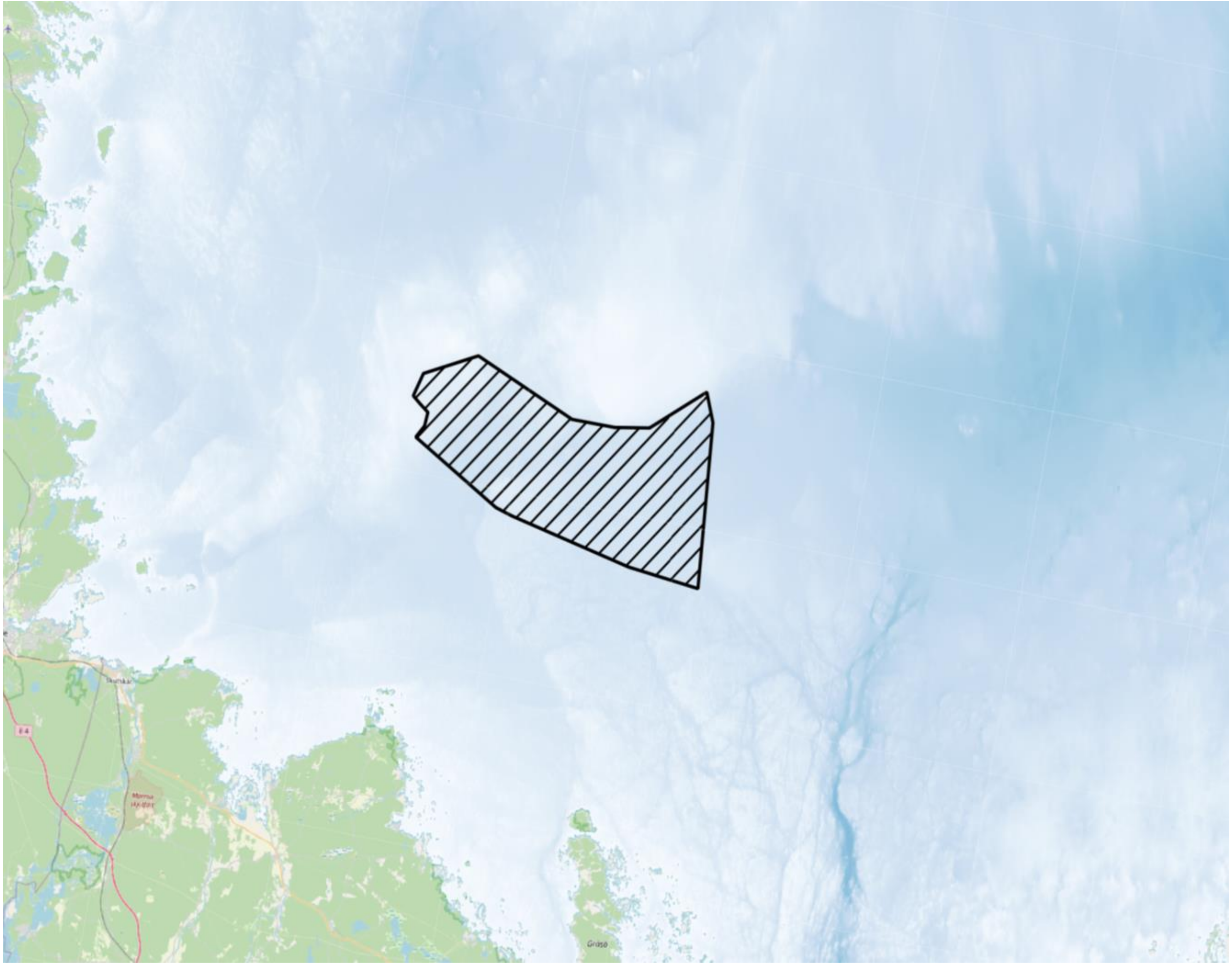

# Olof Skötkonung Offshore Wind Farm

## Underwater Noise

Construction and operation

NIRAS A/S

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# Contents

# Executive Summary

Deep Wind Offshore is planning the construction of Olof Skötkonung Offshore Wind Farm (OWF), in the Bothnian Sea, approximately 53 km northeast of the city Gävle. Construction and operation of the wind farm involves activities that produce underwater noise, with the potential to disturb and/or harm marine fauna. NIRAS has been tasked with preparation of an underwater noise prognosis for activities relevant to the proposed construction activities and for the operation of the wind farm, to model and assess underwater noise impact ranges for marine mammal and fish species relevant to the local environment.

## Underwater noise during construction

Underwater sound propagation modelling from construction activities included underwater noise from pile driving, in 5 representative worst case positions within the Olof Skötkonung wind farm area. Calculations were carried out for both unmitigated, as well as mitigated, pile driving.

The prognosis included sound propagation modelling of impact pile driving for a jacket foundation with 4x 4 m diameter pin piles.

A source model was derived for the foundation type based on available literature and NIRAS experience from previous projects. Sound propagation from pile driving was modelled without any mitigation measures to determine sound propagation properties of the local environment. The source model included conservative estimates for number of pile strikes, along with the installation procedure and timing, including soft start and ramp up.

All sound propagation modelling represent the installation of a single foundation within a 24 hour duration. For installation of multiple foundations, either concurrently or sequentially within a 24 hour duration, a discussion is provided in Appendix 1, however no calculations of cumulative impact beyond that of a single foundation are provided in this report. The installation of all foundations in the wind farm area does not affect the prognosis, as it considers individual piles. Cumulative effects from the construction of the wind farm are not assessed in this report.

For the project area, underwater sound propagation properties of 13.2 – 15.1 dB/decade, corresponding to a sound level decrease of 13.2 – 15.1 dB for each 10 fold increase of the distance between source and receiver, were found for the 5 different source positions. The sound propagation factor of 13.2 dB/decade represents a sound propagation path with extremely low sound propagation loss, whereas the 15.1 dB/decade factor represents a more average sound propagation for the Bothnian Sea. Overall, the sound propagation potential of the area is considered very strong - strong, and thereby shows potential for significant impact ranges to relevant marine mammal and fish threshold criteria.

For marine mammals, such threshold criteria include hearing loss (threshold shift), resulting from exposure to high noise doses, as well as instantaneous behavioural reaction resulting from a sudden change in the experienced noise level. A noise induced threshold shift is a temporary or permanent reduction in hearing sensitivity, TTS, and PTS respectively, following exposure to loud noise (for example commonly experienced by humans as a temporarily reduced hearing after a loud concert). The level of injury depends on both the intensity and duration of noise exposure. Small amounts of TTS will disappear in a matter of minutes, extending to hours or even days for very large TTS. At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of PTS. An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of generating a PTS (NOAA, 2018). Behavioural reaction on the other hand is linked to the instantaneous change in sound level, causing a reaction, such as avoidance. For fish, TTS threshold criteria is used alongside a physical injury threshold criteria. For larvae and eggs, only the injury criteria is considered.

In order to limit the impact of the activities, noise emission mitigation measures were considered. The effectiveness of the mitigation system type: "Single Big Bubble Curtain (BBC)" and "Double Big Bubble Curtain (DBBC)" were considered. The mitigation effect of such systems, based on available literature, was applied to the calculation of impact ranges. It should be noted, that this does not set a requirement for using a BBC or DBBC system in the actual installation, rather sets a conservative requirement for the emitted noise. During final foundation design, specific mitigation systems must be considered such that the impact ranges in this report are not exceeded.

Underwater sound propagation modelling was carried out in dBSea 2.3.4, using a 3D acoustic environmental model, implementing best available information for bathymetry, seabed sediment composition, water column salinity, temperature, and sound speed profile. For this prognosis, worst case hydrographic conditions, represented by historical data for the month of March, was used. Sound propagation was calculated in a 50 x 0.5 m range-depth grid in 45 directions from each source (8° resolution).

Marine mammals included in the prognosis are harbour porpoise (*Phocoena phocoena*) and earless seals, with threshold criteria for PTS and TTS, as well as behaviour reaction. Fish species included in the prognosis are cod and herring, as well as larvae and eggs, for which relevant TTS and injury threshold criteria were included. Stationary fish, in the context of this report, refers to fish that are not expected to flee as a result of exposure to sound.

With mitigation applied, the impact ranges for each of the relevant threshold criteria, are listed in Table 1.1 for marine mammals, and in Table 1.2 for fish, larvae and eggs.

*Table 1.1: Impact ranges for marine mammal threshold criteria, with mitigation measures*

| | **Impact range for marine mammal threshold criteria** | | | | |
|---|---|---|---|---|---|
| **Position** | PTS | | TTS | | Behaviour |
| | Porpoise (VHF) | Seal (PCW) | Porpoise (VHF) | Seal (PCW) | Porpoise (VHF) |
| 4-legged jacket foundation with 4 m diameter pin piles, BBC, March | | | | | |
| 1 | < 200 m | < 200 m | < 200 m | < 200 m | 7.4 km |
| 2 | < 200 m | < 200 m | < 200 m | < 200 m | 8.7 km |
| 3 | < 200 m | < 200 m | < 200 m | < 200 m | 7.8 km |
| 4 | < 200 m | < 200 m | < 200 m | < 200 m | 8.7 km |
| 5 | < 200 m | < 200 m | < 200 m | < 200 m | 8.8 km |
| 4-legged jacket foundation with 4 m diameter pin piles, DBBC, March | | | | | |
| 1 | < 200 m | < 200 m | < 200 m | < 200 m | 5.0 km |
| 2 | < 200 m | < 200 m | < 200 m | < 200 m | 5.8 km |
| 3 | < 200 m | < 200 m | < 200 m | < 200 m | 6.3 km |
| 4 | < 200 m | < 200 m | < 200 m | < 200 m | 6.6 km |
| 5 | < 200 m | < 200 m | < 200 m | < 200 m | 6.4 km |

For the worst case position, the PTS and TTS impact ranges for both seals and harbour porpoise are up to 200 m, regardless of mitigation system. Behaviour threshold criteria for harbour porpoise is up to 8.8 km with BBC mitigation effect and 6.6 km for DBBC mitigation effect.

*Table 1.2: Impact range for fish threshold criteria, with mitigation measures.*

| Position | Impact range for fish threshold criteria | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Injury ($r_{injury}$) | | | | | TTS ($r_{TTS}$) | | | |
| | Stationary | Juvenile Cod | Adult Cod | Herring | Larvae and eggs | Stationary | Juvenile Cod | Adult Cod | Herring |
| 4-legged jacket foundation with 4 m diameter pin piles, BBC, March | | | | | | | | | |
| 1 | 1.0 km | < 200 m | < 200 m | < 200 m | 625 m | 7.8 km | 1.45 km | < 200 m | < 200 m |
| 2 | 1.55 km | < 200 m | < 200 m | < 200 m | 1.05 km | 14.4 km | 5.3 km | 1.55 km | 1.05 km |
| 3 | 1.55 km | < 200 m | < 200 m | < 200 m | 1.05 km | 15.3 km | 6.2 km | 1.8 km | 1.2 km |
| 4 | 1.8 km | < 200 m | < 200 m | < 200 m | 1.3 km | 21.8 km | 11.1 km | 3.95 km | 3.0 km |
| 5 | 1.4 km | < 200 m | < 200 m | < 200 m | 750 m | 17.3 km | 7.3 km | 1.85 km | 1.15 km |
| 4-legged jacket foundation with 4 m diameter pin piles, DBBC, March | | | | | | | | | |
| 1 | 650 m | < 200 m | < 200 m | < 200 m | 450 m | 5300 m | 525 m | < 200 m | < 200 m |
| 2 | 1.05 km | < 200 m | < 200 m | < 200 m | 625 m | 11.6 km | 3.1 km | 325 m | < 200 m |
| 3 | 1.05 km | < 200 m | < 200 m | < 200 m | 600 m | 11.4 km | 3.25 km | 325 m | < 200 m |
| 4 | 1.3 km | < 200 m | < 200 m | < 200 m | 750 m | 16.4 km | 5.6 km | 1.1 km | 650 m |
| 5 | 775 m | < 200 m | < 200 m | < 200 m | 525 m | 11.9 km | 3.15 km | < 200 m | < 200 m |

For fish, TTS impact ranges extend up to 21.8 km and 16.4 km for jacket foundation with BBC and DBBC mitigation effect, respectively. The impact range is largest for the slowest moving fish (stationary fish being the slowest), whereas faster moving fish have significantly shorter impact range. For herring, TTS impact ranges are therefore, 3 km and 575 m for jacket foundation with BBC and DBBC mitigation effect, respectively. Injury ranges for fish follow the same pattern, with up to 1.8 km and 1.3 km for the stationary fish for jacket foundations with BBC and DBBC mitigation effect respectively and below 200 m for cod and herring regardless of mitigation effect. For larvae and eggs, injury ranges up to 1.3 km and 750 m are calculated for with BBC and DBBC mitigation effect, respectively.

Impact range for PTS, TTS and injury 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. For marine mammals, fleeing behaviour is included. For fish both fleeing behaviour and stationary behaviour is included. Larvae and eggs are considered stationary only.

Impact range for behaviour, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike. For pile strikes at less than 100% hammer energy, such as during soft start and ramp up, the distance is shorter.

## Underwater noise during operation

Underwater noise during operation was evaluated, based on available literature. A review by Tougaard et. al (2020) was examined, and the proposed trend for underwater noise emission as a function of wind turbine size was used to estimate impact ranges for marine mammals and fish. Due to limitations in the available empirical data, caution is however warranted. In a realistic worst case evaluation, the behaviour impact range, as well as PTS and TTS effects are all expected to be below 100 m from any individual turbine within the operational offshore wind farm.

# List of abbreviations

| Full name | Abbreviation | Symbol |
|---|---|---|
| Sound Exposure Level | SEL | $L_{E,p}$ |
| Cumulative Sound Exposure Level | $SEL_{cum,t}$ | $L_{E,cum,t}$ |
| Sound Exposure Level - single pile strike | $SEL_{SS}$ | $L_{E100}$ |
| Sound Pressure Level | SPL | $L_p$ |
| Source Level at 1 m | SL | $L_S$ |
| Sound exposure source level at 1 m | ESL | $L_{S,E}$ |
| Permanent Threshold Shift | PTS | |
| Temporary Threshold Shift | TTS | |
| National Oceanographic and Atmospheric Administration | NOAA | |
| Offshore Wind farm | OWF | |
| Low frequency | LF | |
| High frequency | HF | |
| Very High frequency | VHF | |
| Phocid Pinniped | PCW | |
| Big Bubble Curtain | BBC | |
| Double Big Bubble Curtain | DBBC | |
| Hydro Sound Damper | HSD | |
| IHC Noise Mitigation Screen | IHC-NMS | |
| World Ocean Atlas 2023 | WOA23 | |
| Sound Exposure Propagation loss | EPL | |
| National Marine Fisheries Service | NMFS | |
| Wind Turbine Generators | WTG | |
| Maximum-over-depth | MOD | |

# 1. Introduction and objectives

NIRAS has been tasked by Deep Wind Offshore with undertaking underwater noise prognosis and ambient underwater noise description for the construction and operation of the Olof Skötkonung offshore wind farm (OWF). Such activities produce underwater noise, potentially capable of disturbing and/or harming marine fauna.

The objective of this report is to provide an ambient underwater noise description and an underwater noise prognosis covering relevant activities during construction of the OWF, and for the wind farm during operation, and their potential impact on relevant marine mammal and fish species.

# 2. Project description

Olof Skötkonung OWF is located in the Bothnian Sea, approximately 53 km northeast from the city Gävle. The project area (Figure 2.1) is 482 km$^2$, and is located 34 km west from the Finland-Sweden maritime border.

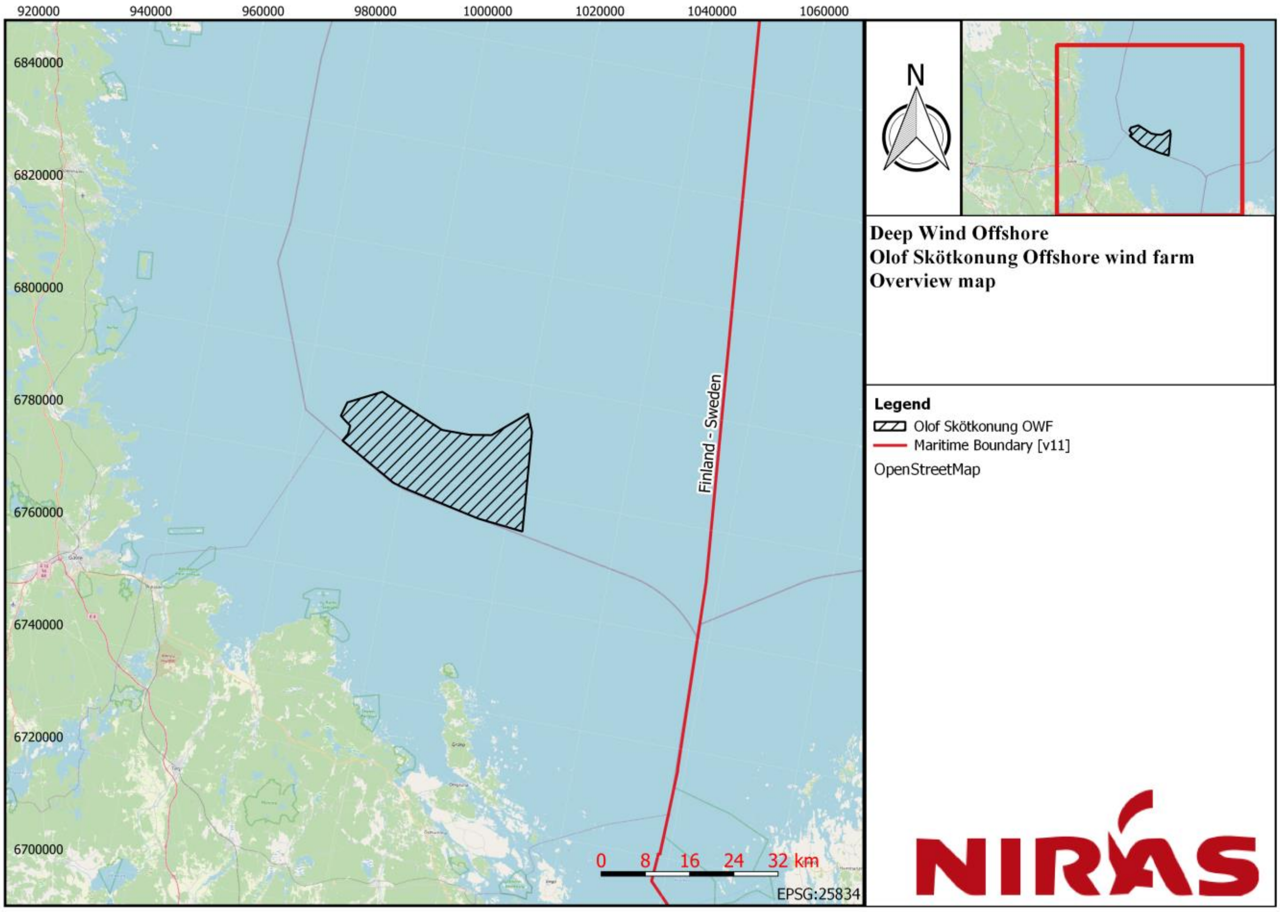



*Figure 2.1: Overview of the planned Olof Skötkonung OWF project area.*

## 2.1. Description of Activities

Underwater noise emission is expected to occur during geophysical and geotechnical surveys, construction, and operation of the OWF. This report however only concerns that of construction and operation.

### 2.1.1. Construction of wind farm

The project includes up to 70 20MW wind turbine generators (WTG) and up to 2 offshore platforms (sub station) within the project area shown in Figure 2.1.

Activities during construction of the wind farm, includes installation and support vessels, foundation handling and installation.

The most common foundation types used for WTGs and substations include monopiles and jacket foundations. Floating foundations are still an emerging technology under rapid development. In Figure 2.2, the different foundation types are illustrated along with their suitability for different depths. Other foundation types, such as gravity based foundations (GBF) and suction bucket are less common, however the underwater noise emission from these foundation types is limited. From a worst-case underwater noise emission perspective, monopile, jacket and floating foundations are considered relevant. A brief description of these foundation types are provided below.

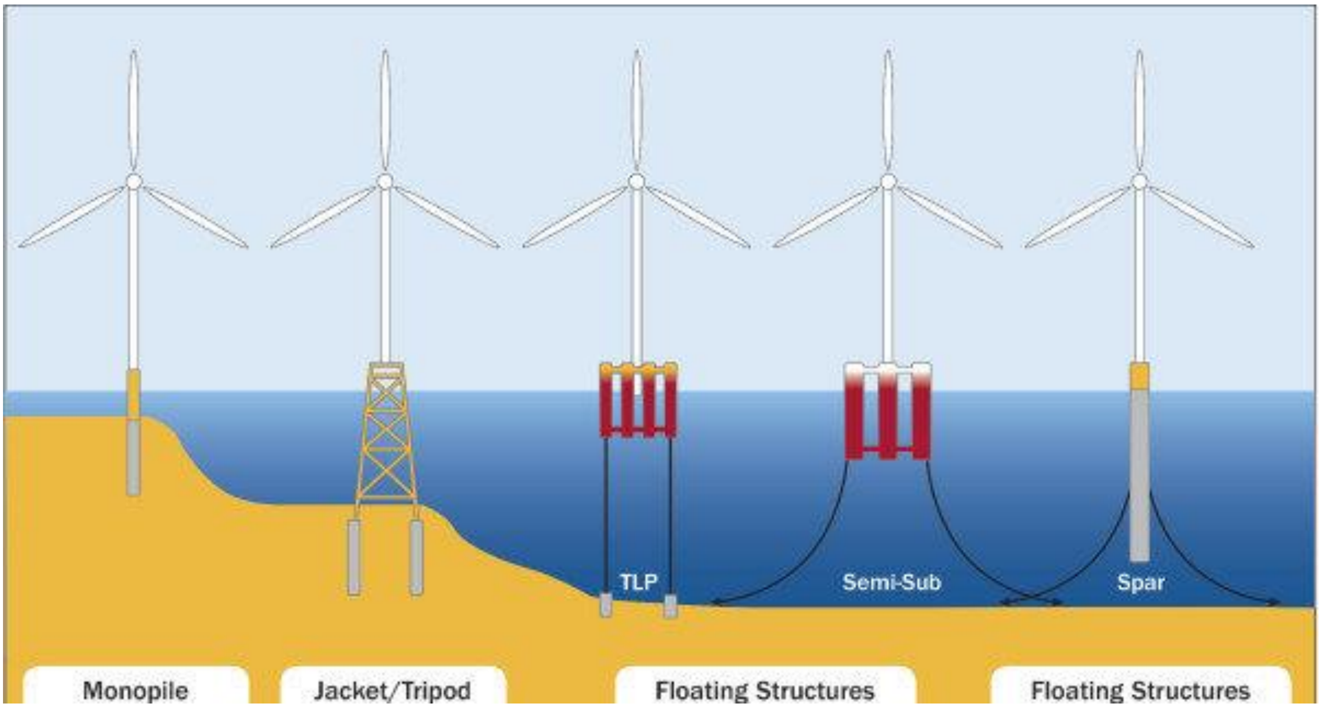



*Figure 2.2: Illustration of foundation types and suitability in different water depths (Bailey, et al., 2014).*

Steel monopile foundations are hollow cylindrical steel structures that are driven into the seabed using an impact pile driving hammer. Jacket foundations, on the other hand, are installed by impact pile driving of a number of pin piles securing each leg of the jacket steel structure. Of the two, the monopiles have significantly larger pile diameter, however more pin piles are required per jacket foundation; one or more piles per leg of the jacket structure, typically with 3 or 4 legs.

