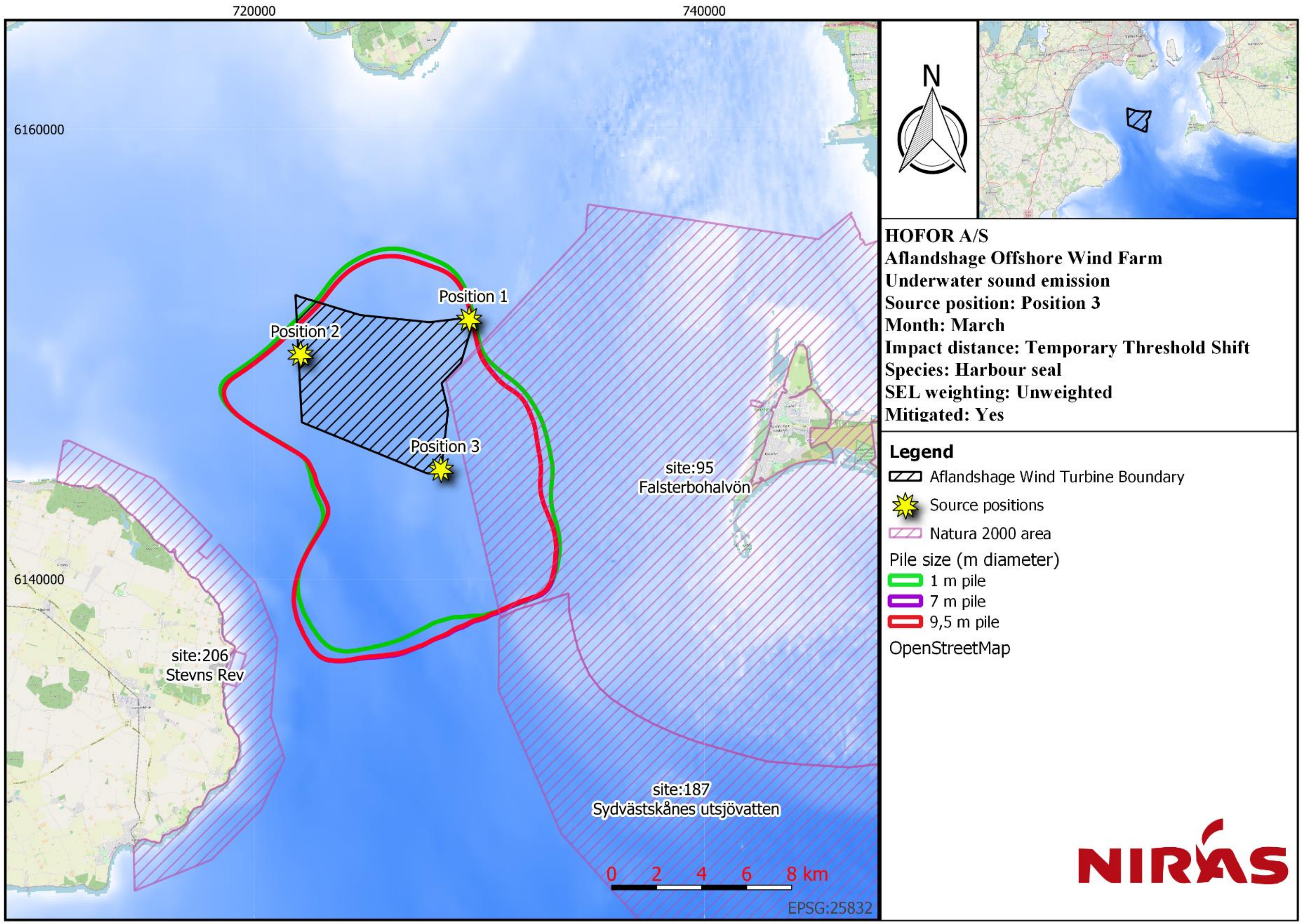
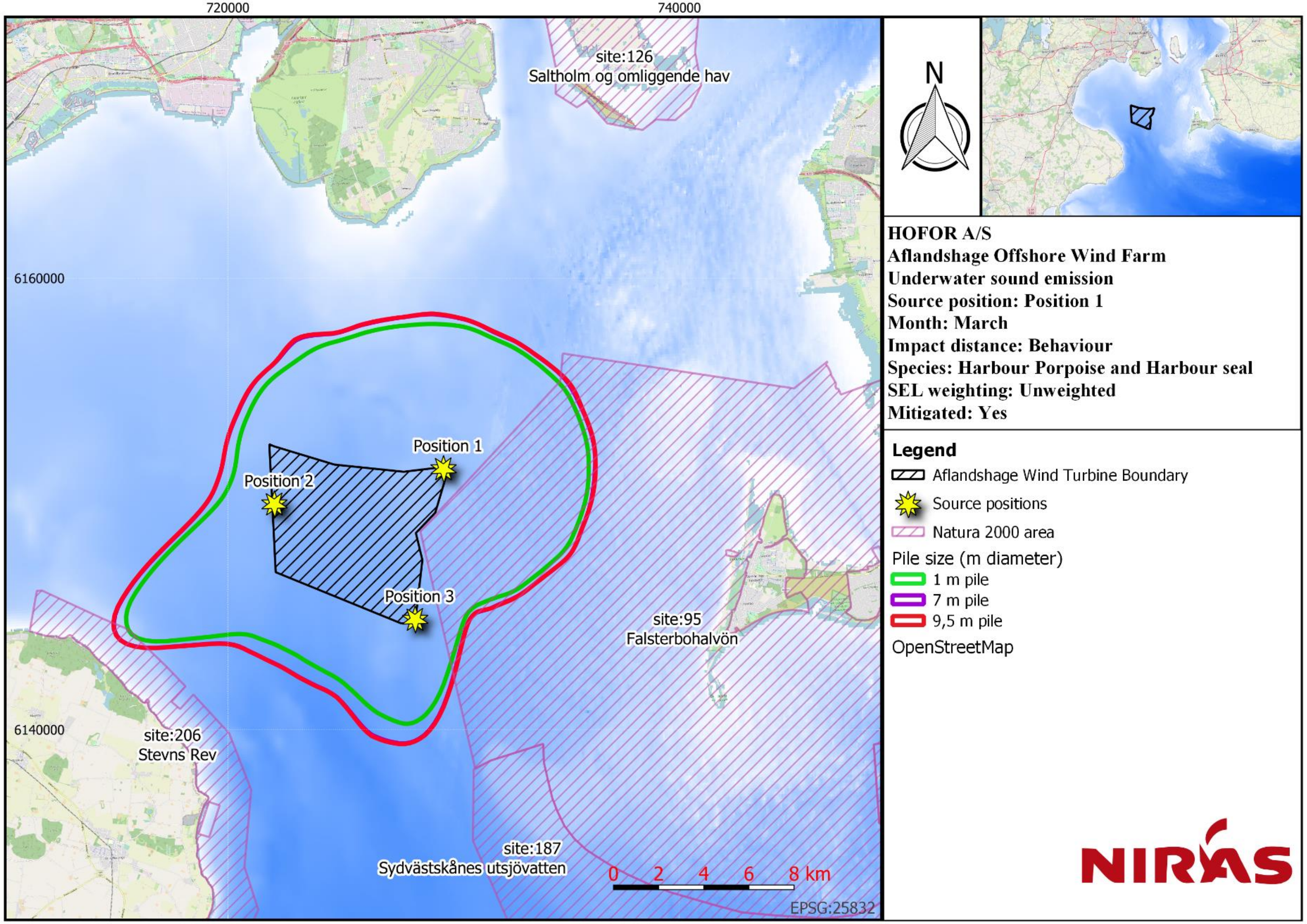
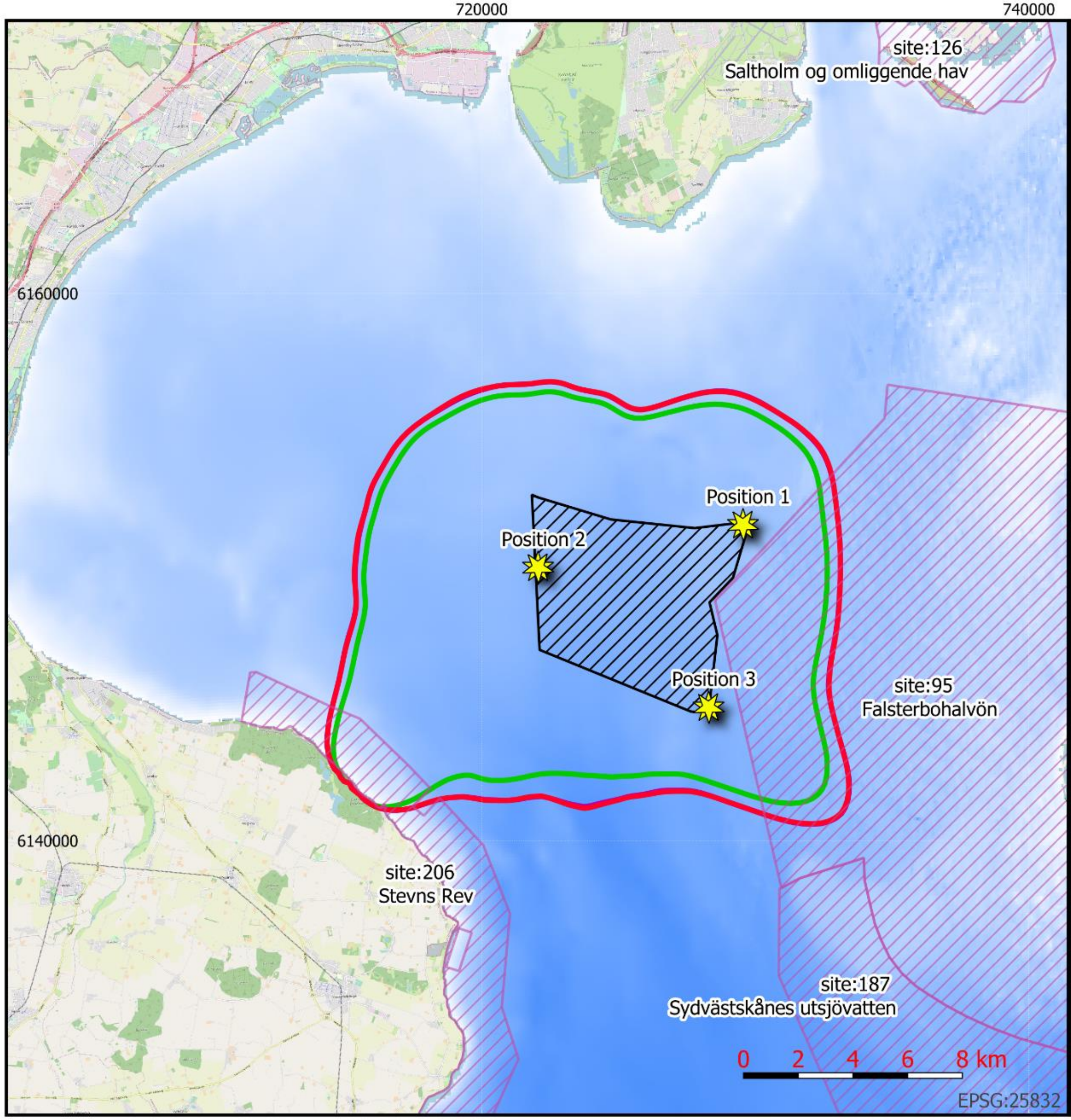
740000
6160000
6140000
site:126
Saltholm og omliggende hav
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 2
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour seal
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap


720000
740000
6160000
6140000
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 3
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour Porpoise
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
NIRAS


720000
740000
6160000
6140000
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 3
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour seal
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
NIRAS



HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 1
Month: March
Impact distance: Behaviour
Species: Harbour Porpoise and Harbour seal
SEL weighting: Unweighted
Mitigated: Yes



HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 2
Month: March
Impact distance: Behaviour
Species: Harbour Porpoise and Harbour seal
SEL weighting: Unweighted
Mitigated: Yes

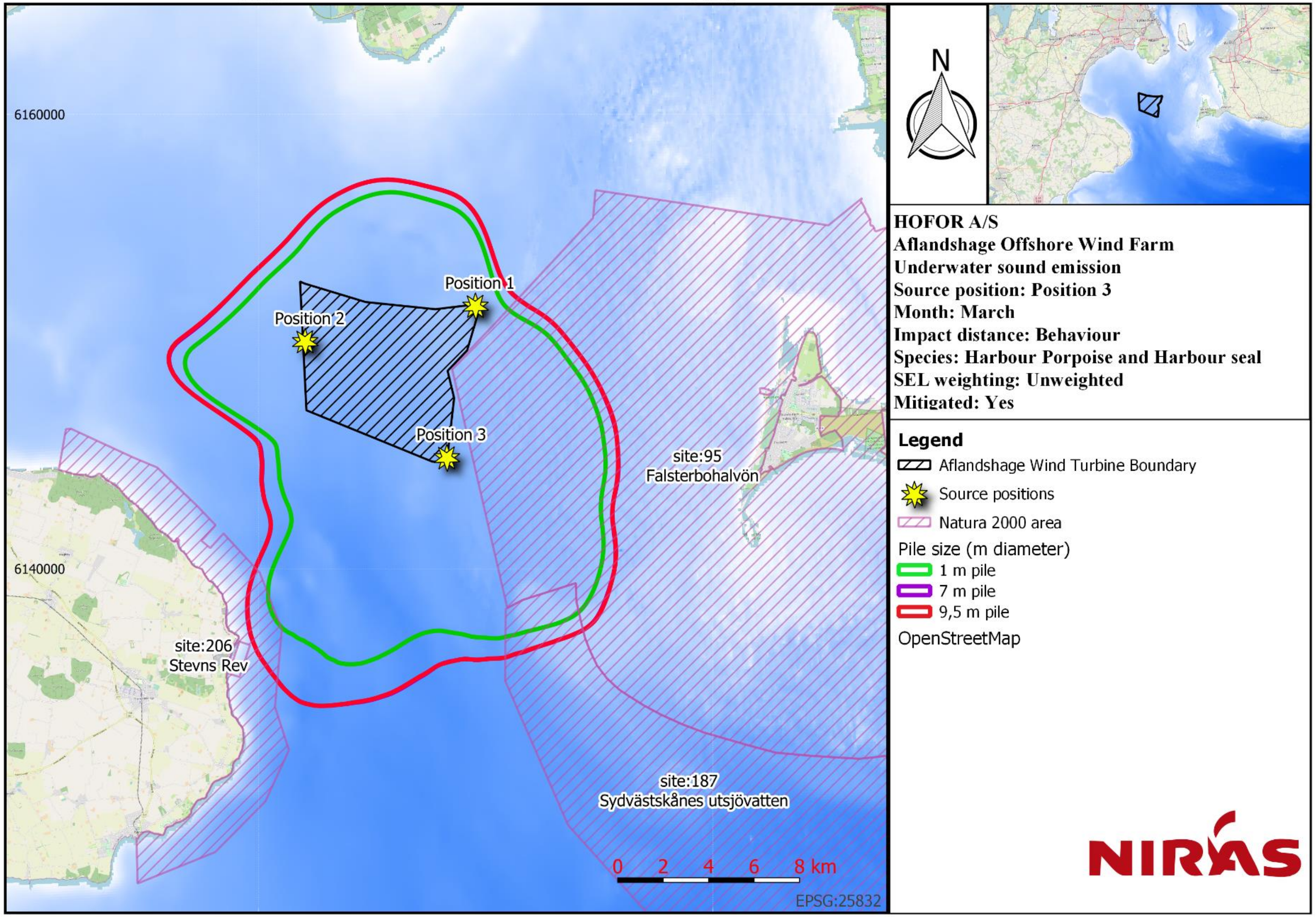
Legend

- Aflandshage Wind Turbine Boundary
- Source positions
- Natura 2000 area

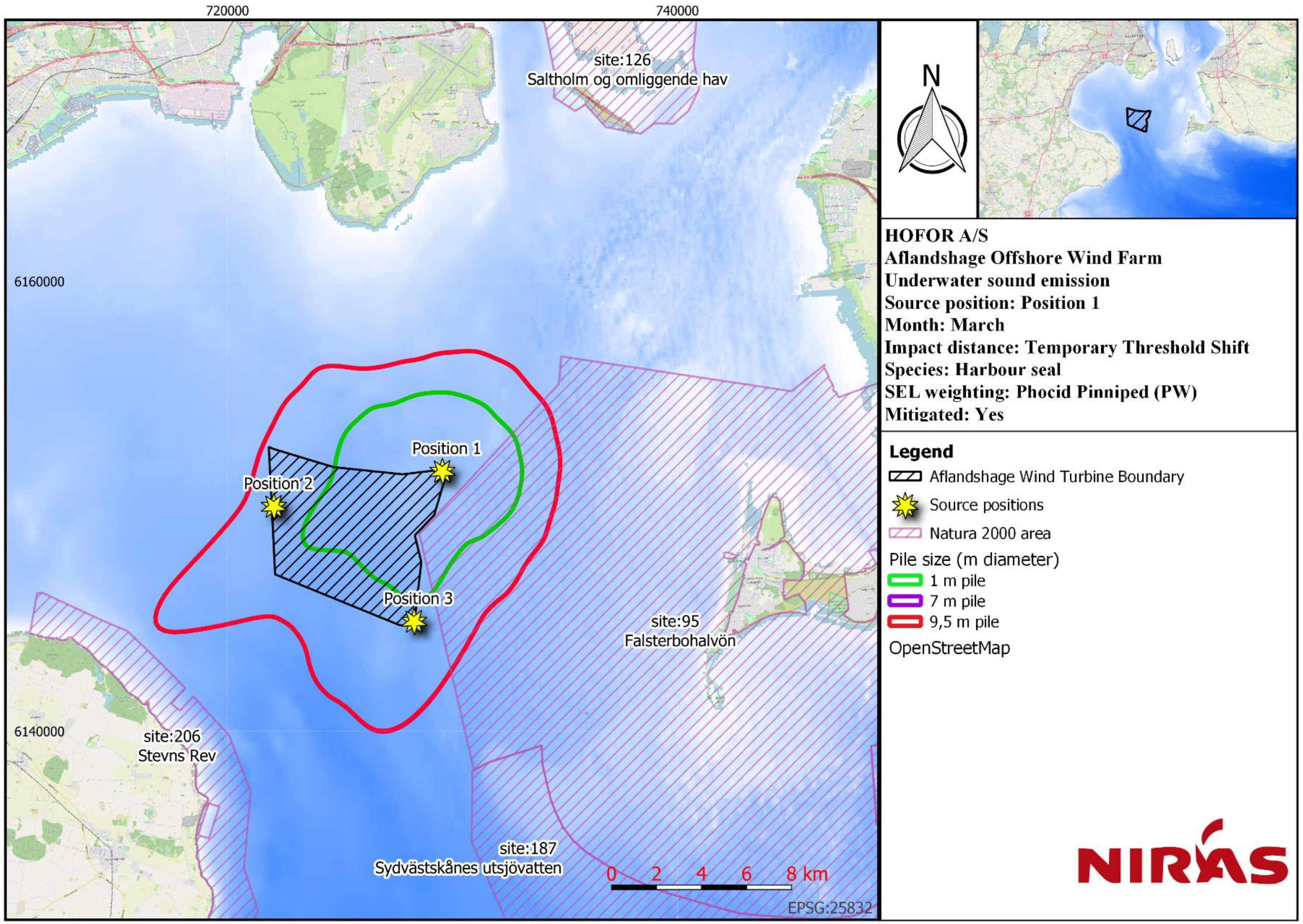
Pile size (m diameter)