Installation of monopile foundations therefore typically requires a larger hammer and more force, and as a result, causes higher underwater noise emission than a smaller pin pile for a jacket foundation. Due to the complex steel structure of the jacket foundation, the emitted noise from pin pile installation is however likely to be more high frequent in nature.

Additionally, the same mitigation measures used for monopiles might not be suitable for jacket structures. It is therefore not a guarantee that the larger pile diameter results in the largest impact. Jacket foundations also have a larger number of piles per foundation and therefore has a longer installation time.

Gravitation and suction bucket foundations are the foundation types with the lowest underwater noise emissions, and are considered negligible from an underwater noise impact perspective. These options are not considered further in this prognosis.

Floating foundation is an emerging foundation type, typically suited for projects where the water depth prevents the use of conventional methods. As an emerging foundation type, different concepts are still being tested. The general concept is that the turbine is mounted on a floating steel frame, which is anchored to the seabed through a number of anchor lines. Each anchor line would then be securely fastened in the seabed using one or more anchor piles, or gravitation anchors. Since floating foundation types are still largely untested, little data is available on pile sizes and the number of piles to be used per anchor line, however it is expected that pile size and number of piles is inversely proportional. So the more anchor piles used per anchor line, the smaller each pile would be. It is not expected that the anchor pile diameter in any case would exceed that of a corresponding pin pile in a jacket foundation. Installation in deeper waters would also typically imply that the pile does not cover the entire water column, but both pile and hammer is submerged. Mitigation system effectiveness is also unknown, as traditional methods such as bubble curtains have not been tested at depths beyond several tens of meters.

Foundation handling/positioning is typically considered a low-noise activity compared to the installation of the foundation, especially if impact pile driving is required. Noise from installation and service vessels is also expected to occur, however only considered of relevance if pile driving activities are absent.

### 2.1.2. Operation of wind farm

During the operation of an OWF, underwater noise emission occurs as a result of various sources, most notably vibrations when blades pass the tower, noise from gearboxes, as well as the movement of support and maintenance vessels.

# 3. Prognosis methodology

The underwater noise prognosis aims to determine conservative impact ranges for underwater noise from construction and operation, based on best-available knowledge for project specific parameters and local environmental conditions. The prognosis also considers and describes uncertainties related to the prognosis, based on the current project stage and best available information.

The project is located in Sweden, where there are currently no guidelines for emission of underwater noise. Therefore, the prognosis is based on best available scientific knowledge.

A general set of underwater acoustic definitions used throughout the report are provided in chapter 4, while prognosis threshold criteria, are presented in chapter 5.

The sound propagation model, including a description of the environmental acoustic model used in the prognosis, is described in chapter 6.

This report includes the following:

1. Ambient underwater noise study in the project area (chapter 7).
2. Underwater noise prognosis for construction, using numerical sound propagation modelling of pile driving (chapter 8) including:
   a. Realistic worst case sound propagation for the unmitigated pile strikes.
   b. Underwater noise contour maps, illustrating impact distance and affected areas for relevant threshold criteria for mitigated pile driving.
   c. Numerical results showing detailed impact ranges for mitigated pile driving.
3. Underwater noise evaluation for the wind farm in operation, including underwater noise from wind turbines and service vessels (chapter 9).

# 4. Definitions

Acoustic metrics and relevant terms used in the report are defined in this chapter. Terminology generally follows ISO standard 18405 (DS/ISO 18405, 2017).

## 4.1. Sound Pressure Level

The Sound Pressure Level (SPL), $L_p$, is used to describe the noise level. The definition for SPL is shown in Equation *1* (Erbe, 2011):

$$L_p = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{T}\right)\int_0^T p(t)^2}\right) \quad [\text{dB re. } 1\mu\text{Pa}] \qquad \text{Equation 1}$$

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. $L_p$ is the average unweighted SPL over a measured period of time.

For ambient underwater noise and for operational underwater noise, $L_p$ is the preferred metric.

In order to evaluate the behavioural response of the marine mammal a time window is needed. Often, a fixed time window of 125 ms. is used due to the integration time of the ear of mammals (Tougaard & Beedholm, 2018). The metric is then referred to as $L_{p,125ms}$ and the definition is shown in Equation *2* (Tougaard, 2021).

$$L_{p,125ms} = L_{E,p} - 10 * \log_{10}(0.125) = L_{E,p} + 9\text{ dB} \quad [\text{dB re. } 1\mu\text{Pa}] \qquad \text{Equation 2}$$

Where $L_{E,p}$is the sound exposure level, which are explained in the next section.

## 4.2. Sound Exposure Level

The Sound Exposure Level (SEL), $L_{E,p}$, 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 start to 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 *3*.

$$L_{E,p} = 10 * \log_{10}\left(\frac{1}{T_0 p_0^2}\int_0^T p^2(t)\right) \quad [\text{dB re. } 1\mu\text{Pa}^2\text{s}] \qquad \text{Equation 3}$$

Where $T_0$ is 1 second, 0 is the starting time and $T$ is end time of the noise event, $p$ is the pressure, and $p_0$ is the reference sound pressure which is $1\ \mu Pa$.

The relationship between SPL, Equation *1*, and SEL, Equation *3*, is given by Equation *4* (Erbe, 2011).

$$L_{E,p} = L_p + 10 * \log_{10}(T) \qquad \text{Equation 4}$$

When SEL is used to describe the sum of noise from more than a single event/pulse, the term Cumulative SEL, $(SEL_{cum,t})$, $L_{E,cum,t}$, is used, while the SEL for a single event/pulse, is the single-strike SEL ($SEL_{SS}$), $L_{E100}$. The $SEL_{SS}$ is calculated on the base of 100% pulse energy over the pulse duration.

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. SEL is therefore a commonly used metric to assess the risk of hearing impairment as a result of noisy activities (Martin, et al., 2019).

## 4.3. Cumulative Sound Exposure level

In the assessment of auditory impact on marine mammals, Temporary Threshold Shift (TTS), and Permanent Threshold Shift (PTS) criteria are based on received cumulative SEL ($L_{E,cum,t}$) as a result of an underwater noise emitting activity. For fish, TTS and injury criteria are used, also based on $L_{E,cum,t}$.

For a stationary source, such as installation of a foundation, the installation procedure, as well as the swim speed for marine mammals and fish, must be included. A method for implementing such conditions in the calculation of $SEL_{cum,t}$ has been proposed by (Energistyrelsen, 2022), for the Danish guidelines for pile driving activities, as given by Equation *5*. The duration is fixed to 24 hour to represent the daily cumulative SEL, $L_{E,cum,24h}$. If multiple foundations are installed in the same 24 hour window, all must be included in the calculation.

$$L_{E,cum,24h} = 10 * \log_{10}\left(\sum_{i=1}^{N} \frac{S_i}{100\%} * 10^{\left(\frac{L_{S,E} - X*\log_{10}(r_0+v_f*t_i) - A*(r_0+v_f*t_i)}{10}\right)}\right) \qquad \text{Equation 5}$$

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.
- $L_{S,E}$ is the sound exposure source level at 1 m distance at 100% hammer energy.
- $X$ and $A$ describe the sound exposure propagation losses (EPL) for the specific project site.
- $r_0$ is the marine mammal or fish distance to source at the onset of piling.
- $v_f$ is the swim speed of the marine mammal or fish, swimming directly away from the noise source.
- $t_i$ is the time difference between onset of piling, and the $i^{th}$ strike.

The pile driving parameters related to the source level, hammer energy, number of strikes and time interval between each strike should be based on realistic worst-case assumptions. For projects in final design phase, pile-specific drivability analysis is preferred. 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 advanced sound propagation modelling, in which all relevant site-specific environmental parameters are considered.

## 4.4. Source level

Two representations for the acoustic output of pile driving are used in this report, namely Source Level (SL), $L_S$, and the sound exposure source level (ESL), $L_{S,E}$.

SL is defined for a continuous source as the $SPL_{rms}$ at a distance of 1 m from the source with a reference value of $1\ \mu Pa \cdot m$. The metric is used primarily for non-impulsive source types, such as vessels and operational noise from turbines.

ESL is used to describe a transient sound source and is defined as the $SEL$ at a distance of 1 m from the source with a reference value of $1\ \mu Pa^2\ m^2\ s$. This is the standard metric used to describe the source level of impact pile driving activities, as well as a number of geophysical equipment types.

## 4.5. Frequency weighting functions

In underwater noise assessments, frequency weighting is often used to reflect the underwater noise impact more accurately on specific marine mammals.

Humans 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 *6* (NOAA, 2018).

$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right)\ [dB] \qquad \text{Equation 6}$$

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.
- $\mathbf{f_1}$ is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [kHz]
- $\mathbf{f_2}$ is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [kHz]
- **C** is the function gain [dB].

For an illustration of the parameters see Figure 4.1.

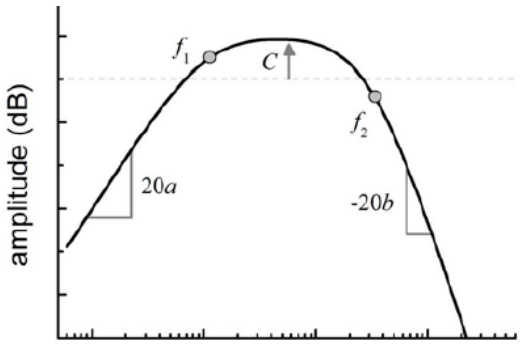



*Figure 4.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).*

Marine mammals are divided into four hearing groups, in regard 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 Carnivores in Water (**PCW**) (NOAA, 2018; Southall, et al., 2019). The parameters in Equation *6* are defined for the hearing groups and the values are presented in Table 4.1.

*Table 4.1: Parameters for the weighting function for the relevant hearing groups (NOAA, 2018).*

| Hearing Group | a | b | $f_1$ [kHz] | $f_2$ [kHz] | C [dB] |
|---|---|---|---|---|---|
| Low frequency (LF) Cetaceans | 1.0 | 2 | 0.2 | 19 | 0.13 |
| High frequency (HF) Cetaceans | 1.6 | 2 | 8.8 | 110 | 1.20 |
| Very high frequency (VHF) Cetaceans | 1.8 | 2 | 12 | 140 | 1.36 |
| Phocid Carnivores in Water (PCW) | 1.0 | 2 | 1.9 | 30 | 0.75 |

The weighting function amplitude for the four hearing groups is achieved by inserting the values from Table 4.1 into Equation 6. The resulting spectra for the four hearing groups are shown in Figure 4.2.

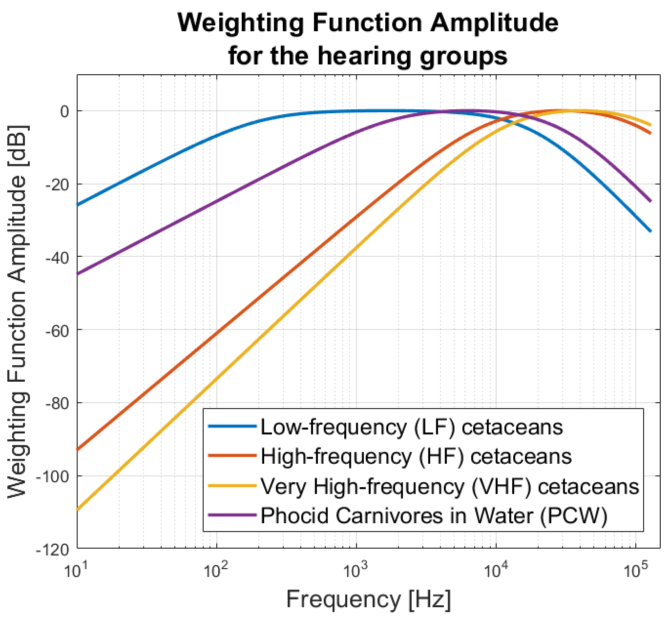



*Figure 4.2: The weighting functions for the different hearing groups.*

For this project, relevant species include seal (classified as a Phocid Carnivores in Water (PCW)), and harbour porpoise (classified as a Very High Frequency Cetacean (VHF)). Frequency weighting functions are not used for fish.

# 5. Underwater Noise Threshold Criteria

Guidance or threshold criteria for underwater noise emission during construction of OWFs (pile driving) have been developed by several different countries, such as Denmark and Germany, however not in Sweden, where underwater conditions are set on a project-by-project basis. Furthermore, regulation and conditions typically concern marine mammals, and not fish, and do not include any threshold criteria for operational noise.

Since Sweden does not have guidelines or threshold criteria for the emission of underwater noise, best available scientific knowledge from (NOAA, 2018), (Tougaard, 2021), (Energistyrelsen, 2022) is used in this project.

Section 5.1 presents the threshold criteria and swim speeds for fish, utilized in the underwater noise prognosis for impulsive noise sources. Threshold criteria for non-impulsive noise sources for fish are not scientifically established for the relevant fish species. In section 5.2, corresponding values are provided for marine mammals for both impulsive and non-impulsive noise sources.

## 5.1. Threshold criteria for fish

Assessment of the noise impact on fish, larvae and eggs are all based on unweighted threshold levels using the metric $\mathrm{L}_{\mathrm{E,cum,24h}}$, defined in section 4.3 for stationary sources. The criteria and swim speed for the different fish species are adopted from (Andersson, et al., 2016) and (Popper, et al., 2014). Modelling also includes calculations assuming stationary, non-fleeing fish.

*Table 5.1: Threshold criteria for fish. TTS and injury criteria are unweighted (Andersson, et al., 2016), (Popper, et al., 2014).*

| Species | Swim speed [m/s] | Threshold criteria, $L_{E,cum,24h}$ $[dB\ re.1\ \mu Pa^2 s]$ | |
|---|---|---|---|
| | | TTS [dB] | Injury [dB] |
| Stationary (Non-fleeing fish) | 0.00 | 186 | 204 |
| Juvenile Cod | 0.38 | 186 | 204 |
| Adult Cod | 0.90 | 186 | 204 |
| Herring | 1.04 | 186 | 204 |
| Larvae and eggs | - | - | 207 |

## 5.2. Threshold criteria for marine mammals

Based on the newest scientific literature, species specific frequency weighted $\mathrm{L}_{\mathrm{E,cum,24h}}$ threshold values (NOAA, 2018), (Southall, et al., 2019) for TTS and PTS are used, Table 5.2. For avoidance behaviour, $\mathrm{L}_{\mathrm{p,125ms,VHF}} = 103\ \mathrm{dB\ re.}\,1\ \mu\mathrm{Pa}$ (Tougaard, 2021) is used for harbour porpoise.

There is a general lack of quantitative information about avoidance behaviour and impact ranges of seals exposed to pile driving noise and the few studies point in different directions. During construction of OWF in the Wash, south-east England in 2012, harbour seals abundance was significantly reduced up to 25 km from the pile driving site during unmitigated pile driving (Russell, et al., 2016). Based on the results, Russell et al. (2016) suggested that the reaction distance for seals to unmitigated pile driving was comparable to that of harbour porpoises. On the other hand, Blackwell et al. (2004) studied the reaction of ringed seals to pile driving in connection with establishment of an artificial island in the arctic and saw limited reactions to the noise. As a precautionary approach, it is conservatively assumed that seals react to underwater noise from pile driving at the same distances as harbour porpoise.

*Table 5.2: Threshold criteria for marine mammals. PTS and TTS criteria (NOAA, 2018), behaviour criteria (Tougaard, 2021) for hearing group classifications in (Southall, et al., 2019). "xx" notation refers to species specific weighted levels.*

| Species | Swim speed [m/s] | Threshold criteria $L_{E,cum,24h,xx}$ $[dB\ re.1\ \mu Pa^2 s]$ | | | | Threshold criteria $L_{p,125ms,xx}$ $[dB\ re.1\ \mu Pa]$ |
|---|---|---|---|---|---|---|
| | | PTS | | TTS | | Behaviour |
| | | Non-impulsive | impulsive | Non-impulsive | Impulsive | |
| Porpoise (VHF) | 1.5 | 173 dB | 155 dB | 153 dB | 140 dB | 103 dB |
| Seal (PCW) | 1.5 | 201 dB | 185 dB | 181 dB | 170 dB | - |

In differentiating between impulsive and non-impulsive criteria for PTS and TTS criteria, the following characterisation from (NOAA, 2018) is followed:

- Impulsive: Sounds that are typically transient, brief (duration < 1 s), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay.
- Non-impulsive: Sounds that can be broadband, narrowband, or tonal, brief, or prolonged, continuous, or intermittent, and typically do not have a high peak sound pressure with rapid rise nor decay time.

Source types which fall under the impulsive PTS/TTS criteria include impact pile driving.

For the non-impulsive PTS/TTS criteria, source types include vibratory pile driving, noise from operational wind turbines and vessel noise. The definition of impulsive vs. non-impulsive above, does not apply for the behaviour criteria, only for PTS and TTS.

# 6. Underwater Sound Propagation

The basic principles of underwater sound propagation, as a function of the environmental factors are described in this chapter, and the project specific environmental parameters used for sound propagation modelling are presented. The environmental model is used for the prognosis of underwater noise from pile driving activities. The environmental model is implemented in the underwater sound propagation software tool dBSea. While most environmental parameters are common regardless of the underwater source type, certain parameters differ; those are covered in chapter 8 for pile driving noise.

## 6.1. Environmental sound propagation model

Sound travels faster and farther in water than in air because water is denser and more efficient at transmitting sound waves. However, the aquatic environment is complex and heterogeneous, and sound propagation is influenced by a number of environmental parameters:

- Bathymetry,
- seabed sediments,
- temperature, salinity, and sound speed,
- sea surface roughness, and
- volume attenuation.

These factors can cause sound to refract, reflect, scatter, and attenuate as the sound waves propagate through water, making it challenging to predict its behaviour. These factors, and their implementation for sound propagation modelling, are described in the following sections.

#### 6.1.1. Bathymetry

The shape and composition of the seafloor plays a critical role in the propagation of sound waves through the water. The seafloor can act as a barrier or a reflector for sound waves, depending on its composition and shape. A smooth, flat seafloor can reflect sound waves back towards the surface, whereas a rough, irregular seafloor can scatter sound waves in different directions, causing them to lose intensity and become weaker over distance.

Additionally, underwater ridges, canyons, and other geological features can act as waveguides, trapping and focusing sound waves in specific depths or regions.

Overall, bathymetry affects underwater sound propagation by influencing the speed, direction, and intensity of sound waves as they travel through the water. A detailed understanding of the bathymetry is critical for predicting and modelling the nature of underwater sound propagation in a real world scenario.

If project specific high resolution bathymetry is available, this is typically preferred over publicly available databases, which tend to be of lower resolution. Project specific bathymetry however seldomly extend beyond the project boundary. To calculate impact ranges for marine mammals and fish, it is necessary for the sound propagation model to extend 40 km beyond the project boundary. Project specific bathymetry can therefore seldomly be used alone.

For projects where no high resolution bathymetry is available, or where it is limited to the project boundary, publicly available databases, such as (EMODnet, 2021), can be used. A map of the bathymetry for Europe is shown in Figure 6.1, where darker colours indicate deeper areas, and lighter colours indicate more shallow water (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).*

The bathymetry for the project area and surroundings consists of information from the sources listed in Table 6.1. A visualisation of the bathymetry model for the project area and surroundings is shown in Figure 6.2.

*Table 6.1: Bathymetry model data sources.*

| Data source | Reference |
|---|---|
| Bathymetry | EMODnet 2021 (EMODnet, 2021) . |

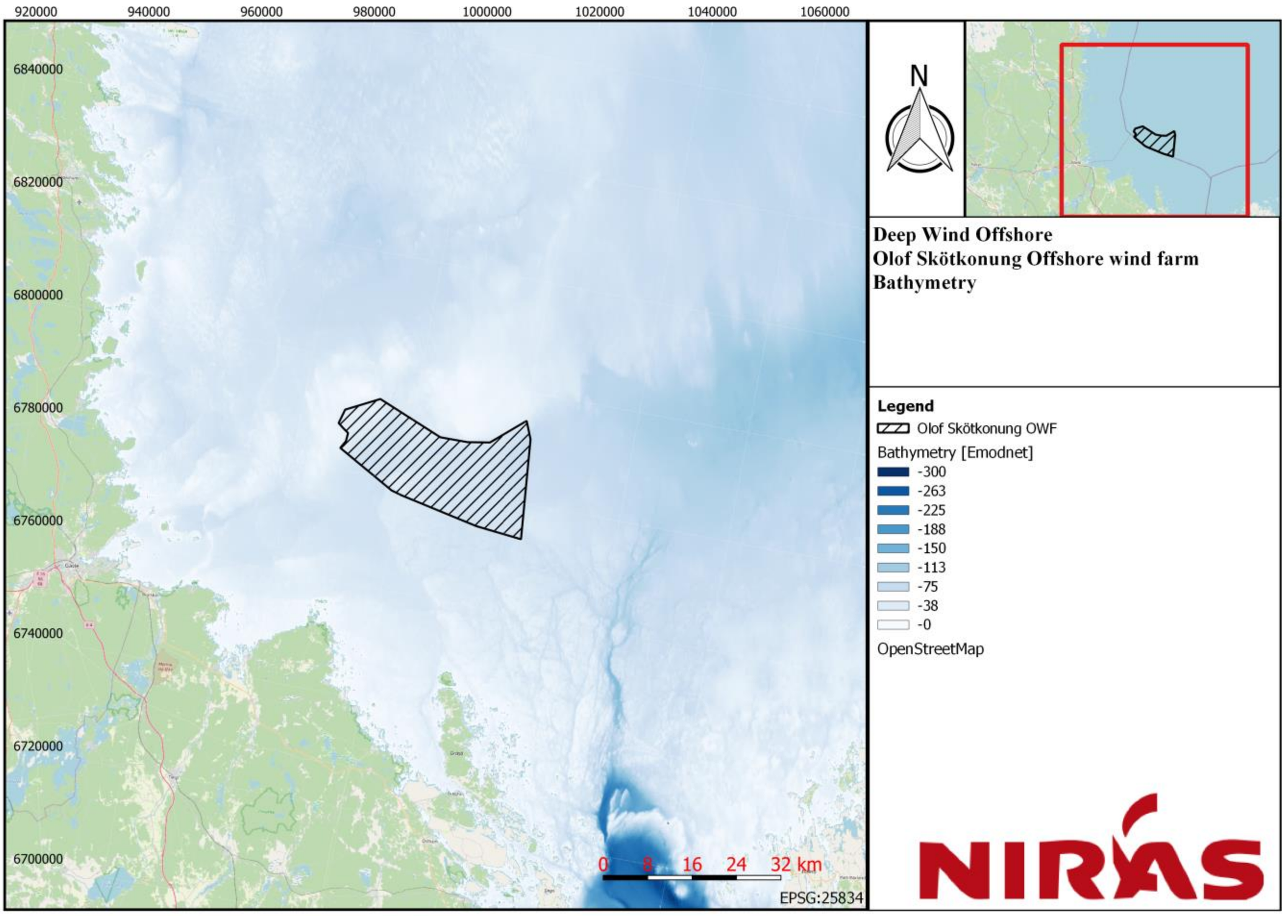



*Figure 6.2: Bathymetry for the project area and surroundings, sources as listed in Table 6.1.*

### 6.1.2. Seabed sediment

Seabed sediment layers can have a significant effect on the propagation of sound waves through the water. The acoustic properties of sediment layers are influenced by several factors, including the composition, density, porosity, and grain size distribution of the sediments. Generally, sediments with larger grain sizes and lower porosity have higher acoustic velocities and can transmit sound waves more efficiently than finer grained and more porous sediments.

The properties of sediment layers can also affect the reflection, refraction, and attenuation of sound waves. For example, a layer of fine-grained, soft sediment can absorb and scatter sound waves, causing them to lose intensity and become weaker over distance. Conversely, a layer of hard, compacted sediment can reflect sound waves, resulting in increased sound intensity in certain areas.

The thickness of sediment layers can also play a role in underwater sound propagation. Thicker sediment layers can absorb and scatter sound waves more effectively, while shallower sediment layers can reflect and refract sound waves more strongly.

The thickness and acoustic properties of each seabed layer, from seabed to bedrock, is generally obtained through site specific literature research in combination with available site-specific survey findings.

Where site specific surveys do not reveal the top layer conditions, or where the site specific information is limited to the project boundary, publicly available databases, such as the seabed substrate map from (EMODnet, 2021) (Figure 6.3) is generally used.

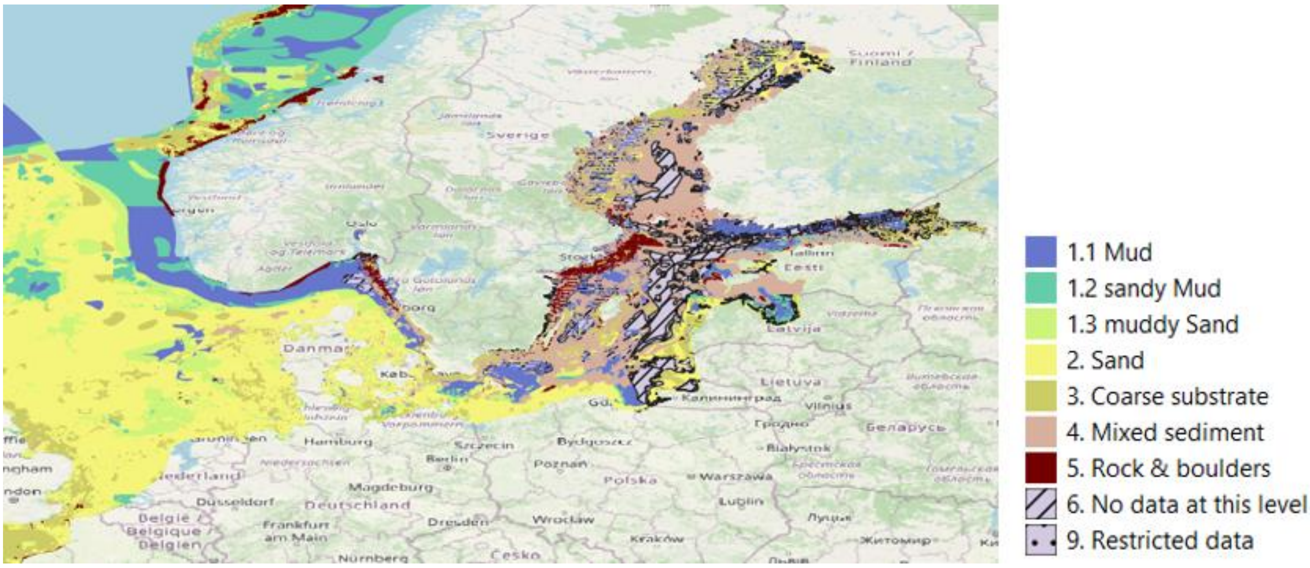



*Figure 6.3: A section of the seabed substrate map, (Folk 7) (EMODnet, 2021).*

From the available sediment data sources, a discretized and simplified version is created, whereby the layer thicknesses and sediment types are defined in a number of points. A high number of sediment points is necessary, when the variation in sediment types and thicknesses within the project area and surroundings increases.

For each point in the model, the sediment layer types are translated into geoacoustic parameters, in accordance with Table 6.2, utilizing information from (Jensen, et al., 2011; Hamilton, 1980).

*Table 6.2: Geoacoustic properties of sediment layers used in the environmental model. Sources: (Jensen, et al., 2011; Hamilton, 1980). Note, mixed sediment is based on a mix of sand, silt, and gravel. Moraine boulders is similarly a mix of primarily moraine with boulders.*

| **Sediment** | **Sound Speed [m/s]** | **Density [kg/m³]** | **Attenuation factor [dB/λ]** |
|---|---|---|---|
| Clay | 1500 | 1500 | 0.2 |
| Silt | 1575 | 1700 | 1.0 |
| Mud (clay-silt) | 1550 | 1500 | 1.0 |
| Sandy mud | 1600 | 1550 | 1.0 |
| Sand | 1650 | 1900 | 0.8 |
| Muddy sand | 1600 | 1850 | 0.8 |
| Coarse substrate | 1800 | 2000 | 0.6 |
| Gravel | 1800 | 2000 | 0.6 |
| Mixed sediment | 1700 | 1900 | 0.7 |
| Moraine | 1950 | 2100 | 0.4 |
| Moraine Boulders | 2200 | 2200 | 0.3 |
| Rock and boulders | 5000 | 2700 | 0.1 |
| Chalk | 2400 | 2000 | 0.2 |

The sediment model is constructed using available sources, see Table 6.3, and resulted in a 450 point sediment model, with topsoil types shown in Figure 6.4. Primary seabed surface layers in the project area are clay, sand, and mixed sediment. Layer thickness of the upper sediment is available in (GEO PROVIDER, 2023), and is used to inform the model. Acoustic parameters for each layer are shown in Table 6.2. As it is not feasible to create an infinitely detailed sediment model, conservative layer thickness, and sediment types are used to provide a worst-case sediment model. The data source used to inform the sediment model implementation, is shown in Figure 6.5.

*Table 6.3: Sediment model data sources.*

| **Data source** | **Reference** |
|---|---|
| Seabed substrate map | Inside OWF: (GEO PROVIDER, 2023),<br>Outside OWF: (EMODnet, 2021) |
| Sediment profile map | (GEO PROVIDER, 2023) |
| Bedrock / pre-quaternary map | (GEO PROVIDER, 2023) |
| Acoustic parameter model for sediment types | Table 6.2 |

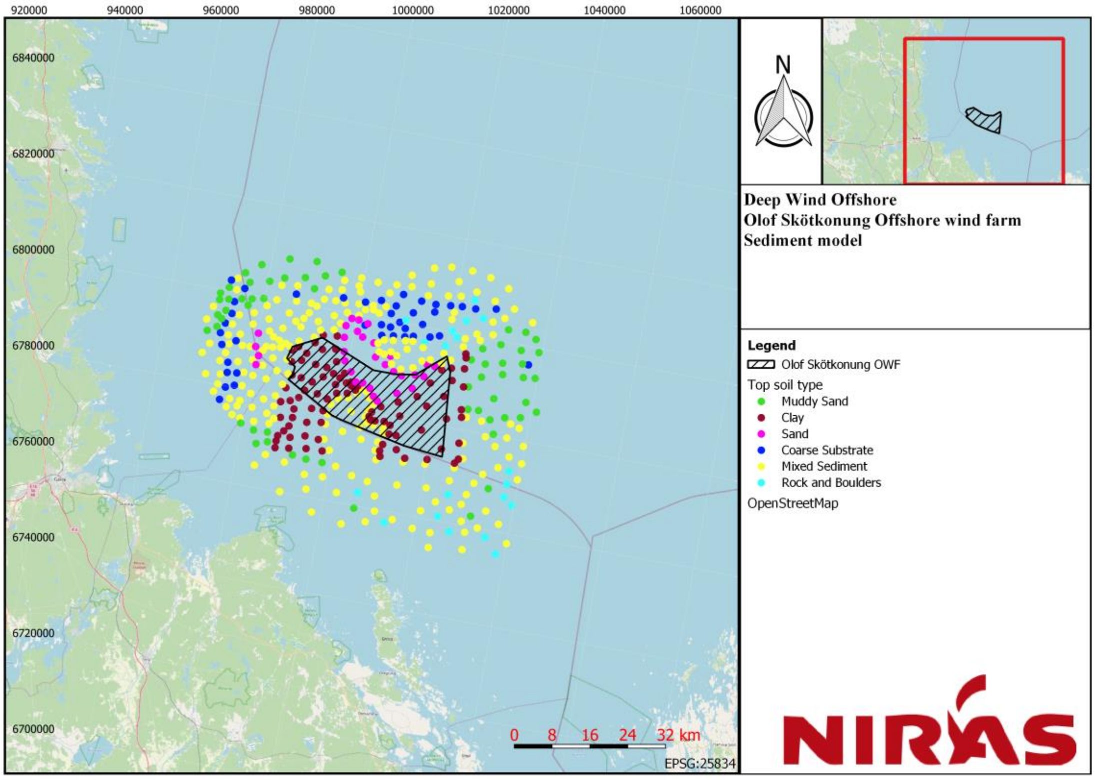



*Figure 6.4: Sediment model points and topsoil layer type.*

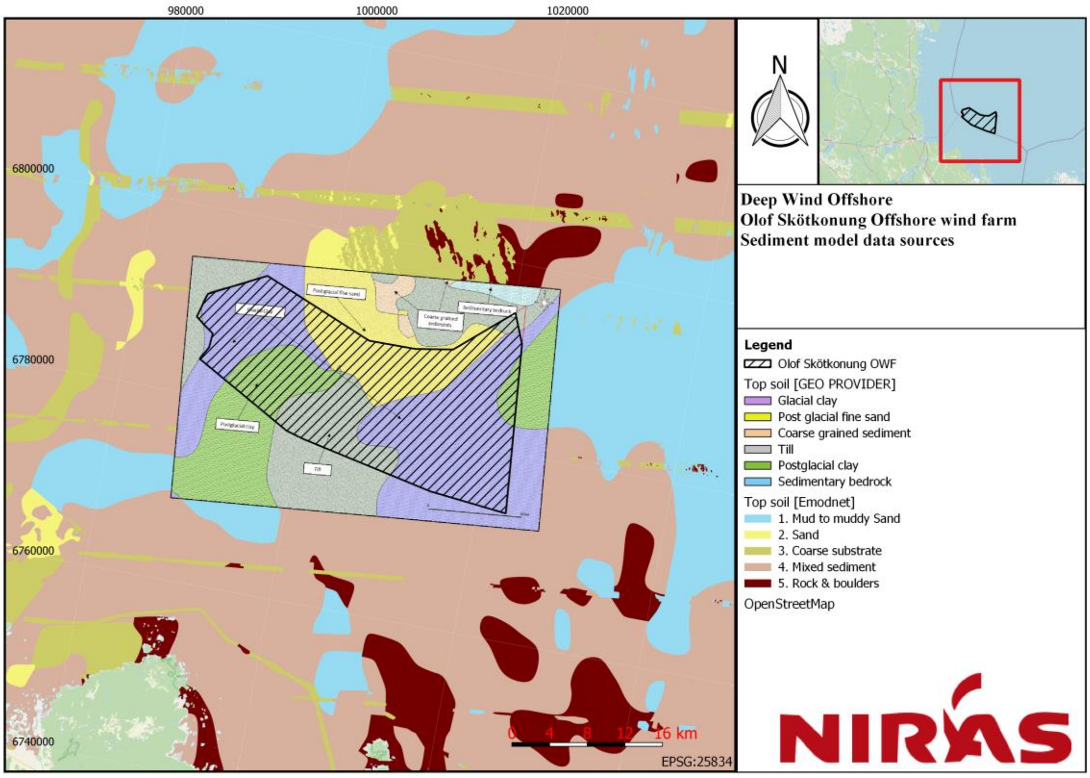



*Figure 6.5: Sediment model data source, as listed in Table 6.3.*

### 6.1.3. Temperature, salinity, and sound speed profile

The combined effects of temperature and salinity on seawater density can create complex sound speed profiles in the sea, particularly in areas with strong vertical stratification or gradients in temperature and salinity. These variations in sound speed can have important implications for underwater sound propagation.

As stated by Snell's law, Equation 7, sound waves bend toward regions of low sound speed (Jensen, et al., 2011). The implications for sound in sea water are, that sound, entering a low velocity layer in the water column, can get trapped there. This results in sound travelling far with very low propagation loss.

$$\frac{\cos(\theta)}{c} = \text{constant} \qquad \text{Equation 7}$$

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

There are three main types of sound speed profiles for seawater:

1. **Uniform sound speed profile**: In a uniform sound speed profile, the speed of sound is the same at all depths. This can occur in regions of the sea where temperature and salinity are relatively constant with depth.
2. **Upward refracting sound speed profile**: When the sound speed increases with depth, it is called an upward refracting sound speed profile. Sound waves in this type of environment can be refracted upward and away from the seabed, potentially travelling over longer distances with lower absorption losses from seabed interaction.
3. **Downward refracting sound speed profile**: When the sound speed decreases with depth, it is called a downward refracting sound speed profile. Sound waves will, in this environment, be refracted downward to a higher degree and toward the seabed, potentially causing them to lose energy and travel shorter distances.

Special cases, where a low speed region is present at a depth in between sea surface and seabed can create channels where specific ranges of frequencies can get trapped and propagate without ever reaching neither seabed nor sea surface. The potential transmission range in such a channel is significantly longer than in any of the typical three sound speed profile types listed above.

In the Bothnian Sea, underwater sound propagation varies with season, with upward refracting sound speed profiles in the coldest winter months, downward refracting sound speed profiles in spring – autumn, with the strongest effects during summer. Subsea channels with sound speed minimum within the water column can occur.

The sound speed profiles for a certain project area are calculated using Coppens equation (Coppens, 1981), based on available temperature and salinity data for the area. Data sources for the temperature and salinity profiles can be either based on empirical data, or predictive models. It is important to note, that while empirical data and predictive models can provide a historically likely scenario, they can not accurately predict the weather conditions when the project activities will occur.

For each of the sediment model points, described in section 6.1.2, the nearest available sound speed profile, as well as average temperature and salinity are extracted for the desired months. Temperature and salinity profiles for this project, were extracted from the data sources in Table 6.4, and through the NIRAS software tool "TRANSMIT", turned into sound speed profiles.

Table 6.4: Temperature, salinity, and sound speed data sources.

| Data source | Reference |
|---|---|
| Temperature | 2x2 km grid, monthly averages based on physical forecast (Copernicus, 2023) |
| Salinity | 2x2 km grid, monthly averages based on physical forecast (Copernicus, 2023) |
| Sound speed profile | Coppens equation (Coppens, 1981) implemented in NIRAS "TRANSMIT" |

The temperature and salinity change both temporally (over the year), as well as spatially. Both the timeframe and position of the activities included in sound propagation modelling must therefore be taken into account, when evaluating which sound speed profiles should be used for any given model. The project specific profiles used, are therefore described under each activity included in sound propagation modelling in chapter 8.

### 6.1.4. Sea surface roughness

Sea surface roughness, either from waves or ice cover can cause sound waves to scatter in many different directions, making it more difficult to propagate through the water. This can result in increased attenuation, backscattering and reduced range of underwater sound propagation, particularly at high frequencies.

As a precautionary approach, sound propagation modelling typically regards the sea surface as a perfect mirror (calm water), as this is also the conditions under which pile installation would be preferred. The model is therefore likely to overestimate sound propagation for any conditions where calm water is not the case.

### 6.1.5. Volume attenuation

Another parameter that has influence on especially the high frequency propagation 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 using Equation 8, from which is inferred that increasing frequency leads to increased absorption (Jensen, et al., 2011).

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4}f^2 \quad \left[\frac{\mathrm{dB}}{\mathrm{km}}\right] \qquad \text{Equation 8}$$

Where f is the frequency of the wave in kHz.

Volume attenuation is taken into account within dBSea, which is used for sound propagation modelling.

## 6.2. Software

Numerical models can be used to simulate and predict underwater sound propagation in sea water. These models involve a computer-based simulation that uses mathematical equations to describe the sound propagation as it travels through the sea. In this regard, environmental conditions such as temperature, salinity, sediment, and bathymetry must be taken into account. Different numerical models exist to treat different environmental and source specific conditions, and the choice of numerical model should always be based on the project specific environmental parameters.

NIRAS uses the software tool dBSea, which incorporates three numerical algorithms for predicting sound propagation in complex underwater environments: dBSeaRay, dBSeaPE, and dBSeaNM.

**dBSeaRay** is a ray-tracing algorithm that simulates the paths of individual sound rays as they travel through the sea, taking into account the effects of sea properties, such as temperature, salinity, and bathymetry, on sound propagation. This allows users to predict sound propagation in a wide range of ocean environments. Inherent limitations for this algorithm limit its use in shallow waters for very low frequencies below a few hundred Hz.

**dBSeaPE** is a parabolic equation algorithm that solves the parabolic wave equation to simulate sound propagation in the ocean. It is particularly useful for modelling sound propagation over long distances or in areas with complex bathymetry. It however lacks computational efficiency at higher frequencies and is primarily suited for low frequencies.

**dBSeaNM** uses the normal modes method to predict sound propagation in the ocean. This algorithm takes into account the effects of vertical variations in ocean properties, such as sound speed and density, on sound propagation. It is particularly useful for predicting sound propagation in regions with significant vertical mixing or internal waves, and is most suitable for low frequencies, up to several hundred Hz.

Depending on the local environment and source characteristics, a mix of two numerical models may provide the best result, whereby one algorithm handles the low frequencies, and another handles the high frequencies.

Typically, dBSeaNM or dBSeaPE is used for low frequencies and dBSeaRay for high frequencies with a split frequency between the two algorithms, based on $f = \frac{8 \cdot c}{d}$ [Hz], where $c$ is the speed of sound in water [m/s] and $d$ is the average bathymetry depth [m].

Output from dBSea is primarily numerical, where each modelled sound propagation radial (direction from source) is represented by the maximum-over-depth *(MOD)* sound level at each modelled range step. *MOD*, in this regard, is found by taking the maximum sound level for each range step over all modelled depths. It therefore does not represent the sound level at a specific depth, but is a more conservative measure for the highest possible exposure at every range. An example of this concept is shown in Figure 6.6, showing the sound level (x-axis) in dB over depth (y-axis), for a specific distance and direction. On the left side, the MOD is located at 1 m depth below sea-surface and is 114.2 dB, while on the right side, in another direction from the source, MOD is located at 28 m depth and is 114.6 dB. The sound levels at all other depths are ignored in the result output.

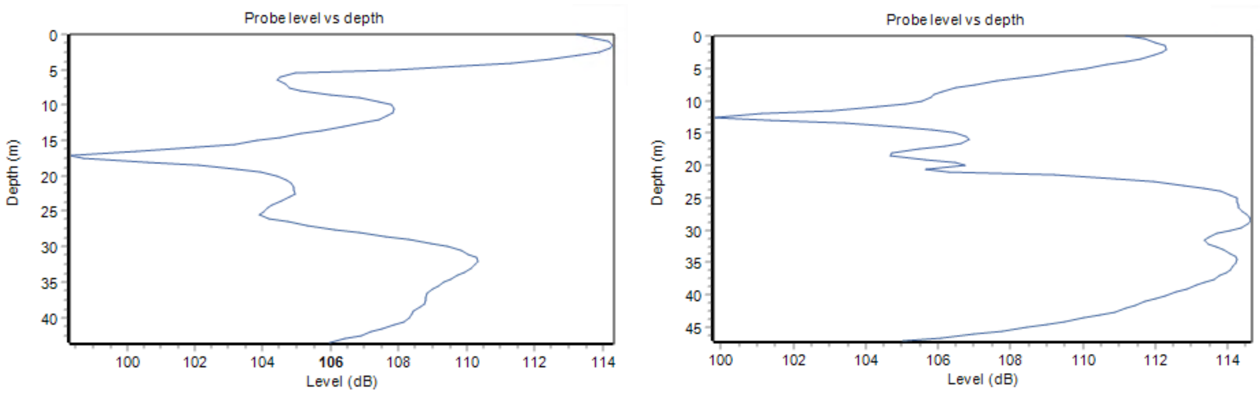



*Figure 6.6: Concept of MOD, where the maximum sound level at any depth is extracted for each distance and radial interval. Example shows an MOD value of 114.2 dB (left side) at 1 m depth, and MOD value of 114.6 dB (right side) at 28 m depth.*

Prognosis specific parameters for the dBSea setup is specific to the source types included, and is therefore described separately for the different source types in the prognosis.