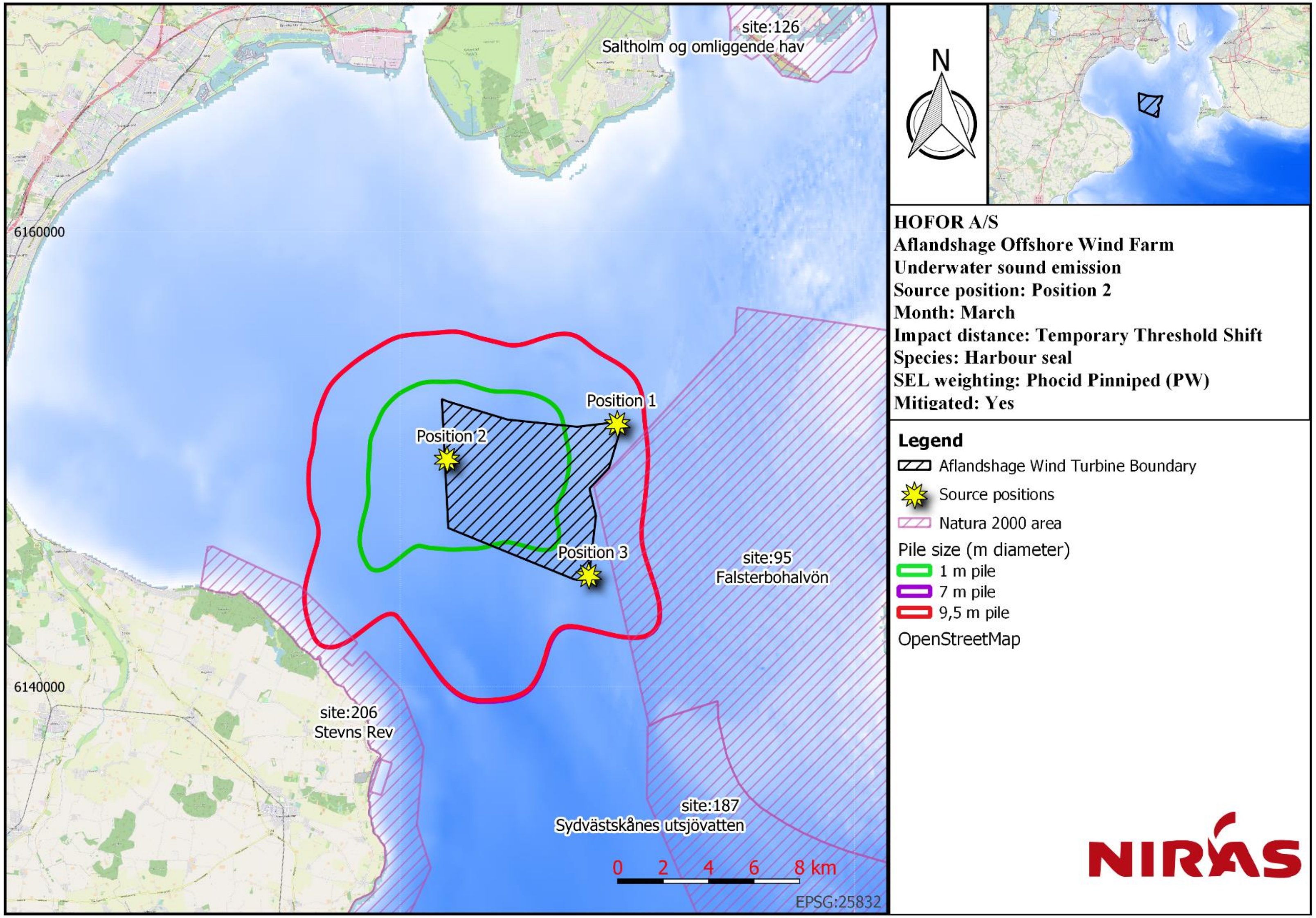
- 1 m pile
- 7 m pile
- 9,5 m pile

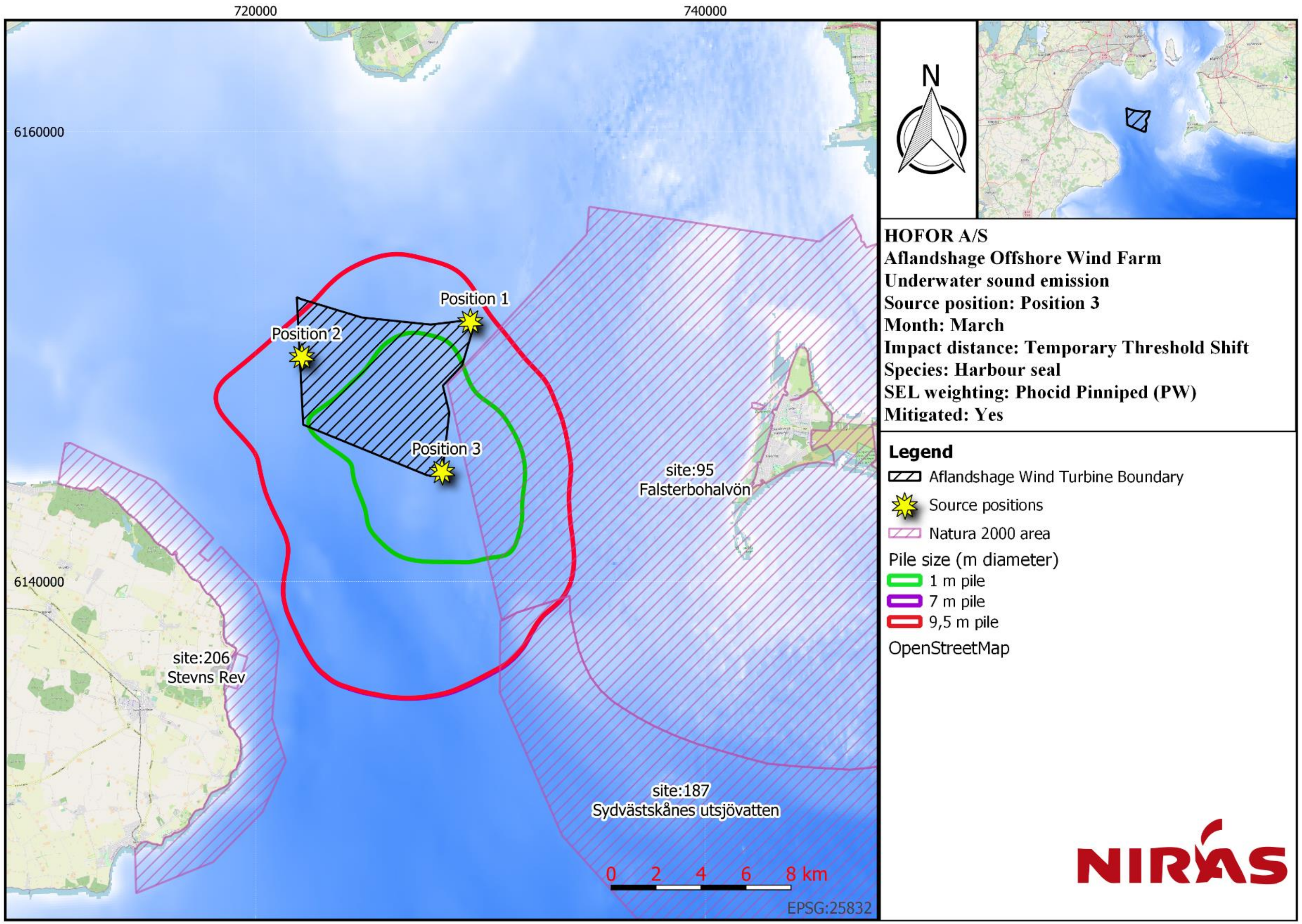
OpenStreetMap

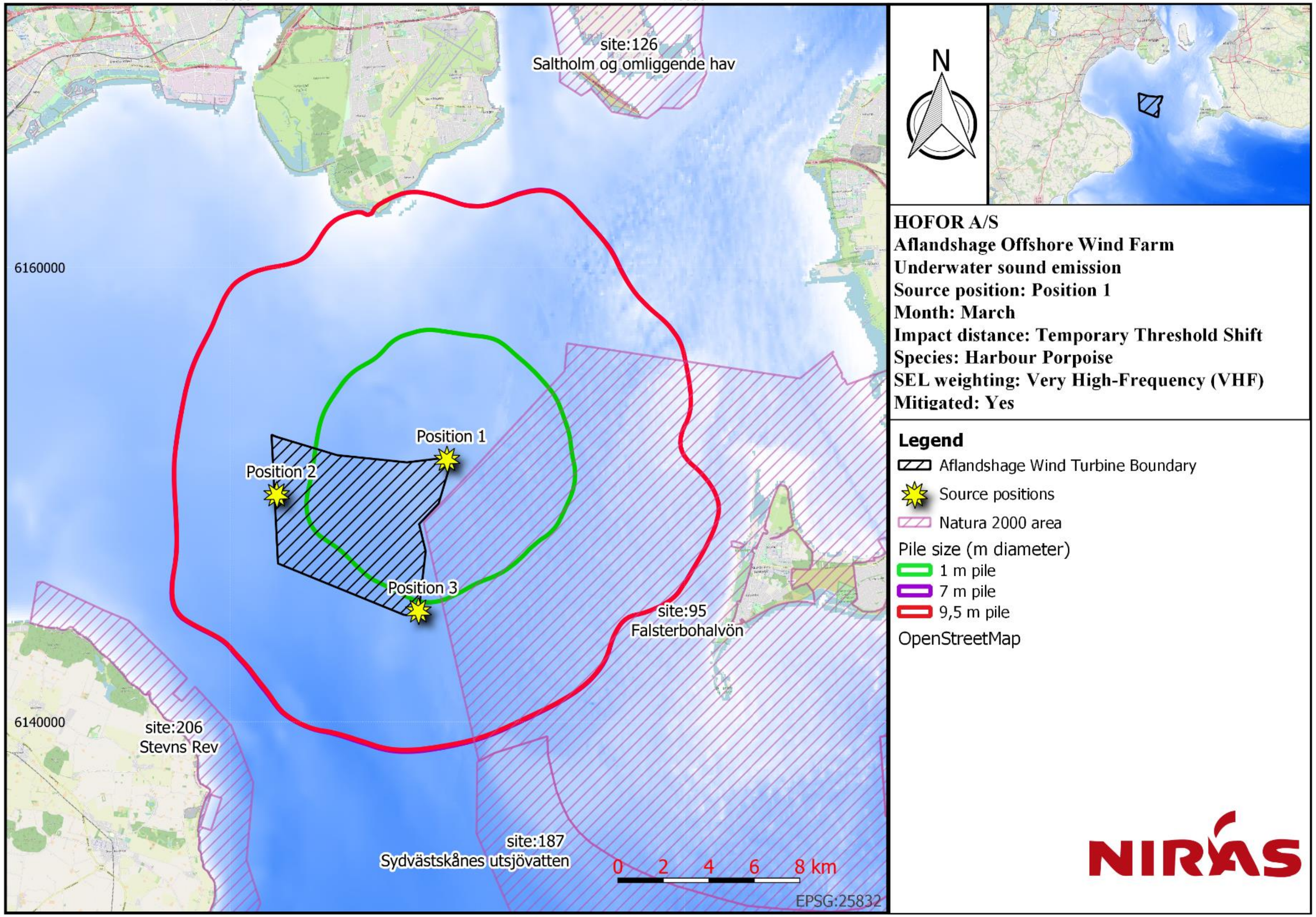

720000
740000
6160000
6140000
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 3
Month: March
Impact distance: Behaviour
Species: Harbour Porpoise and Harbour seal
SEL weighting: Unweighted