# 7. Ambient Underwater Noise Study

In this chapter, the ambient noise levels in the region are examined, based on available information, and the implications are discussed.

## 7.1. Ambient noise level

No site specific measurements of ambient noise for the Olof Skötkonung OWF area were carried out. For the Bothnian Sea however, the ICES continuous underwater noise dataset (ICES, 2018), presents the underwater noise levels in the Bothnian Sea as an average of each quarter of 2018 (Q1 – Q4). The noise maps represent a simplified modelled ambient noise level consisting of underwater noise from wind speed and vessel noise (based on AIS data). Noise levels are presented for individual 1/3 octave frequency bands as the median ambient noise level ($SPL_{rms}$) over all water depths for the quarter.

The noise levels are limited to three frequency bands of 63, 125 and 500 Hz. The two one-third octave band acoustic measurements centred at 63 and 125 Hz are used as international (European Union Marine Strategy Framework Directive) indicators for underwater ambient noise levels driven by shipping activity (EC Decision 2017/848, 2017). Noise maps for the project area and surroundings are shown in Figure 7.1 - Figure 7.3, for the frequency bands 63 Hz, 125 Hz and 500 Hz respectively. In addition to the 2018 data set, the data portal also features a 2014 data set (ICES, 2014) including a modelled noise map for the frequency band 2 kHz, see Figure 7.4.

The ICES maps show that the ambient noise levels vary significantly with season, and with frequency. The levels at 63 Hz are thus higher than 125 Hz, which in turn are higher than 500 Hz. Noise levels in Q1 and Q4 are also typically higher in all frequencies, than for Q2 and Q3. The latter is a result of the hydrography, whereby the sound propagation in the Bothnian Sea during the warmer months has higher attenuation of underwater noise.

What is also visible from the maps, is that variations spatially tend to correlate with shipping traffic, illustrated in Figure 7.5. Here, the EMODnet vessel density map (EMODnet, CLS, 2022), is shown for the project area and surroundings for the months of February, May, August, and November (as representative months for Q1 – Q4).

It is clear that underwater noise from vessels in the nearby shipping lane east of the OWF area greatly influence the overall ambient noise level inside and outside the project area, as well as in the nearby Natura 2000 area.

It should be noted that the ambient noise level is only modelled for four frequency bands, making it difficult to compare the impacts on marine life, especially for species with a high frequency hearing like harbour porpoise.

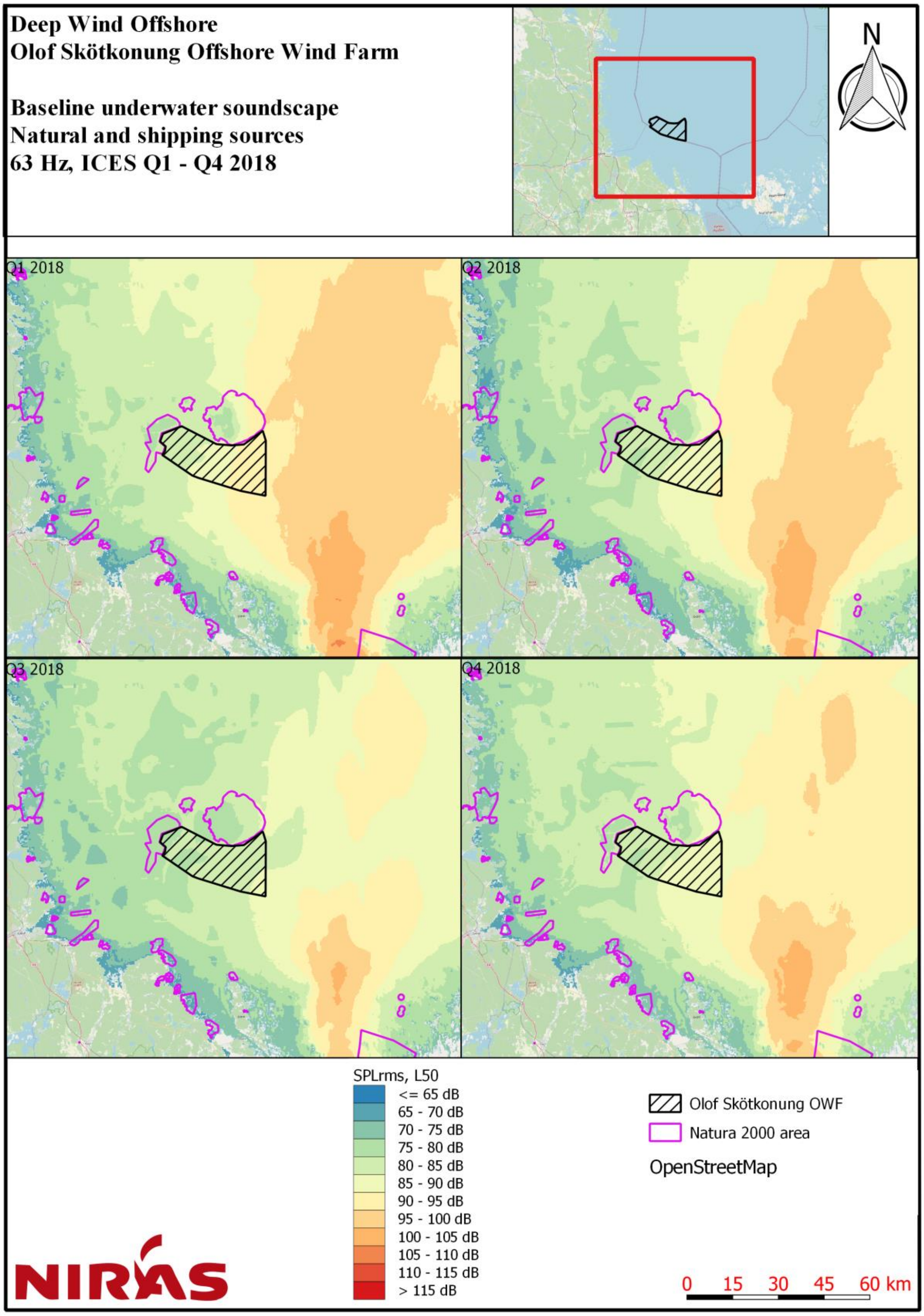



*Figure 7.1: ICES soundscape map for the OWF area and surrounding waters during Q1-Q4 2018, 50th percentile* $SPL_{rms,63Hz}$ $[dB\ re.1\mu Pa^2]$.

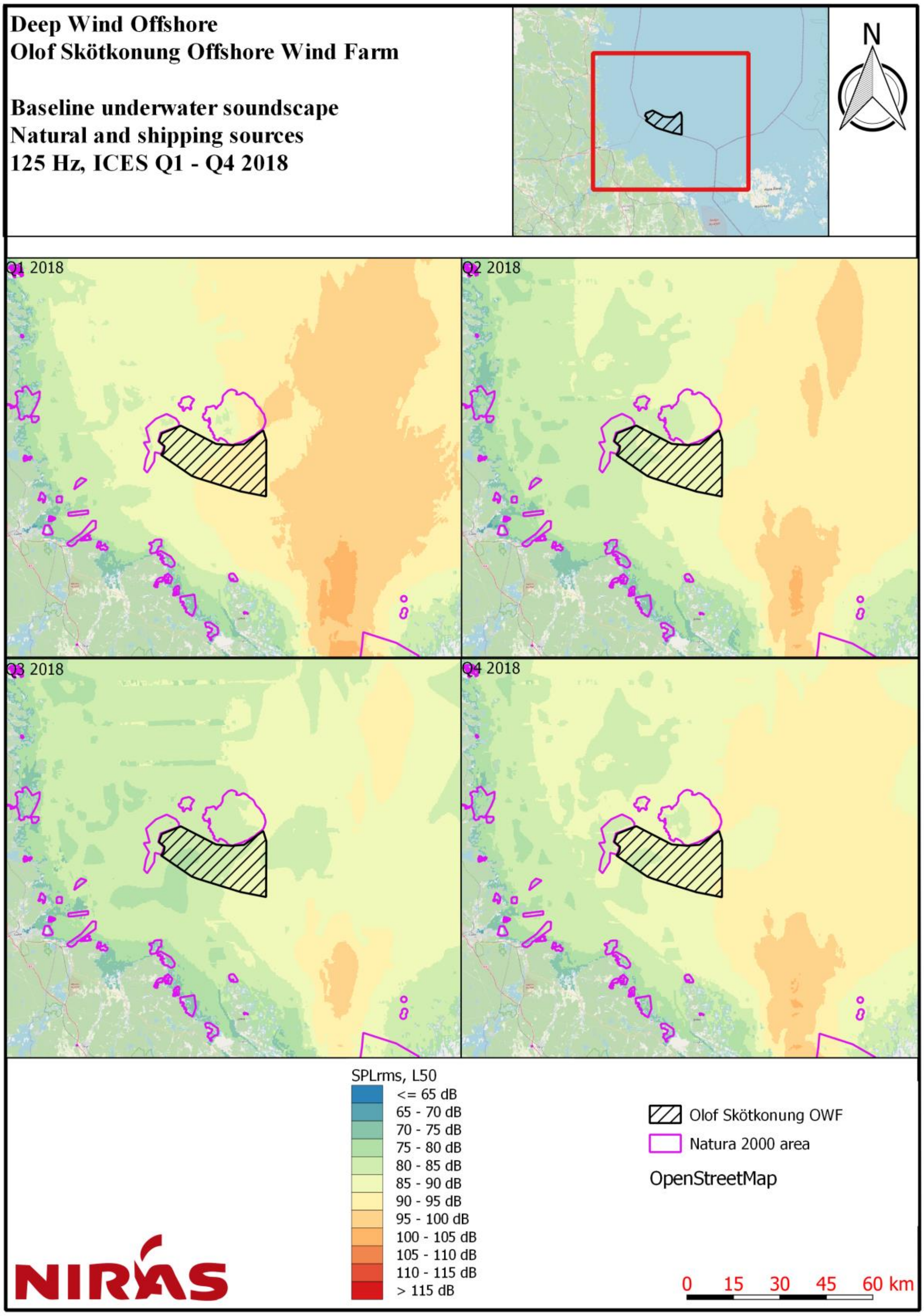



*Figure 7.2: ICES soundscape map for the OWF area and surrounding waters during Q1-Q4 2018, 50th percentile* $SPL_{rms,125Hz}$ $[dB\ re. 1\mu Pa^2]$.

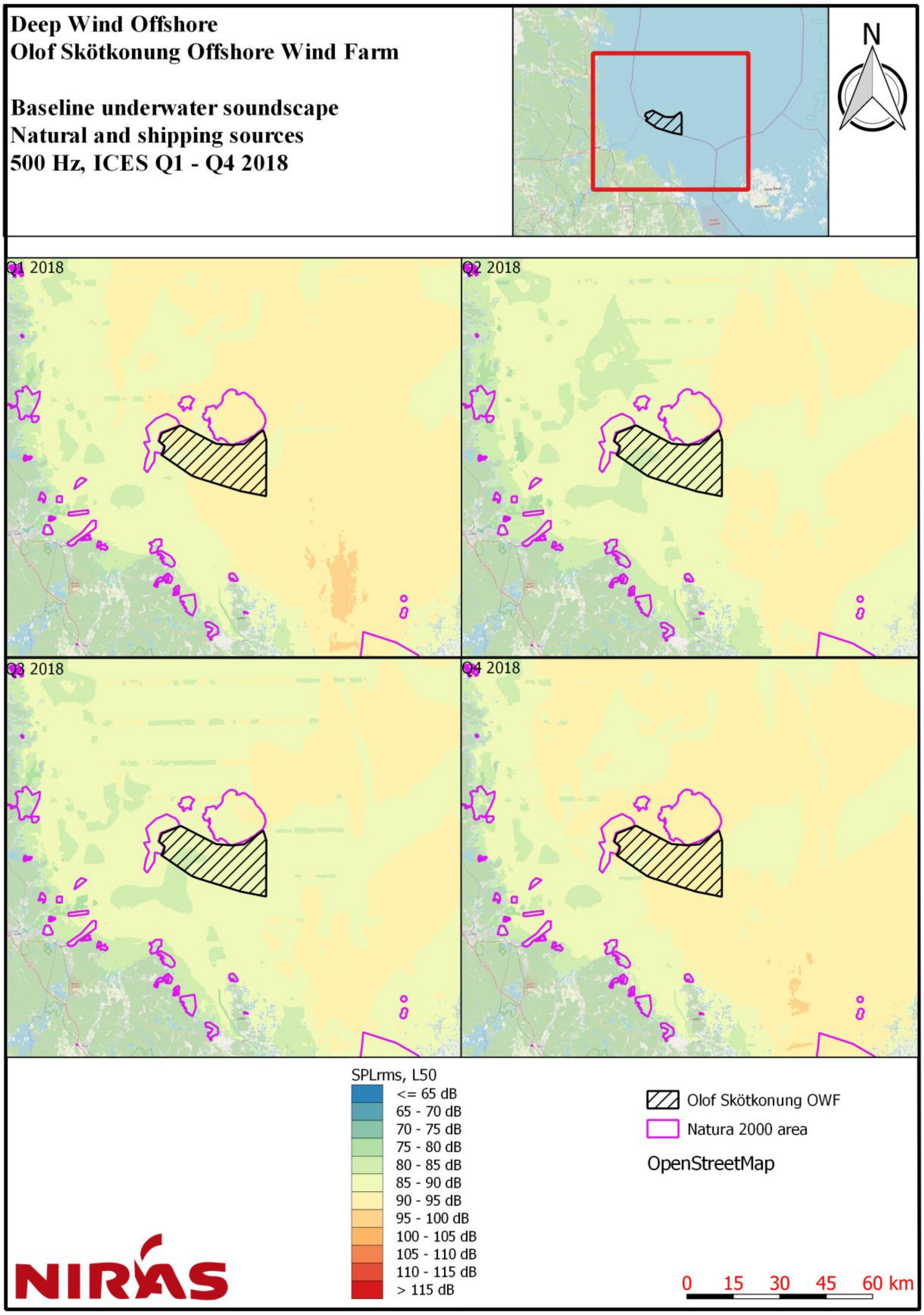



*Figure 7.3: ICES soundscape map for the OWF area and surrounding waters during Q1-Q4 2018, 50th percentile* $SPL_{rms,500Hz}$ $[dB\ re.\ 1\mu Pa^2]$.

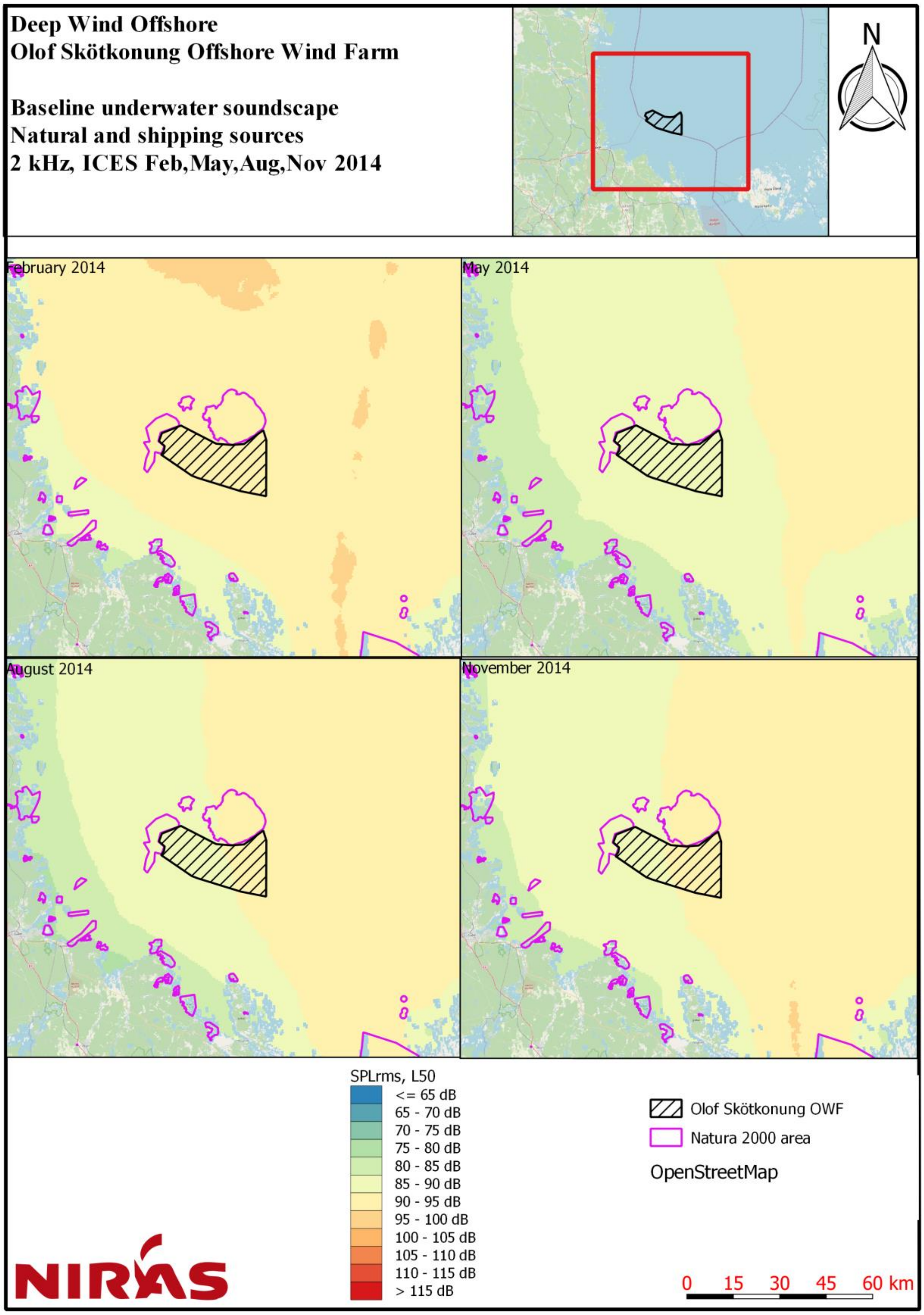



*Figure 7.4: ICES soundscape map for the OWF area and surrounding waters during Feb, May, Aug, Nov 2014, 50th percentile* $SPL_{rms,2kHz}$ $[dB\ re. 1\mu Pa^2]$.

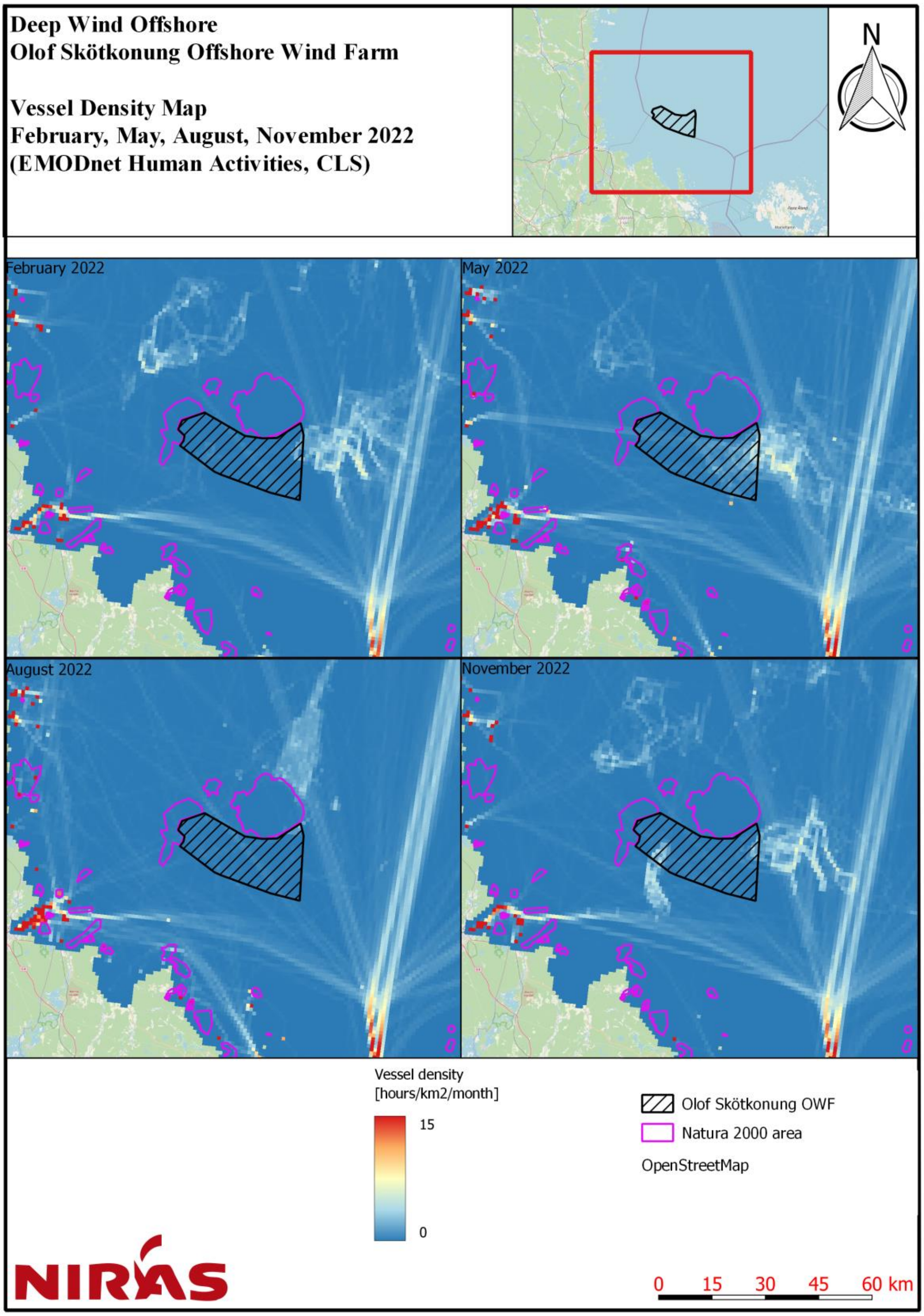



*Figure 7.5: Vessel density map from 2022, from EMODnet (EMODnet, CLS, 2022) based on AIS data from CLS.*

# 8. Underwater noise prognosis for construction phase

During the construction phase, the most significant underwater noise pressure on marine mammals and fish, is noise from pile driving, which has the potential to cause avoidance response, TTS, and PTS in marine mammals (Madsen, et al., 2006), as well as avoidance response, TTS and injury in fish (Popper, et al., 2014) (Andersson, et al., 2016).

Sound propagation modelling is undertaken for foundations individually, and while the project includes up to 70 foundations, this does not affect the prognosis. For a discussion on installation of multiple piles, either concurrently or sequentially within a 24 hour duration, see Appendix 1. For the cumulative impact from the installation of all foundations within the wind farm, this is not part of the sound propagation modelling, and is typically handled in the impact assessment for the relevant species. Underwater sound propagation modelling requires three different parts.

- A source model, charactering the noise source (pile driving), and the emission of noise into the water column (section 8.1).
- An environmental model, charactering the marine environment and its acoustic properties. The environmental model follows the project specific approach described in chapter 6, with further details provided in section 8.3.
- A sound propagation model, through which the source and environmental model is used to determine the sound propagation, following the approach in chapter 6, and with further details provided in section 8.4.

Results for the unmitigated pile driving is reported in section 8.5. Based on the outcomes of these results, mitigation measures are proposed in section 8.7, based on literature review in section 8.6. Results for the mitigated pile driving activities are provided in section 8.8.

## 8.1. Source Model

The source model represents the underwater noise emission from the pile driving activity as accurately as possible at the current project stage. The client has supplied preliminary project specific details on the realistic worst case installation scenario, see section 8.1.1. Available literature on source characteristics is reviewed in section 8.1.2, from which an appropriate conservative source model is derived, section 8.1.3.

### 8.1.1. Project specific inputs

Deep Wind Offshore has informed NIRAS, that the most likely foundation type is 4-legged jacket foundations with up to 4 m diameter pin piles.

The sound propagation modelling assumes up to 4 pin piles installed per 24 hours. For a discussion on possible implications of multiple foundations installed simultaneously, see Appendix 1. The technical specifications for the pile installation are provided in Table 8.1.

Soft start and ramp-up procedures are employed during pile driving, as the upper sediment layers are typically softer and require less energy to penetrate. It also minimizes the potential environmental impact and protect marine life. Instead of starting at full power immediately, the pile driving equipment begins with reduced energy and then gradually ramps up to full power, whereby marine mammals and fish have opportunity to increase their distance to the pile installation location before full power is applied.

Parameters for pile installation procedure, including number of pile strikes, intervals and hammer energy levels were chosen in cooperation with Deep Wind Offshore, as realistic worst-case values. It must be recognized that these parameters are not resembling any real-world empirical pile driving data, nor a pile specific drivability analysis, as the final design is still unknown.

*Table 8.1: Technical specifications and pile driving procedure for Jacket foundation with 4 pin piles. Technical parameters are based on worst-case assumptions.*

Technical specification for jacket foundation with 4 m pin piles

| | | | |
|---|---|---|---|
| Foundation type | | Jacket | |
| Impact hammer energy | | 5000 kJ | |
| Pile diameter | | 4 m | |
| Total number of strikes pr. pile | | 11100 | |
| Number of piles per foundation | | 4 | |
| Time delay between the installation of each pile | | 0 minutes | |
| Pile driving procedure | | | |
| Name | Number of strikes | % of maximum hammer energy | Time interval between strikes [s] |
| Soft start | 100 | 10 | 2 |
| Ramp-up | 500 500 500 500 | 20 40 60 80 | 2 |
| Full power | 9000 | 100 | 1.2 |

### 8.1.2. Source model methodology

The best available knowledge on the relationship between pile size and underwater sound level, comes from a report on measured sound levels from 21 OWF construction projects involving pile driving activities in the German EEZ of the North Sea and Baltic Sea between 2012 - 2019 (Bellmann, et al., 2020). The sound levels were measured at a distance of 750 m and a graphic summary of the measured sound levels as a function of pile diameter is shown in Figure 8.1. The measurements are all normalized to 750 m distance from the pile.

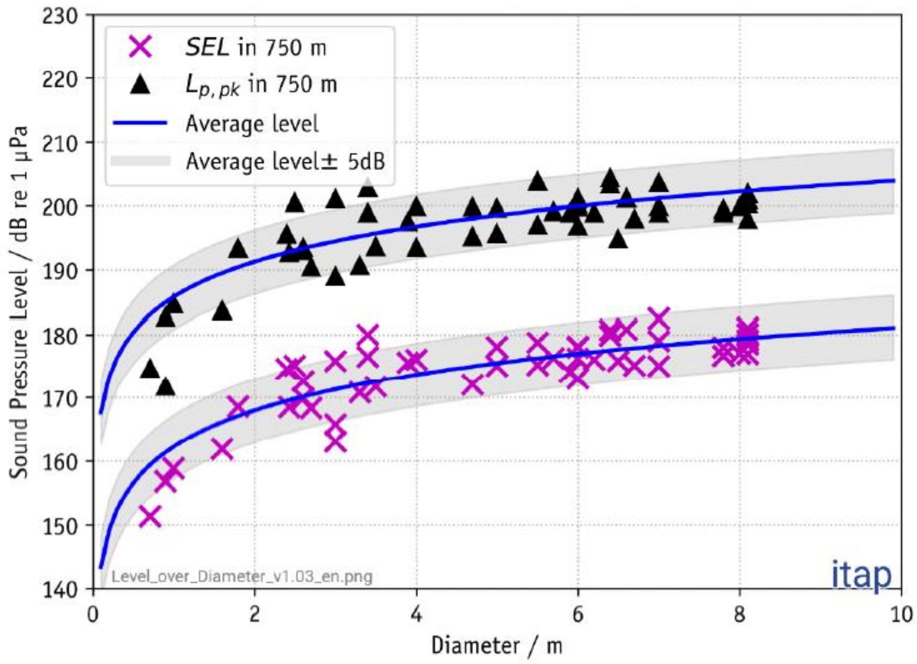



*Figure 8.1: Relationship between peak and SEL, measured at 750 m distance, and pile size (Bellmann, et al., 2020).*

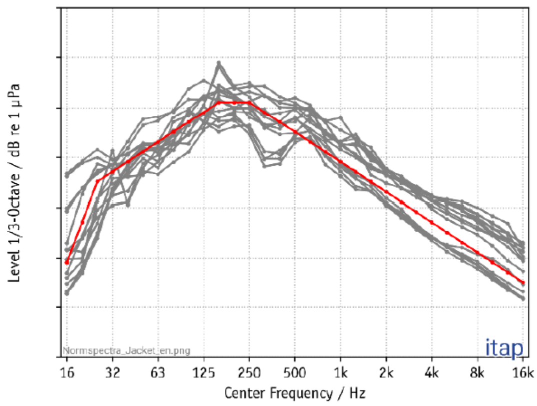
The blue curves in Figure 8.1 indicate the best fit of the measurement results. For the SEL results, this relationship between pile size and measured level is approximately $\Delta\mathrm{SEL} = 20 * \log 10\left(\frac{\mathrm{D2}}{\mathrm{D1}}\right)$ where D1 and D2 are the diameter of 2 piles, and ΔSEL is the dB difference in sound level between the two. This relationship indicates an increase of 6 dB when doubling the pile diameter.

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 in Figure 8.1. This spread gives a 95%-confidence interval of ±5 dB which is indicated by the grey shaded areas. This spread, and the parameters associated with it, are discussed further in section 8.1.4.

NIRAS' empirical source model is based partly on the relationship between pile diameter and measured sound levels derived from (Bellmann, et al., 2020), as well as from empirical data available through own and other measurements. The source model is represented by the ESL at 1 m distance from the pile. It is a back-calculated approximation using an equivalent point source that in 750 m distance follows the empirical data, and at ranges beyond this, will provide a conservative approximation. At ranges closer to the source, uncertainty of prognosis results is however increased, as the equivalent point source model cannot accurately reflect the positive and destructive interference patterns that occur. The approach of MOD modelling is however considered to provide a conservative prognosis, even at shorter ranges.

Due to the natural variations of measured frequency content, 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 area (see grey lines in Figure 8.2).

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



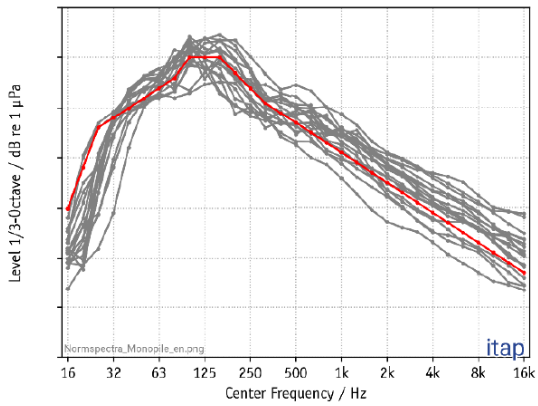




*Figure 8.2: Measured pile driving frequency spectrum (grey lines) at 750 m, with the averaged spectrum shown as the red line (Bellmann, et al., 2020). The spectrum ranges from 110-180 dB.*

The spectrum shown to the left in Figure 8.2 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 8.2 shows the pile driving frequency spectrum (grey lines) measured at 750 m for monopiles with diameter of 5 - 8 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.

As mentioned in section 8.1.2, NIRAS uses the empirical 750 m data presented in (Bellmann, et al., 2020) to generate a source level at 1 m distance. Similarly, the averaged frequency spectrum at 750 m is used to derive the equivalent 1 m source level in each 1/3 octave band. Since different frequencies attenuate differently with distance, the frequency spectrum used as a model input does not directly match that of Figure 8.2, however is chosen so that it, conservatively approximates it in 750 m.

### 8.1.3. Source model implementation

Project specific pile installation parameters were agreed with the client, see section 8.1.1, and it was decided to carry out a sound propagation modelling without any mitigation measures applied. Soft-start and ramp up were included as these are regarded as part of the installation process, and not as mitigation measures.

#### *8.1.3.1. 4-legged jacket foundation with up to 4 m pin piles*

Following the methodology in section 8.1.2 for setting source level and frequency spectrum, the source model parameters for the 4 m pin pile are presented in Table 8.2, with detailed 1/3-octave band source level shown in Figure 8.3.

*Table 8.2: Broadband source model parameters for impact pile driving of 4 m pin pile.*

| Parameter | Value | Reference |
|---|---|---|
| Unmitigated reference level @750m distance, $\mathbf{L_{E,p,750m}}$ (unweighted) | 174.5 dB | Relationship between pile diameter and sound level, Figure 8.1 (Bellmann, et al., 2020). |
| Unmitigated source level @ 1m distance, $\mathbf{L_{S,E}}$ (Unweighted / PCW / VHF) | 216.3 dB (-)<br>198.8 dB (PCW)<br>178.1 dB (VHF) | Back-calculated using NIRAS empirical model, section 8.1.2. |

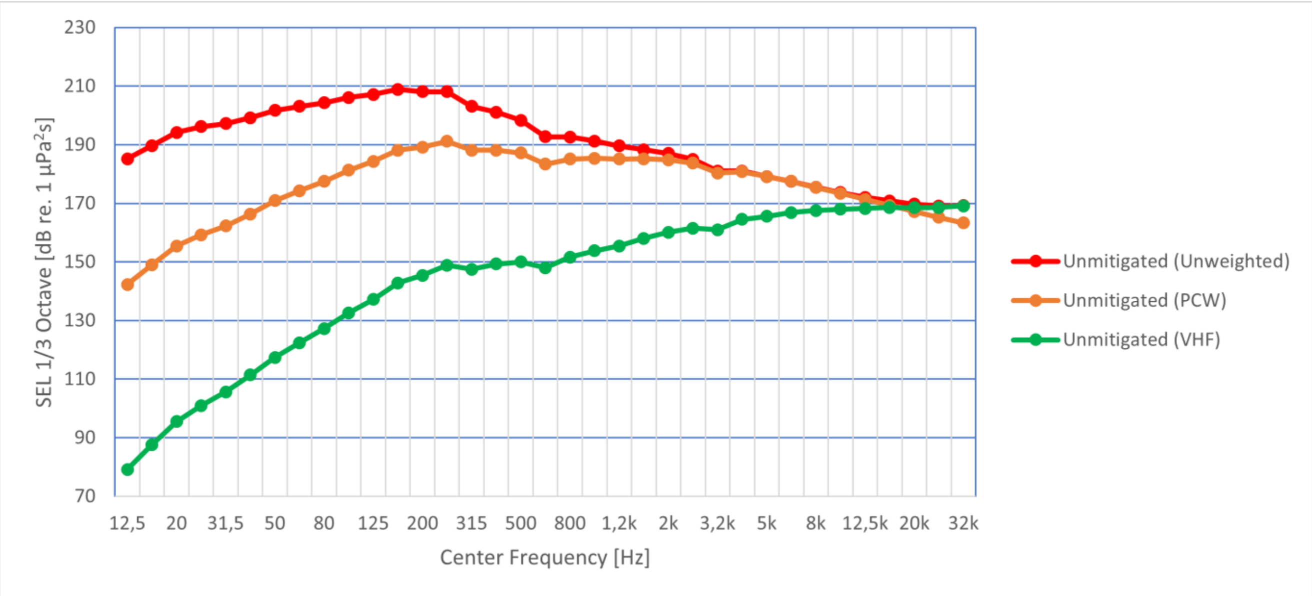



*Figure 8.3: Source spectrum at 1 m distance, unmitigated, for pile driving of 4 m pin pile.*

### 8.1.4. Source model uncertainties

As briefly described in the previous sections 8.1.2 - 8.1.3, the source model is largely based on empirical data from previous pile driving installations from OWFs. For both the absolute source level, frequency spectrum and mitigation measures, uncertainties exist. These are elaborated on in this section.

*8.1.4.1. Uncertainties in determining source level*

Beyond the simplified method of representing the complex underwater sound emission of a pile strike through the use of a single point source, project specific conditions will also affect the source level and frequency characteristics of any individual pile installation.

The water depth, in shallow water, can limit the propagation of low frequency noise. In Figure 8.4, the cut-off frequency as a function of water depth is shown. 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., 2020). As an example from Figure 8.4, frequencies below 200 Hz cannot propagate properly in water depths less than ~4 m with a sandy sediment.

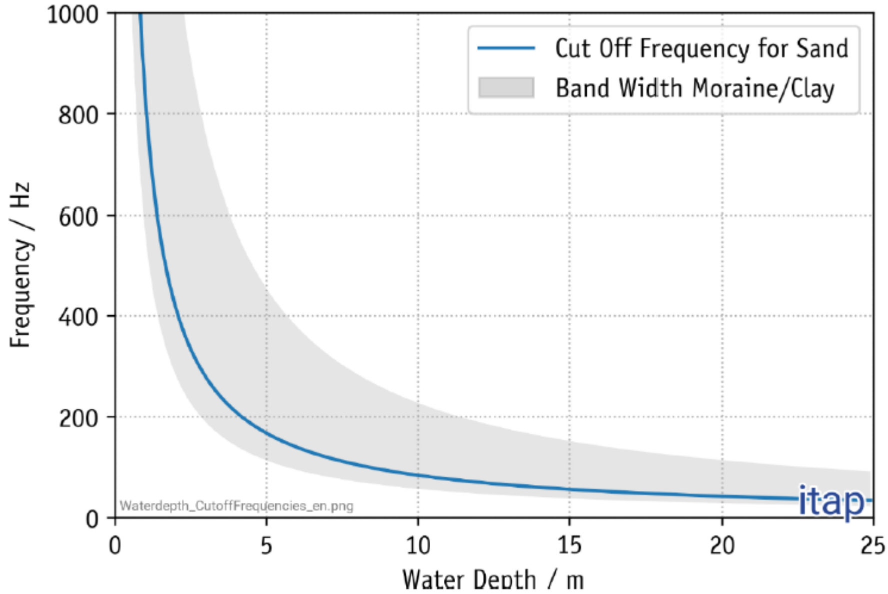



*Figure 8.4: Cut off frequency and its dependency on sediment type (in this example: sand) and water depth (Bellmann, et al., 2020).*

The hammer energy describes the energy (measured in kJ) applied for each pile strike. The hammer energy required to install the pile varies over the installation of a pile, and primarily depends on the soil resistance of the different sediment layers the pile has to penetrate. An increase in hammer energy, will transfer more energy into the pile and therefore also typically results in a higher noise emission. Figure 8.5 shows the SEL versus penetration depth and blow energy, from which it is seen that for the first half of the piling sequence, increasing 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., 2020). In the second half of the piling sequence, the blow energy is still increasing, however the measured SEL does not increase. One possible explanation for this is that a larger part of the applied energy is converted into downward motion of the pile, rather than radiated to the water column as excess.

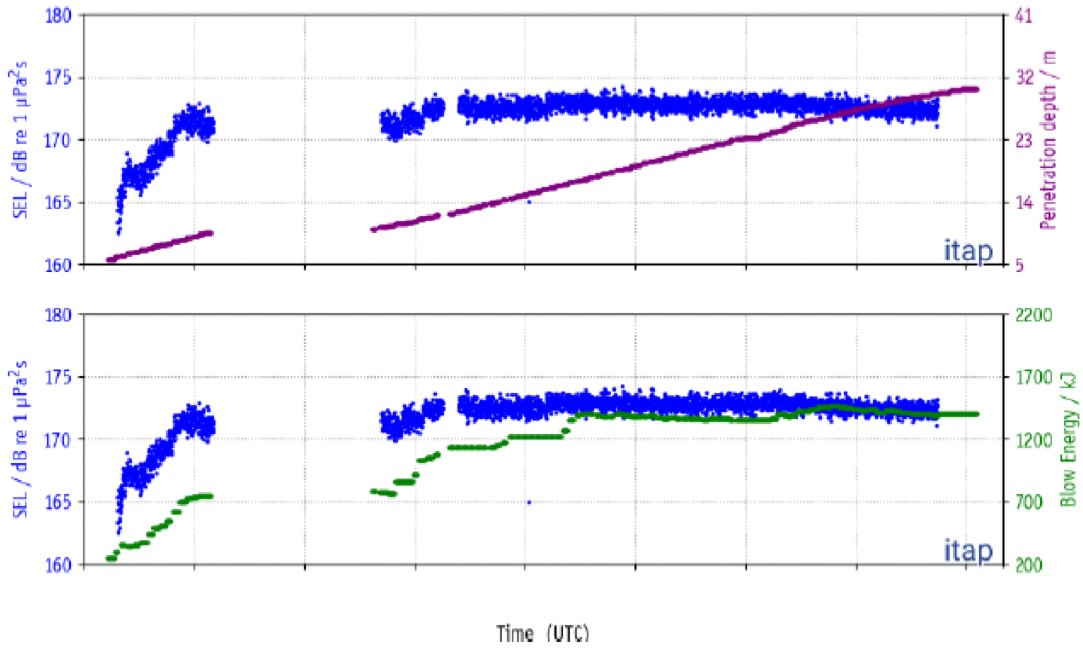



*Figure 8.5: Relationship between SEL versus penetration depths and blow energy (Bellmann, et al., 2020).*

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 reasons, lead to lower noise output compared to that from a smaller impact hammer using 100% capacity to achieve the same blow energy. 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. Different impact hammers can give up to several decibels difference (Bellmann, et al., 2020).

A pile installation can be carried out through either above sea level piling, where the pile head is located above water level, or through 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., 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 if the pile head is above water level (Bellmann, et al., 2020). Reductions in SEL near the end of pile driving sequence for jacket foundations, all other parameters equal, are therefore more likely to occur.

In summary, there are several parameters introducing uncertainty to predicting the source level for pile driving activities before a final design and detailed site-specific data is available.

#### *8.1.4.2. Uncertainties in determining source frequency spectrum*
The source frequency spectrum is represented through 1/3-octave values based on the proposed spectrum in Figure 8.2, page 34, and while it is an idealized spectrum it is recognized, that it is unlikely to represent the spectrum of any individual pile.

The frequency spectrum of pile driving noise depends on various factors such as the pile's dimensions and the properties of the seabed.

The frequency spectrum of the pile depends on its length, diameter, and wall thickness as well as other physical properties. To complicate the matter further, piles will not necessarily have the same dimensions in top and bottom. In early stage prognosis, the pile specific parameters are typically based on worst case preliminary designs and are not considered on a pile-by-pile basis. In general, the larger the pile, the lower the resonance frequency, and thereby the lower the peak frequency. In Figure 8.2, it is visible that for 6 – 8 m diameter monopiles, the peak is located at 100 – 160 Hz, while for pin piles with a diameter up to 3.5 m diameter, the peak is located at 160 – 250 Hz. A frequency shift from the idealized spectrum could therefore be argued as relevant, when considered piles with diameters outside this range, however a suitable relationship between pile diameter and peak frequencies has not been studied. From the perspective of a worst-case prognosis, an unshifted frequency spectrum for larger piles, is considered conservative in a shallow water scenario, where low frequencies need a certain depth to propagate. A downward shift in frequency, would therefore risk increased attenuation, compared to an unshifted scenario.

The frequency spectrum of the emitted noise can also be affected by the properties of the surrounding water and seabed. For example, softer seabed materials can absorb more of the acoustic energy, resulting in a frequency spectrum with less high-frequency noise emitted. Detailed site specific knowledge of the seabed is however required to include any such influence in the prognosis.

#### *8.1.4.3. Summary*
In order to carry out the prognosis, the average relationship between pile size and sound levels (Figure 8.1), is used to determine the source level, while the idealized spectra (Figure 8.2), is used to define the frequency spectrum. In this regard, it was chosen not to shift the frequency spectrum downwards to compensate for the larger piles, as it is assessed that the higher frequency peak will ensure a conservative prognosis, especially for marine mammals sensitive to high frequencies. The uncertainty for the chosen approach, is assessed to be $\pm 5\ dB$.

## 8.2. Source positions
The project is in early stages of development, and final WTG positions have not yet been determined. In order to ensure a worst-case prognosis with regards to local sound propagation conditions, it was agreed with Deep Wind Offshore to select a number of representative positions throughout the OWF area, such that different sound propagation scenarios within the site are covered. Areas where sound propagation most likely results in the longest impact ranges are identified, taking into account nearby marine mammal and/or fish protection areas if relevant. The chosen source positions are listed in Table 8.3, along with coordinates, and distances to nearby areas of interest. The positions are also shown in Figure 8.6.