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
NIRAS

Appendix D: Noise Contours with mitigation, expected future guidelines




720000
740000
6160000
6140000
site:126
Saltholm og omliggende hav
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 2
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour seal
SEL weighting: Phocid Pinniped (PW)
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap
NIRAS

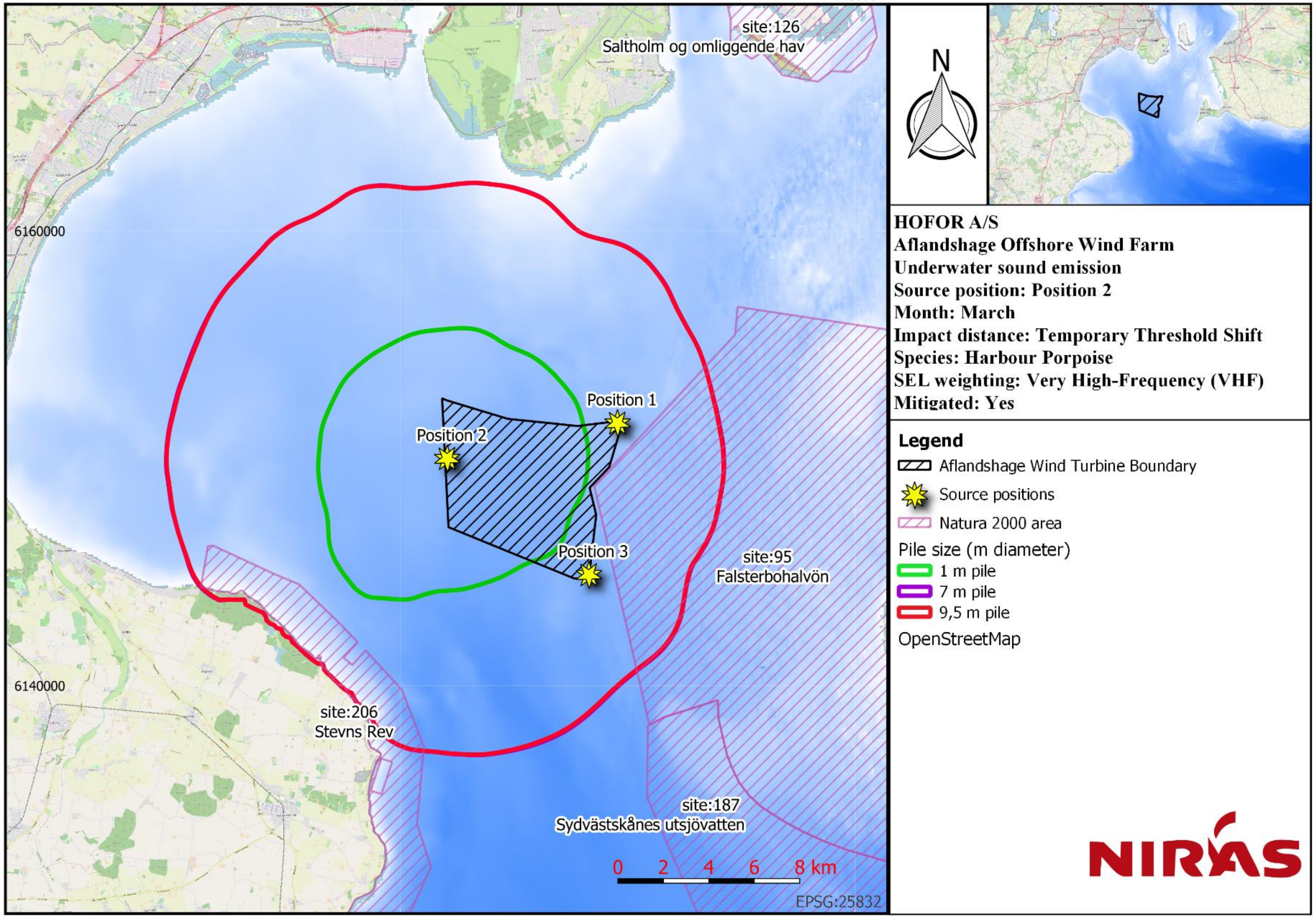

720000
740000
6160000
6140000
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 3
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour seal
SEL weighting: Phocid Pinniped (PW)
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap



HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 1
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour Porpoise
SEL weighting: Very High-Frequency (VHF)
Mitigated: Yes

Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
Pile size (m diameter)
1 m pile
7 m pile
9,5 m pile
OpenStreetMap

NIRAS


720000
740000
6160000
6140000
site:126
Saltholm og omliggende hav
Position 1
Position 2
Position 3
site:95
Falsterbohalvön
site:206
Stevns Rev
site:187
Sydvästskånes utsjövatten
0 2 4 6 8 km
EPSG:25832
N
HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 2
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour Porpoise
SEL weighting: Very High-Frequency (VHF)
Mitigated: Yes
Legend
Aflandshage Wind Turbine Boundary
Source positions
Natura 2000 area
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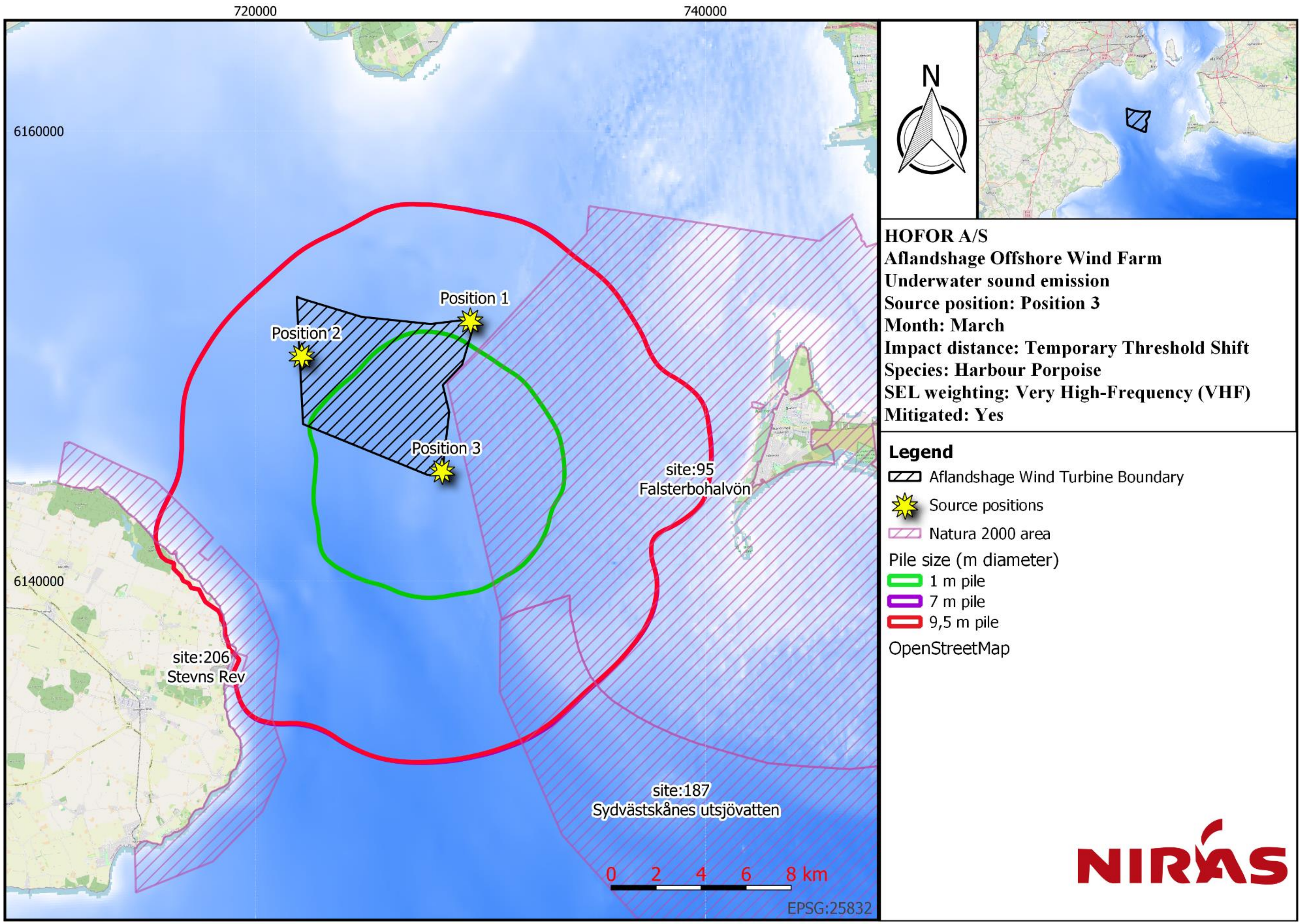
9,5 m pile
OpenStreetMap
NIRAS



HOFOR A/S
Aflandshage Offshore Wind Farm
Underwater sound emission
Source position: Position 3
Month: March
Impact distance: Temporary Threshold Shift
Species: Harbour Porpoise
SEL weighting: Very High-Frequency (VHF)
Mitigated: Yes

Legend
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Pile size (m diameter)
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OpenStreetMap