Table 8.3: Source positions used for sound propagation modelling of underwater noise during construction phase.

| Position ID | Easting | Northing | EPSG | Nearby areas of interest |
|---|---|---|---|---|
| 1 | 340418 | 6758365 | 25834 | Nat2000 area "Finngrundet-Östra banken", 14 km distance<br>Nat2000 area "Finngrundet-Norra banken", 11 km distance<br>Nat2000 area "Finngrundet-Västra banken", 3 km distance<br>Maritime boundary "Finland-Sweden", 66 km distance<br>City of Gävle, 57 km distance |
| 2 | 348136 | 6749872 | 25834 | Nat2000 area "Finngrundet-Östra banken", 11 km distance<br>Nat2000 area "Finngrundet-Norra banken", 18 km distance<br>Nat2000 area "Finngrundet-Västra banken", 11 km distance<br>Maritime boundary "Finland-Sweden", 57 km distance<br>City of Gävle, 61 km distance |
| 3 | 356927 | 6755358 | 25834 | Nat2000 area "Finngrundet-Östra banken", 2 km distance<br>Nat2000 area "Finngrundet-Norra banken", 15 km distance<br>Nat2000 area "Finngrundet-Västra banken", 15 km distance<br>Maritime boundary "Finland-Sweden", 49 km distance<br>City of Gävle, 71 km distance |
| 4 | 368674 | 6739852 | 25834 | Nat2000 area "Finngrundet-Östra banken", 16 km distance<br>Nat2000 area "Finngrundet-Norra banken", 34 km distance<br>Nat2000 area "Finngrundet-Västra banken", 34 km distance<br>Maritime boundary "Finland-Sweden", 36 km distance<br>City of Gävle, 80 km distance |
| 5 | 372098 | 6758816 | 25834 | Nat2000 area "Finngrundet-Östra banken", 1 km distance<br>Nat2000 area "Finngrundet-Norra banken", 25 km distance<br>Nat2000 area "Finngrundet-Västra banken", 28 km distance<br>Maritime boundary "Finland-Sweden", 34 km distance<br>City of Gävle, 87 km distance |

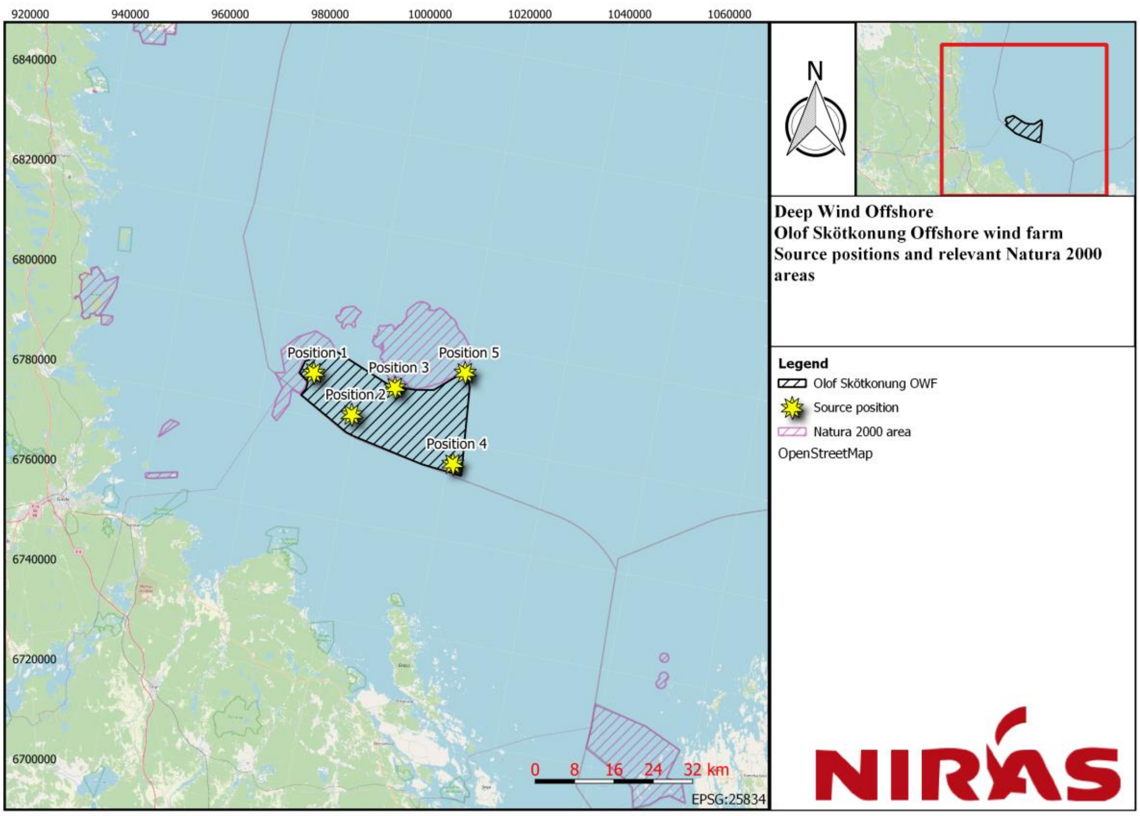



Figure 8.6: Source positions chosen for sound propagation modelling as well as nearby relevant Natura 2000 areas.

## 8.3. Environmental Model Implementation

The environmental model consists of a bathymetry layer for the entire area, a number of discrete sediment profiles, for which also the sound speed profile, average temperature and salinity are defined. In section 6.1, the bathymetry and sediment model for the entire prognosis was described, while temperature, salinity and sound speed profiles are source dependent. These parameters are documented in section 8.3.1 for the pile driving sound propagation modelling, as they depend on installation time frame and source positions for the activity.

### 8.3.1. Temperature, salinity, and sound speed profile

With regards to hydrographic conditions, a realistic worst case approach was agreed with Deep Wind Offshore. The temperature, salinity and sound speed profiles for the area are therefore examined for all 12 months, to determine which month has conditions most likely to result in the furthest sound propagation.

Temperature, salinity, and sound speed profiles were extracted for a radius of 20 km around each source position mentioned in section 8.2. From these profiles, it was assessed, that profiles with the potential for the strongest sound propagation, are those of March. Graphical representations of all profiles for position 1 are given in Figure 8.7 (temperature), Figure 8.8 (salinity), and in Figure 8.9 (sound speed). Profiles for the remaining positions are attached in Appendix 2. The figures each show the nearest 9 data points from the temperature and salinity databases, relative to the source location. These are shown in a gridded x-y format, with the centre plot representing the data point closest to the source location. Empty plots can occur where land masses are present. The coordinates for each data point are provided above the individual plots in EPSG: 4326.

To ensure a realistic worst case approach for the prognosis, sound propagation modelling implements the profiles for March.

For each sediment model position, the spatially closest data point for average temperature and salinity, as well as sound speed profiles, were assigned to the sediment model through the NIRAS software tool "TRANSMIT", which combines sediment, temperature, salinity, and sound speed data, into dBSea import files.

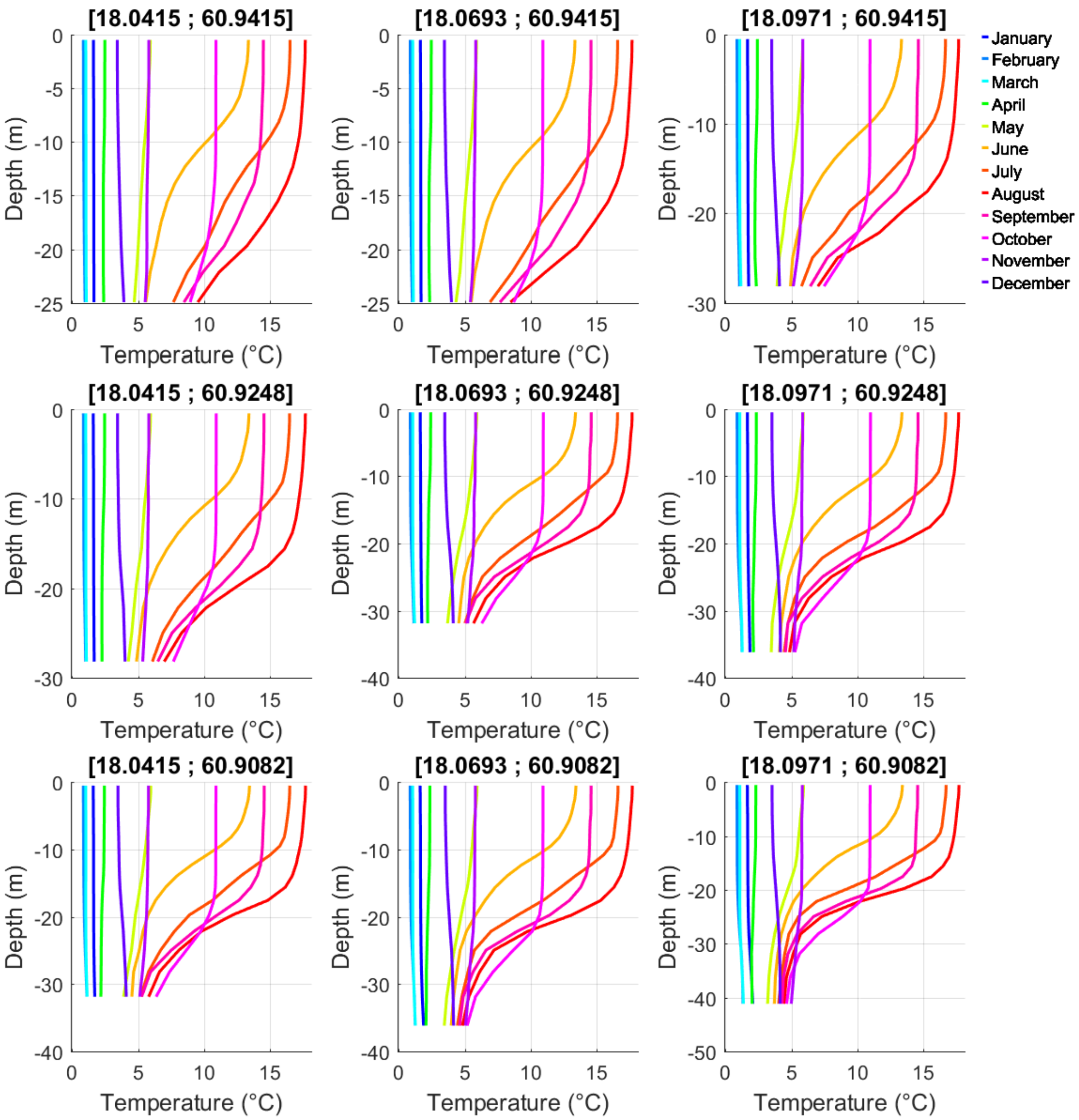



*Figure 8.7: Temperature profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.*

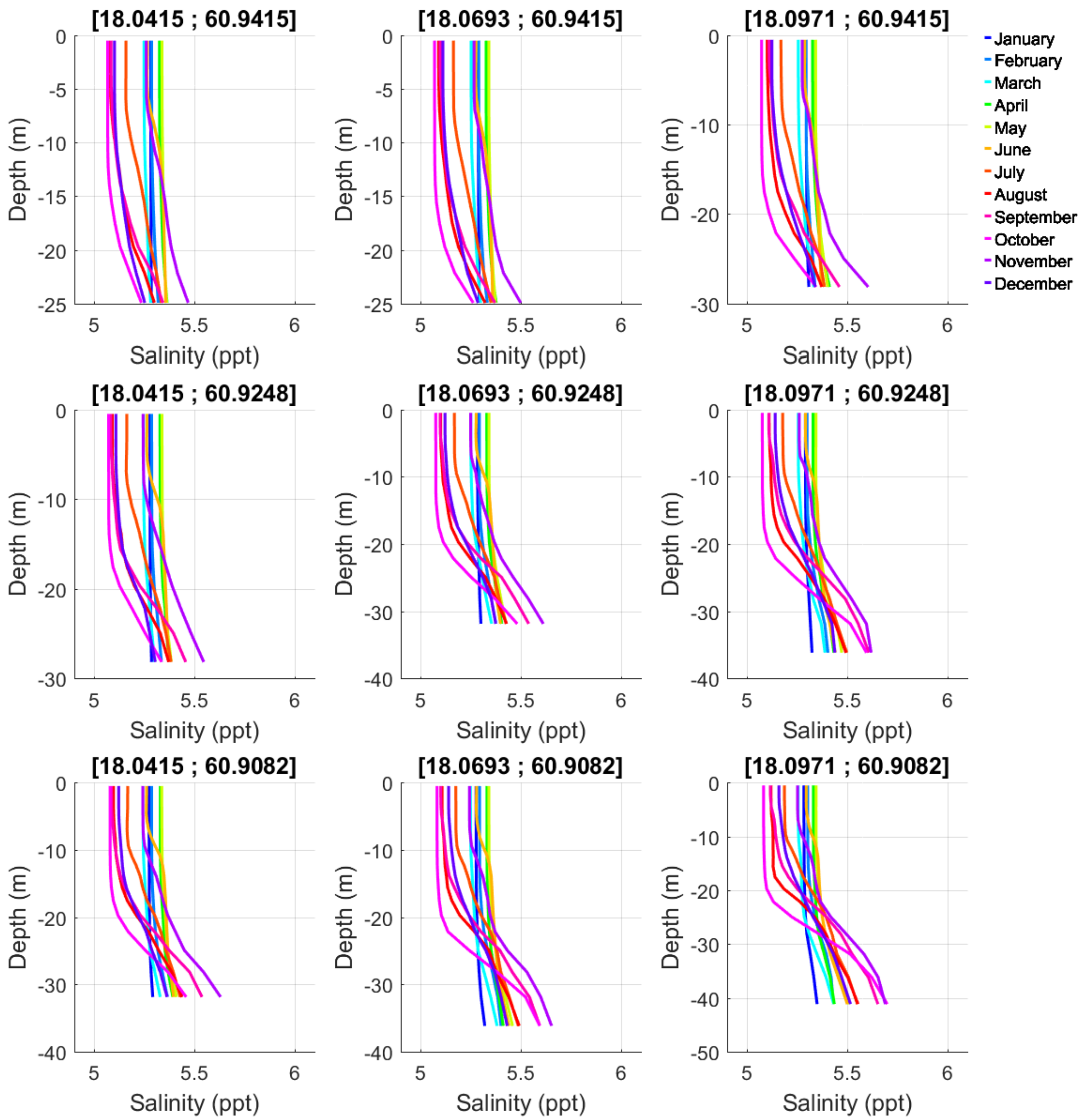



*Figure 8.8: Salinity profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.*

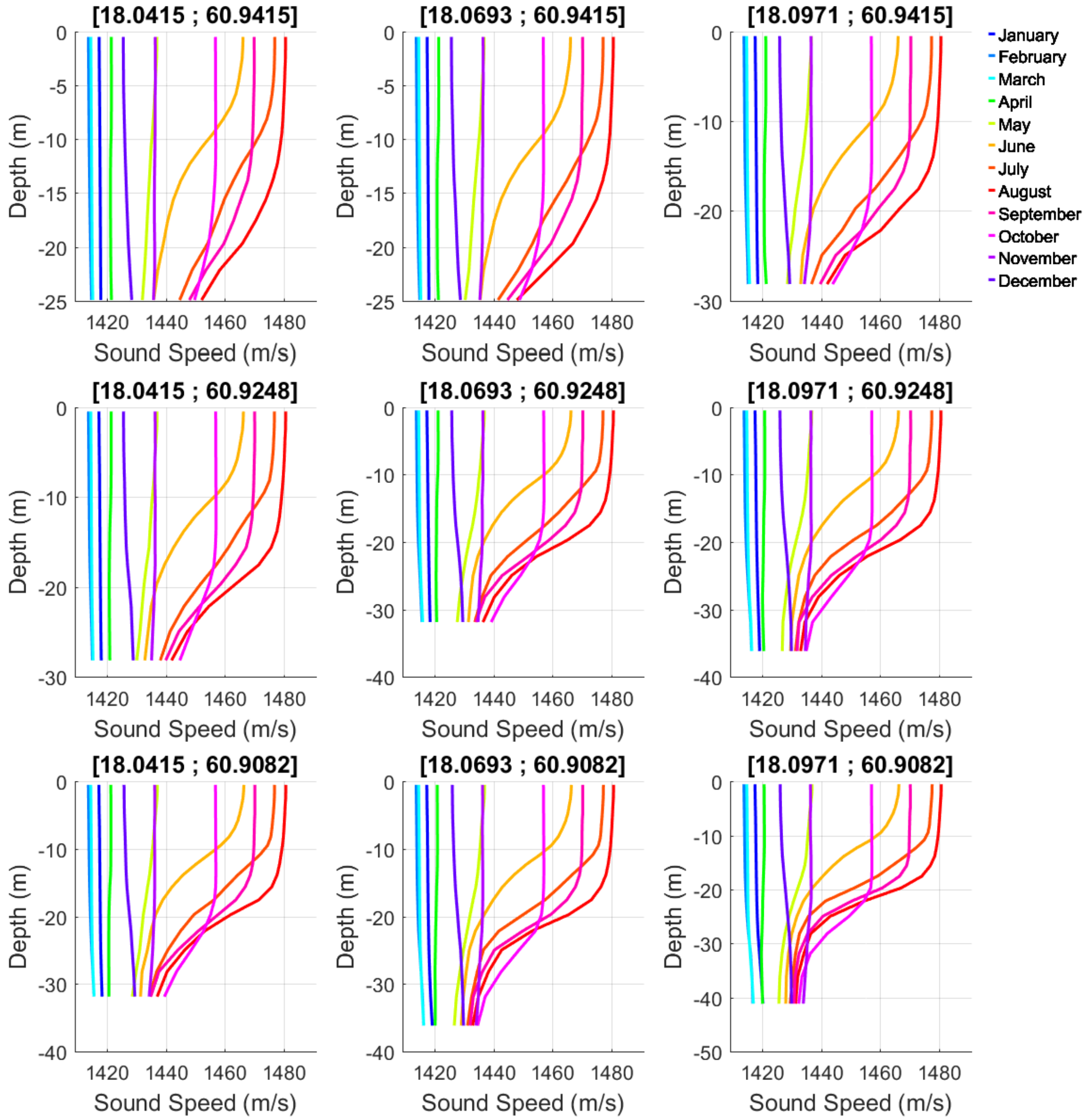



*Figure 8.9: Sound speed profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.*

## 8.4. Sound Propagation Software

The software tool dBSea was used for sound propagation modelling, with the configuration listed in Table 8.4.

*Table 8.4: Sound propagation modelling tool settings for dBSea.*

| Parameter | Value |
|---|---|
| Software version | 2.3.4 |
| Grid (range x depth) resolution | 50 m x 0.5 m |
| Number of radials/transects | 45 (8°) |
| Low frequency solver | dBSeaNM |
| High frequency solver | dBSeaRay |
| Solver split frequency | P1-P2: 250 Hz - 315 Hz<br>P3-P5: 200 Hz - 250 Hz |

Post-processing of the raw sound propagation results into impact ranges was done in NIRAS software tool "SILENCE", which implements Equation 5, page 13 for batch processing of different installation scenarios and threshold values.

## 8.5. Unmitigated pile driving results

Unmitigated pile driving results were calculated in dBSea. Using NIRAS SILENCE toolbox, curve fits were calculated for the direction with the strongest sound propagation for each position. The curve fit interpolates and extrapolates calculated values to obtain best possible fit in the range 1 m – 500 km. It should be noted, that extrapolation does not factor in any bathymetry beyond the model range including the occurrence of land masses. Extrapolation beyond the model range is therefore extremely conservative. Any land mass in the path would effectively stop sound propagation in that direction. Extrapolated values for unmitigated scenarios are therefore only useful in examining the general trend of sound propagation and should not be considered plausible as they do not take the actual environment beyond the model range into consideration. Caution is warranted if extrapolated values are used to calculate impact ranges.

### 8.5.1. 4-legged jacket foundation with up to 4 m pin pile

The unmitigated resulting curve fits, for the 4 m pin pile, are shown in Figure 8.10 – Figure 8.14 without any frequency weighting.

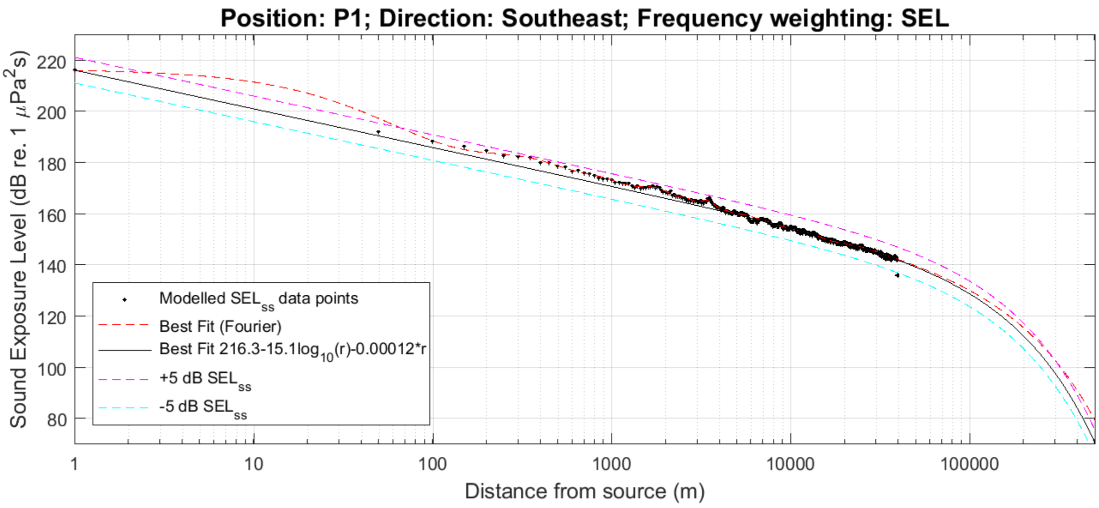



*Figure 8.10: Sound propagation results for unmitigated pile driving. Best logarithmic fit and fourier (SILENCE) curve fit are also shown. Scenario: 4-legged jacked foundation; 4 m pin pile; March; P1.*

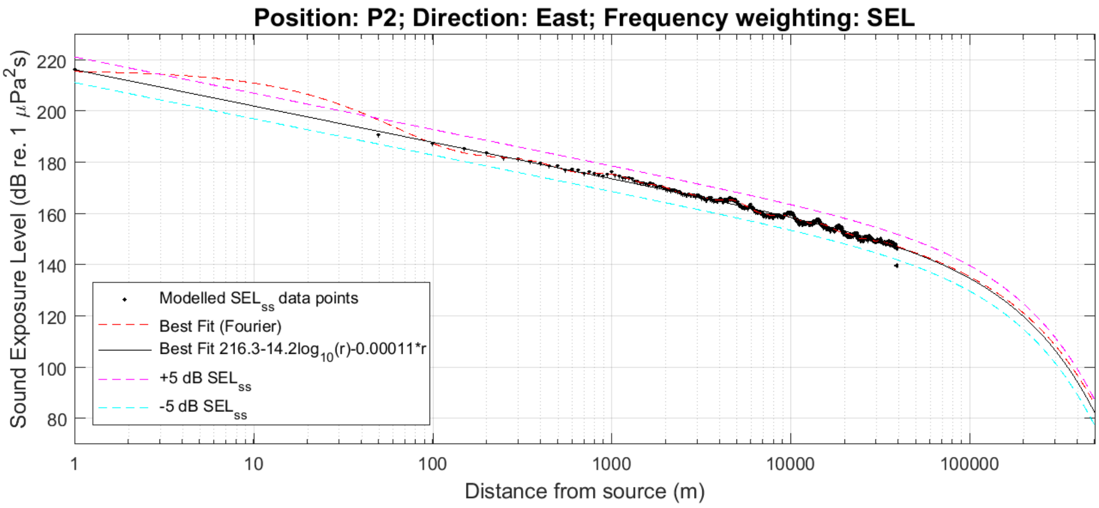



*Figure 8.11: Sound propagation results for unmitigated pile driving. Best logarithmic fit and fourier (SILENCE) curve fit are also shown. Scenario: 4-legged jacked foundation; 4 m pin pile; March; P2.*

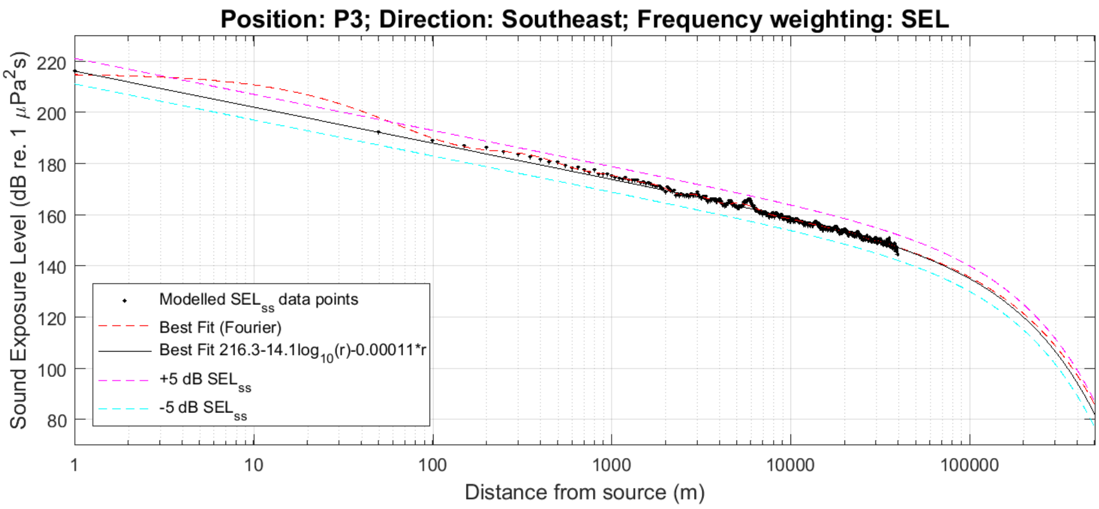



*Figure 8.12: Sound propagation results for unmitigated pile driving. Best logarithmic fit and fourier (SILENCE) curve fit are also shown. Scenario: 4-legged jacked foundation; 4 m pin pile; March; P3.*

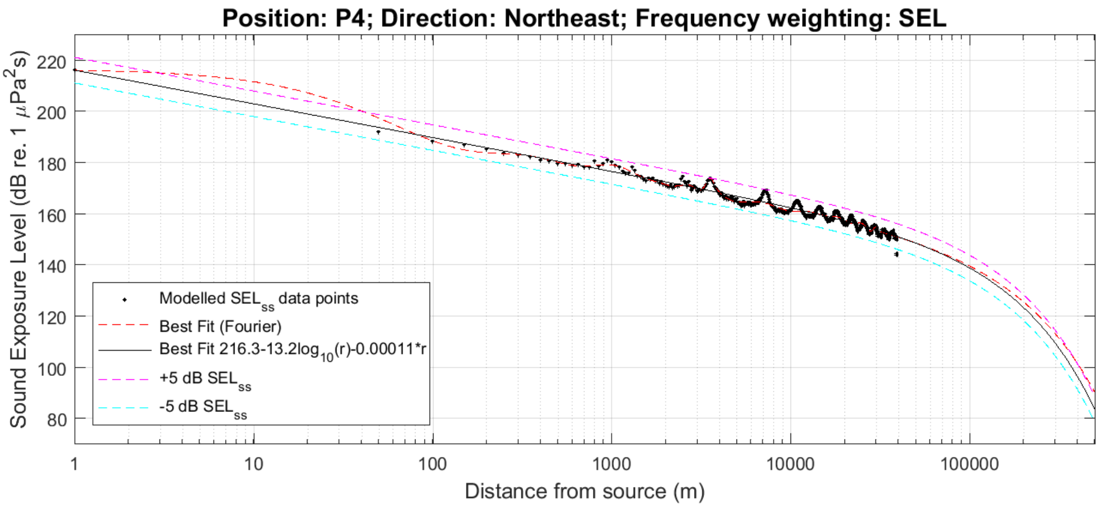



*Figure 8.13: Sound propagation results for unmitigated pile driving. Best logarithmic fit and fourier (SILENCE) curve fit are also shown. Scenario: 4-legged jacked foundation; 4 m pin pile; March; P4.*

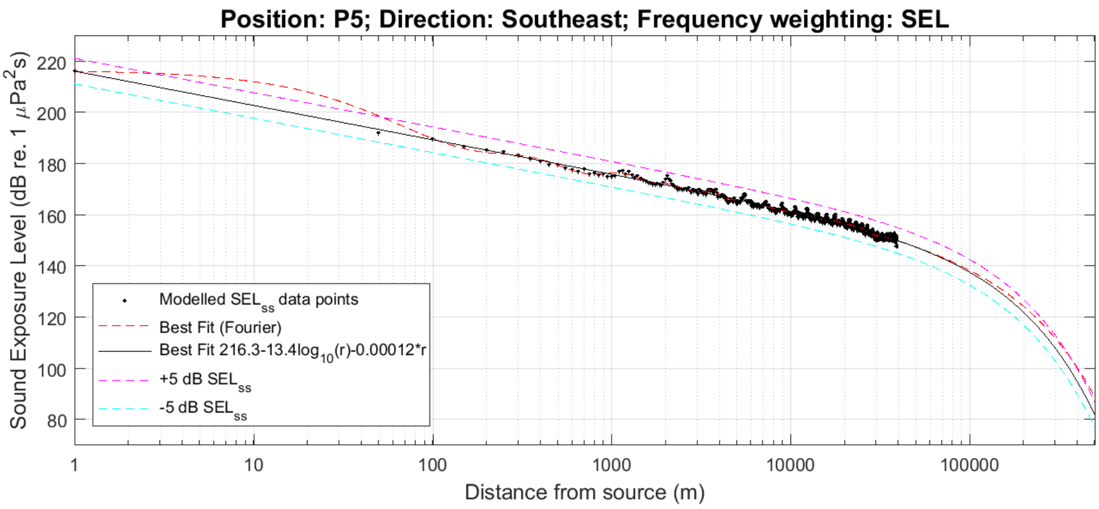



*Figure 8.14: Sound propagation results for unmitigated pile driving. Best logarithmic fit and fourier (SILENCE) curve fit are also shown. Scenario: 4-legged jacked foundation; 4 m pin pile; March; P5.*

## 8.6. Mitigation

This section provides a brief description of different noise mitigation measures, both existing systems, and systems currently in development. The systems can be either on-pile systems (actively reducing the source level) or near-pile which reduces the noise emission after it has entered the water column and sediment.

### 8.6.1. Existing mitigation measures

This section provides a brief description of different existing and proven noise mitigation measures.

#### *8.6.1.1. Reduced hammer blow energy*

While not necessarily a mitigation system in itself, reducing the hammer energy applied to each pile strike would consequently result in lower emitted underwater noise levels per pile strike. It might however also lead to slower installation speed and a need for additional pile strikes, or in the worst case failure to reach target depth.

An increased number of pile strikes, could also lead to increased PTS and TTS distances, as these are affected by not only the source level, but also the number of pile strikes and the frequency.

*8.6.1.2. Big Bubble curtains (BBC, DBBC)*

A frequently applied technique uses either a single big bubble curtain (BBC), or double (DBBC). Bubble curtains consist of a series of perforated pipes or hoses that release a continuous stream of air bubbles into the water column, thereby creating a barrier made of air, which effectively traps the acoustic energy inside the barrier. While bubble curtains are effective at reducing underwater noise, they have some limitations. The effectiveness of the curtain depends on the depth of the water, the size of the bubbles, and the distance between the noise source and the curtain. Additionally, the installation and operation of the curtains can be expensive, and the use of air compressors to generate the bubbles requires a lot of energy. The DBBC is illustrated in Figure 8.15.

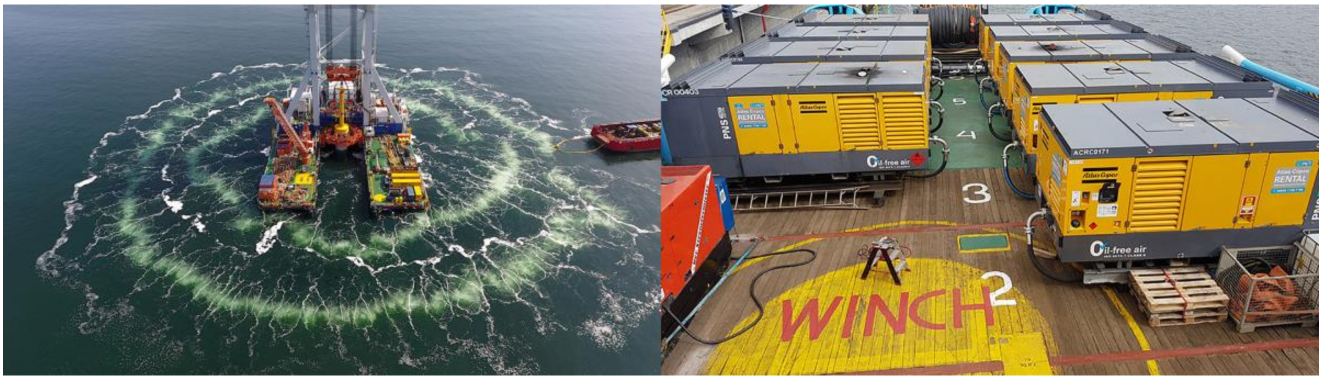



*Figure 8.15: Illustration of a DBBC mitigation system (Left: in effect; Right: compressors for creating the air pressure) (Source: hydrotechnik-luebeck.de).*

The curtains are typically positioned at 50 – 200 m radius around the pile. Due to the change in impedance in the water-air-water bubble interface, a significant part of the outgoing noise is reflected backwards and kept near the pile, just like the water surface prevents underwater sound from being transmitted into the air. Noise energy going through the bubble curtain is greatly attenuated (Tsouvalas, 2020). The success depends 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).

Part of the noise emission from pile driving occurs through the pile striking the sediment. The sound moves through the sediment and is then partially reintroduced to the water column further from the pile. The distances to which sound reintroduced to the water column is of significant amplitude depends on the seabed characteristics at and near the pile site. The further from the pile the bubble curtain(s) are located, the more of the reintroduced sound can be captured. It is however in most cases considered impossible to avoid reintroduced sound from the sediment solely by use of bubble curtains given the typical bubble curtain radius of up to 200 m. The upper limit to the effectiveness of bubble curtains is therefore often dependent on the sediment.

*8.6.1.3. Pile sleeves*

A pile sleeve is an on-pile mitigation system forming a physical wall around the pile. One such system is the Noise Mitigation Screen from IHC (IHC-NMS) where a double walled steel sleeve with an air-filled cavity is positioned over the pile (Figure 8.16). This system utilises the impedance difference in the water-steel-air-steel-water interfaces to reduce the sound transmission. This system has been used for example at the German wind park Riffgat. Noise mitigation was assessed to be around 16-18 dB (Verfuß, 2014).


*Figure 8.16: Illustration of IHC-NMS system (source: iqip.com)*

Often, a pile sleeve is applied in combination with a bubble curtain solution to increase the overall mitigation effect. The pile sleeve however has an important limitation when it comes to future installations, as the weight of the system is significant. With increasing pile sizes, the pile sleeve also increases in size, and thereby weight. It is uncertain whether this system is applicable for large future monopiles. For jacket foundations, the applicability is also uncertain, as the pin piles are often installed into a template, thus preventing a seal towards the seabed.

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 that it can be difficult to keep the water out of the cofferdam, as local sediment conditions can prevent a perfect water-tight seal with the seabed.

*8.6.1.4. Hydro Sound Dampers*

Hydro Sound Damper (HSD) systems are in many ways similar to the bubble curtain, however instead of using hoses with air, the curtain consists of fixed position air-filled balloons or foam-balls (Figure 8.17). The size, spacing and density of the foam balls or air-filled balloons then dictate the achievable noise mitigation. The HSD system, makes it possible to "tune" the system to work optimally at specific frequencies, thus allowing for project specific optimal solutions.

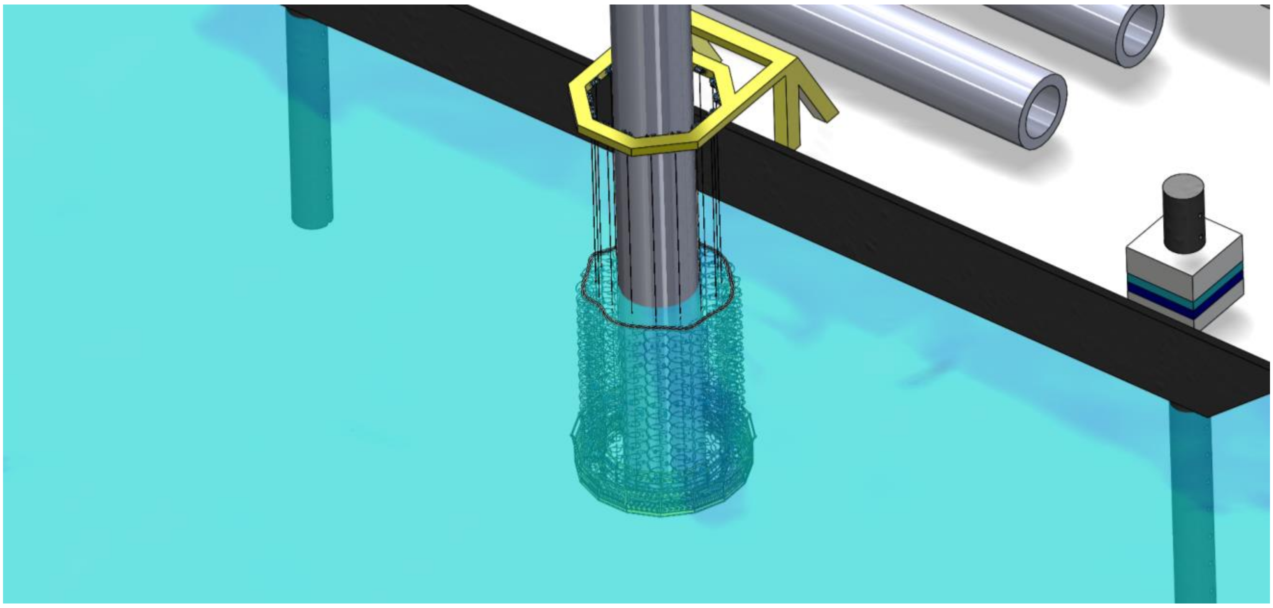


*Figure 8.17: Illustration of the HSD system deployed around a monopile. (source: (Offnoise Solutions, 2023)).*

### 8.6.2. Effectiveness of mitigation measures

For commercially available and proven mitigation systems, a summary of achieved mitigation levels throughout completed installations is given in (Bellmann, et al., 2020), and shown in Figure 8.18, for different configurations of bubble curtains, and in Figure 8.19 for HSD, IHC-NMS and combinations of different types of mitigation systems.

| No. | **Noise Abatement System resp. combination of Noise Abatement Systems** (applied air volume for the (D)BBC; water depth) | **Insertion loss ΔSEL [dB]** (min. / average / max.) | **Number of piles** |
|---|---|---|---|
| 1 | Single Big Bubble Curtain – BBC (> 0.3 $m^3$/(min·m), water depth < 25 m) | $11 \leq 14 \leq 15$ | > 150 |
| 2 | Double Big Bubble Curtain – DBBC (> 0.3 $m^3$/(min·m), water depth < 25 m) | $14 \leq 17 \leq 18$ | > 150 |
| 3 | Single Big Bubble Curtain – BBC (> 0.3 $m^3$/(min·m), water depth ~ 30 m) | $8 \leq 11 \leq 14$ | < 20 |
| 4 | Single Big Bubble Curtain – BBC (> 0.3 $m^3$/(min·m), water depth ~ 40 m) | $7 \leq 9 \leq 11$ | 30 |
| 5 | Double Big Bubble Curtain – DBBC (> 0.3 $m^3$/(min·m), water depth ~ 40 m) | $8 \leq 11 \leq 13$ | 8 |
| 6 | Double Big Bubble Curtain – DBBC (> 0.4 $m^3$/(min·m), water depth ~ 40 m) | $12 \leq 15 \leq 18$ | 3 |
| 7 | Double Big Bubble Curtain - DBBC (> 0.5 $m^3$/(min·m), water depth > 40 m) | ~ 15 – 16 | 1 |

*Figure 8.18: Achieved unweighted broadband mitigation for different configurations of bubble curtain systems. Note: unoptimized configurations yielded significantly lower mitigation effect. (Bellmann, et al., 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)<br>(water depth up to 40 m) | $13 \leq 15 \leq 17$ dB<br>IHC-NMS8000 $15 \leq 16 \leq 17$ dB | > 450<br>> 65 |
| 2 | HSD<br>(water depth up to 40 m) | $10 \leq 11 \leq 12$ dB | > 340 |
| 3 | optimized double BBC*1<br>(> 0,5 $m^3$/(min m), water depth ~ 40 m) | 15 – 16 | 1 |
| 4 | combination IHC-NMS + optimized BBC<br>(> 0,3 $m^3$/(min m), water depth < 25 m) | $17 \leq 19 \leq 23$ | > 100 |
| 5 | combination IHC-NMS + optimized BBC<br>(> 0,4 $m^3$/(min m), water depth ~ 40 m) | 17 – 18 | > 10 |
| 6 | combination IHC-NMS + optimized DBBC<br>(> 0,5 $m^3$/(min m), water depth ~ 40 m) | $19 \leq 21 \leq 22$ | > 65 |
| 7 | combination HSD + optimized BBC<br>(> 0,4 $m^3$/(min m), water depth ~ 30 m) | $15 \leq 16 \leq 20$ | > 30 |
| 8 | combination HSD + optimized DBBC<br>(> 0,5 $m^3$/(min m), water depth ~ 40 m) | 18 – 19 | > 30 |
| 9 | GABC skirt-piles*2<br>(water depth bis ~ 40 m) | ~ 2 – 3 | < 20 |
| 10 | GABC main-piles*3<br>(water depth bis ~ 30 m) | < 7 | < 10 |
| 11 | „noise-optimized" pile-driving procedure<br>(additional additive, primary noise mitigation measure; chapter 5.2.2) | ~ 2 - 3 dB per halving of the blow energy | |

*Figure 8.19: Achieved source mitigation effects at completed projects using different noise mitigation systems, (Bellmann, et al., 2020).*

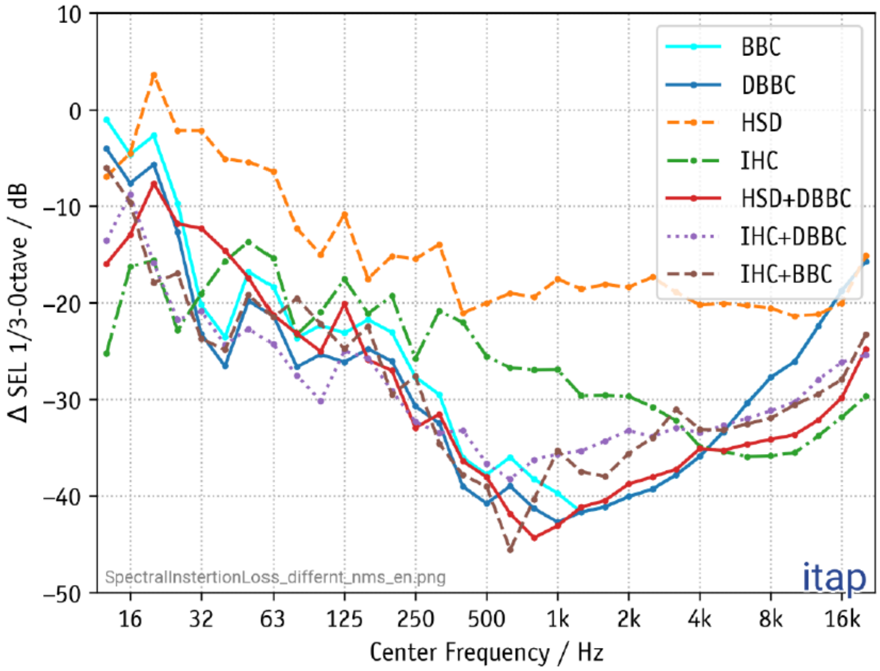



*Figure 8.20: Frequency dependent noise reduction for noise abatement systems, (Bellmann, et al., 2020).*

In Figure 8.20, the noise reduction with the different mitigation systems, are instead given in 1/3 octave bands, thus showing the achieved mitigation per frequency band, however normalized and not reflecting the overall mitigation efficiencies provided in Figure 8.18 and Figure 8.19. The mitigation effect is provided as the noise level relative to installation without any active mitigation measures, so the more negative the value, the better the mitigation effect.

It should be noted from Figure 8.20, that the representation method in (Bellmann, et al., 2020) does not represent the effect of a single fixed system used in different projects, but rather the average of a number of different systems, across different pile installations, across different project areas and environmental conditions. It is not clear from the report, when and where each mitigation system effect was measured, and it is therefore not possible to determine the direct contributors of any variation in effect.

As the measurement results originate from German OWFs, it is however worth noting the measurement procedure for installations including mitigation measures, where one pile is measured without any mitigation active, one pile is measured with each individual mitigation system (such as BBC or IHC-NMS) and the rest of the piles are measured with all mitigation systems active (such as IHC-NMS+DBBC).

It is also worth emphasizing that the mitigation effect presented is the average of achieved mitigation over a number of years, and given the continuous development of mitigation system technology, it is considered likely that performance would typically improve over time. Utilizing the reported average mitigation effect is therefore considered conservative. It should furthermore be expected, that entirely new and more effective mitigation systems and installation methods emerge in the coming years, however until such methods exist, it is not considered feasible to include in a prognosis.

In summary, prediction of achievable mitigation effect for any system, based on past installations, must be considered cautiously, and it should be expected that variations will occur between projects. The previously achieved mitigation effects can however be used more broadly to identify which type(s) of mitigation systems are likely to be useful for the current project, based on typical frequency specific mitigation effects.

If the purpose is to limit broadband noise output, a system with a high broadband mitigation effect could be a good choice. However if the purpose is to reduce the impact on a specific group of marine mammal or fish, the frequency specific mitigation effect should be considered. As an example, DBBC is very effective at reducing the broadband noise level, however for species such as porpoise (VHF) and dolphin (HF), which both have high frequency hearing above 10 kHz, a combination of HSD with DBBC could provide better protection, as indicated by the HSD+DBBC curve in Figure 8.20, for frequencies above 4 kHz. It is therefore recommended to always carry out detailed site and pile specific underwater sound emission modelling with incorporation of mitigation, based on the project specific mitigation purpose. It must also be emphasized, that any mitigation effect included in the prognosis is based on historical data, and not a suppliers guaranteed noise mitigation effect of a specific system. Such guarantee must be procured when final pile design is available, based on the actual installation scenario.

It was chosen not to apply a safety margin on the efficiency of the mitigation systems, but instead use the average broadband reduction values within each system type, as presented in Figure 8.19, with a smoothed 1/3 octave efficiency spectrum based on Figure 8.20.

#### 8.6.3. Uncertainties in determining mitigation effectiveness

A large uncertainty in the source model is the mitigation system effectiveness. While a large review (Bellmann, et al., 2020) contains data on mitigation technique effectiveness, it is reported in a statistical way, not documenting individually measured effectiveness, but averages. It is therefore not possible, from the review, to pinpoint and thereby model, the effectiveness of a specific solution individually. Using the average 1/3 octave band values is considered the best available method, however the uncertainty connected with this approach must be recognized.

Another limitation is the ambient noise level during the measurements. From (Bellmann, et al., 2020), it is noted that especially for the higher frequencies, the measured levels with active mitigation are often not distinguishable from the ambient noise. The actual effectiveness of the mitigation system can therefore not be determined with sufficient accuracy. Provided that the analysis in (Bellmann, et al., 2020) is conservative with regards to high frequency mitigation effect, it is more likely than not, that the implementation of the reported values will lead to a conservative estimate for species sensitive to high frequencies.

From (Bellmann, et al., 2020), it is also noted, that the reported mitigation effectiveness is a result of measurements acquired over a large time span, and with different iterations and variations of the same technology; this development is expected to continue. For prognosis in early stage development, where mitigation effectiveness is based on historical averages, it is likely that future innovation will allow for better mitigation than is currently available.

A large source of uncertainty pertains to the local environmental conditions. For bubble curtains, strong currents have the potential to "blow the bubbles away" and disturb the intended air flow and thereby the acoustic barrier effect. Seabed characteristics can also affect sound emission from the pile, in the sense that harder sediments can lead to increased sound transmission through the sediment, thereby potentially bypassing the mitigation system.

### 8.6.4. Noise mitigation measures currently under development

There is a continuous ongoing development of new noise mitigation measures, as well as improvements of existing technologies. This section provides a brief overview of some systems that have the potential for efficient mitigation of underwater noise in future projects.

#### *8.6.4.1. New hammer technologies*

New hammer technologies are under development, most notably the Menck Noise Reduction Unit (MNRU) and the IQIP PULSE system. Both hammer systems aim to reduce the peak amplitude of the hammer blow, and prolonging the impact pulse. There are currently no full scale measurement results available, and the potential mitigation effect is yet to be proven.

Another such system is the BLUE piling system from IQIP, where an enclosed water mass is used to push the pile into the sediment over a prolonged duration, compared to the impact of a standard hammer. The technology is not yet proven in large scale, and it remains to be seen what levels of noise reduction can be achieved.

#### *8.6.4.2. Enhanced big bubble curtain*

A further development of the single BBC, the enhanced big bubble curtain (eBBC), is a version with significantly increased airflow and larger nozzles. No official documentation of the improvement over a standard BBC is available, however several dBs increase in mitigation effect are expected. It should be noted, that due to the increased air flow, an eBBC will require more compressors than a BBC of equal diameter.

#### *8.6.4.3. Vibro-jetting (SIMPLE)*

The company GBM works is currently developing a vibro-jetting system for installing monopiles. It consists of a number of water hoses mounted inside the monopile, and supplied with high pressure water supply from above. The water hoses end in jet nozzles, located at the pile tip. When the pile has been situated, the water supply is turned on, whereby the water will liquify the soil near the pile wall. This is coupled with a vibratory hammer, which ensures continuous downward motion of the pile. By liquifying the soil, the pile should theoretically progress downwards as long as the water jets are on, and the soil can be liquified. It is uncertain how this system would work in an environment with harder sediments, and full scale offshore tests are still to be carried out. It is therefore uncertain what the mitigation effectiveness of this system will be.

## 8.7. Source Model With Mitigation Measures

In agreement with Deep Wind Offshore, it was chosen to include mitigation measures in the source model equivalent to that of a BBC and DBBC mitigation system with mitigation effectiveness equivalent to that listed in Figure 8.19.

### 8.7.1. 4 m pin pile with BBC mitigation effect

The source model parameters for the 4-legged jacked foundation with 4 m pin pile with BBC equivalent mitigation effect are presented in Table 8.2. The source spectrum with and without mitigation measures is illustrated in Figure 8.3.

*Table 8.5: Broadband source model parameters for impact pile driving of 4 m pin pile with BBC mitigation effect.*

| Parameter | Value | Reference |
|---|---|---|
| Unmitigated reference level @750m distance, $\mathbf{L_{E,p,750m}}$ (unweighted) | 174.5 dB | Relationship between pile diameter and sound level, Figure 8.1. |
| Unmitigated source level @ 1m distance, $\mathbf{L_{S,E}}$ (Unweighted / PCW / VHF) | 216.3 dB (-)<br>198.8 dB (PCW)<br>178.1 dB (VHF) | Back-calculated using NIRAS empirical model, section 8.1.2. |
| Mitigation effectiveness, $\Delta \boldsymbol{SEL_{xx}}$ (Unweighted / PCW / VHF) | 13.5 dB (-)<br>19.2 dB (PCW)<br>24.5 dB (VHF) | Graphical representation in Figure 8.20 (Bellmann, et al., 2020) |
| Mitigated source level (BBC) @ 1m distance, $\mathbf{L_{S,E}}$ (Unweighted / PCW / VHF) | 202.8 dB (-)<br>179.7 dB (PCW)<br>153.7 dB (VHF) | 1/3-octave band source levels unmitigated and mitigated shown in Figure 8.21 |

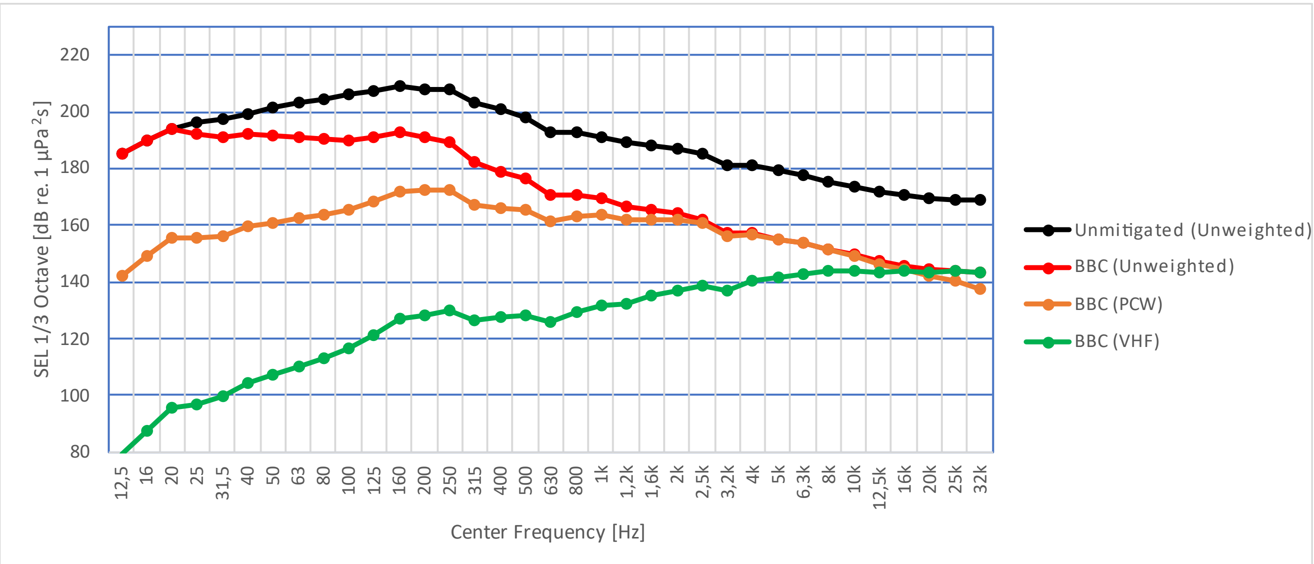



*Figure 8.21: Source spectrum at 1 m distance, 4 m pin pile, unmitigated and with BBC mitigation effect.*

### 8.7.2. 4 m pin pile with DBBC mitigation effect

The source model parameters for the 4-legged jacked foundation with 4 m pin pile with DBBC equivalent mitigation effect are presented in Table 8.6. The source spectrum with and without mitigation measures is illustrated in Figure 8.22.

*Table 8.6: Broadband source model parameters for impact pile driving of 4 m pin pile with DBBC mitigation effect.*

| Parameter | Value | Reference |
|---|---|---|
| Unmitigated reference level @750m distance, $\mathbf{L_{E,p,750m}}$ (unweighted) | 174.5 dB | Relationship between pile diameter and sound level, Figure 8.1. |
| Unmitigated source level @ 1m distance, $\mathbf{L_{S,E}}$ (Unweighted / PCW / VHF) | 216.3 dB (-)<br>198.8 dB (PCW)<br>178.1 dB (VHF) | Back-calculated using NIRAS empirical model, section 8.1.2. |
| Mitigation effectiveness, $\Delta\boldsymbol{SEL_{xx}}$ (Unweighted / PCW / VHF) | 16.2 dB (-)<br>22.2 dB (PCW)<br>27.5 dB (VHF) | Graphical representation in Figure 8.20 (Bellmann, et al., 2020) |
| Mitigated source level (DBBC) @ 1m distance, $\mathbf{L_{S,E}}$ (Unweighted / PCW / VHF) | 200.1 dB (-)<br>176.7 dB (PCW)<br>150.7 dB (VHF) | 1/3-octave band source levels unmitigated and mitigated shown in Figure 8.21 |

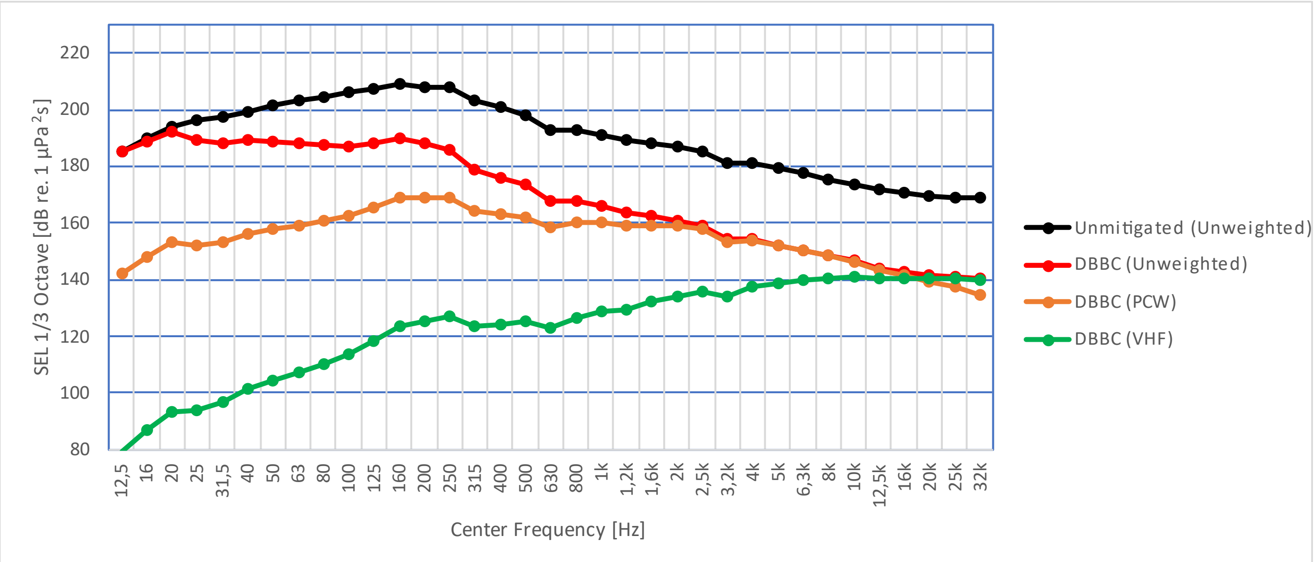



*Figure 8.22: Source spectrum at 1 m distance, 4 m pin pile, unmitigated and with DBBC mitigation effect.*

## 8.8. Mitigated pile driving results

As described in section 8.1.3, sound propagation modelling was carried out in dBSea and post-processing of raw sound levels into impact ranges in NIRAS SILENCE, using the threshold criteria in chapter 5. The results are presented in the following formats:

- **Numerical result tables**: showing the maximum range in any direction from the source to respective threshold criteria. Tables showing the overlap with nearby protection zones, and the total area affected are also provided.
- **Noise contour maps**: showing the direction specific impact range for certain threshold criteria, along with the total area affected.

Distance to PTS, TTS and injury threshold criteria 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 at which distance from the pile driving activities the animals should be, to avoid the respective impact.

Distance to behavioural threshold criteria describe the range at which behavioural reactions are likely to occur when the maximum hammer energy is applied. For pile strikes where less than 100% hammer energy is utilized, the impact range will be shorter.

### 8.8.1. Mitigated impact ranges for fish threshold criteria

For fish, all threshold criteria are based on the frequency unweighted $L_{E,cum,24h}$ [dB re. 1 μPa$^2$s]. Impact ranges are calculated for a series of different swim speeds as well as stationary, as discussed in section 5.1.

Resulting impact ranges are provided in Table 8.7, and affected area for TTS in Table 8.8.

*Table 8.7: Impact range for fish threshold criteria, with mitigation measures.*

**Impact range for fish threshold criteria**

| Position | Injury ($r_{injury}$) | | | | | TTS ($r_{TTS}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Stationary | Juvenile Cod | Adult Cod | Herring | Larvae and eggs | Stationary | Juvenile Cod | Adult Cod | Herring |
| 4-legged jacket foundation with 4 m diameter pin piles, BBC, March | | | | | | | | | |
| 1 | 1.0 km | < 200 m | < 200 m | < 200 m | 625 m | 7.8 km | 1.45 km | < 200 m | < 200 m |
| 2 | 1.55 km | < 200 m | < 200 m | < 200 m | 1.05 km | 14.4 km | 5.3 km | 1.55 km | 1.05 km |
| 3 | 1.55 km | < 200 m | < 200 m | < 200 m | 1.05 km | 15.3 km | 6.2 km | 1.8 km | 1.2 km |
| 4 | 1.8 km | < 200 m | < 200 m | < 200 m | 1.3 km | 21.8 km | 11.1 km | 3.95 km | 3.0 km |
| 5 | 1.4 km | < 200 m | < 200 m | < 200 m | 750 m | 17.3 km | 7.3 km | 1.85 km | 1.15 km |
| 4-legged jacket foundation with 4 m diameter pin piles, DBBC, March | | | | | | | | | |
| 1 | 650 m | < 200 m | < 200 m | < 200 m | 450 m | 5300 m | 525 m | < 200 m | < 200 m |
| 2 | 1.05 km | < 200 m | < 200 m | < 200 m | 625 m | 11.6 km | 3.1 km | 325 m | < 200 m |
| 3 | 1.05 km | < 200 m | < 200 m | < 200 m | 600 m | 11.4 km | 3.25 km | 325 m | < 200 m |
| 4 | 1.3 km | < 200 m | < 200 m | < 200 m | 750 m | 16.4 km | 5.6 km | 1.1 km | 650 m |
| 5 | 775 m | < 200 m | < 200 m | < 200 m | 525 m | 11.9 km | 3.15 km | < 200 m | < 200 m |

*Table 8.8: Area affected for fish TTS.*

| Position | Affected area (TTS) [$km^2$] | | | |
|---|---|---|---|---|
| | Stationary | Juvenile Cod | Adult Cod | Herring |
| | 4-legged jacket foundation with 4 m diameter pin piles, BBC, March | | | |
| 1 | 108 | 4 | < 1 | < 1 |
| 2 | 462 | 56 | 4 | 2 |
| 3 | 359 | 47 | 3 | 1 |
| 4 | 1066 | 223 | 28 | 15 |
| 5 | 458 | 60 | 3 | 1 |
| | 4-legged jacket foundation with 4 m diameter pin piles, DBBC, March | | | |
| 1 | 65 | < 1 | < 1 | < 1 |
| 2 | 290 | 18 | < 1 | < 1 |
| 3 | 206 | 13 | < 1 | < 1 |
| 4 | 589 | 63 | 2 | 1 |
| 5 | 230 | 11 | < 1 | < 1 |

Noise contour maps for fish TTS and Injury with BBC mitigation effect using a BBC mitigation effect are shown in Figure 8.23 - Figure 8.27.

Noise contour maps for fish TTS and Injury with DBBC mitigation effect using a DBBC are shown in Figure 8.28 - Figure 8.32.

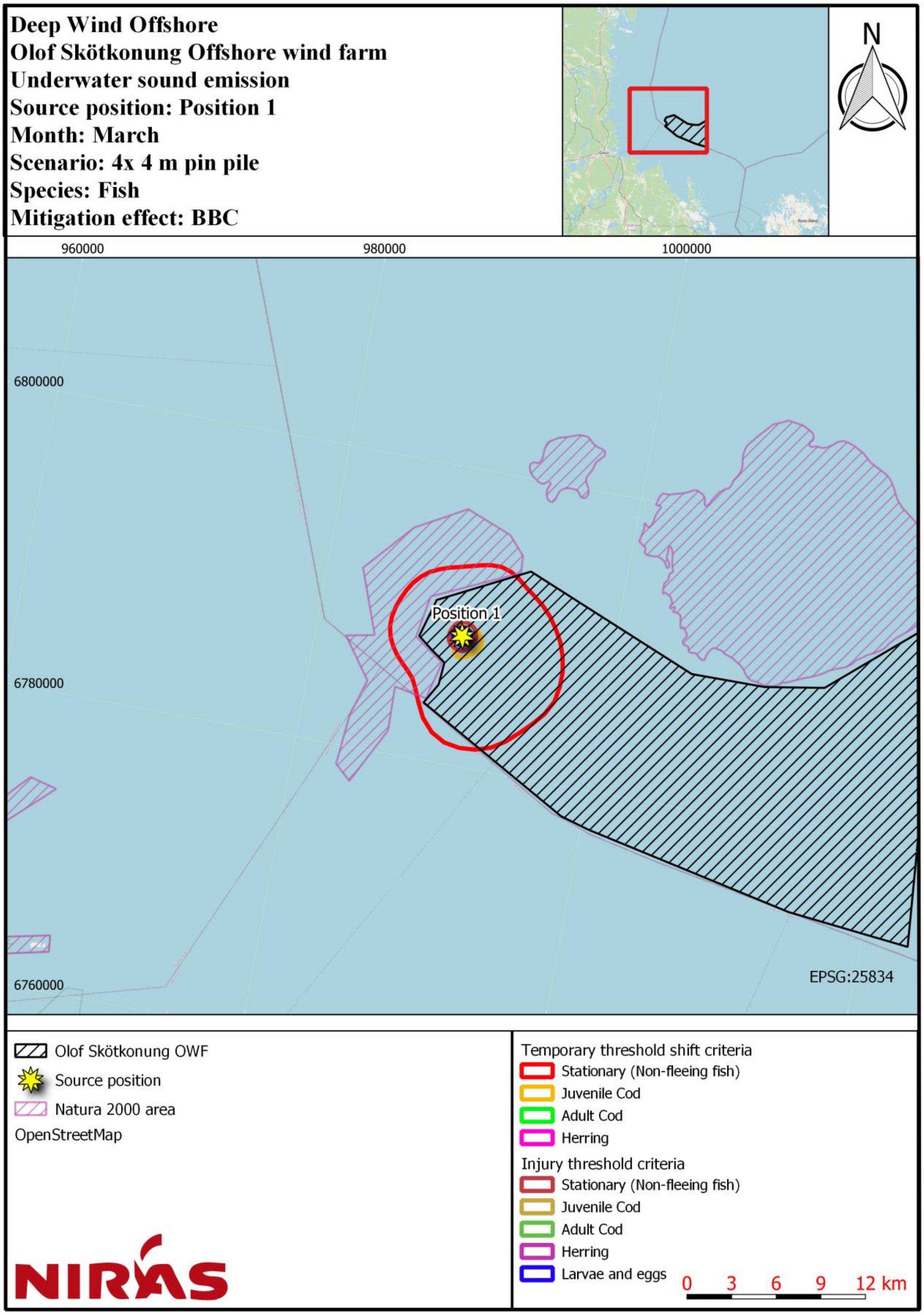



*Figure 8.23: Noise contour map for fish TTS and Injury with BBC mitigation effect; Position 1.*

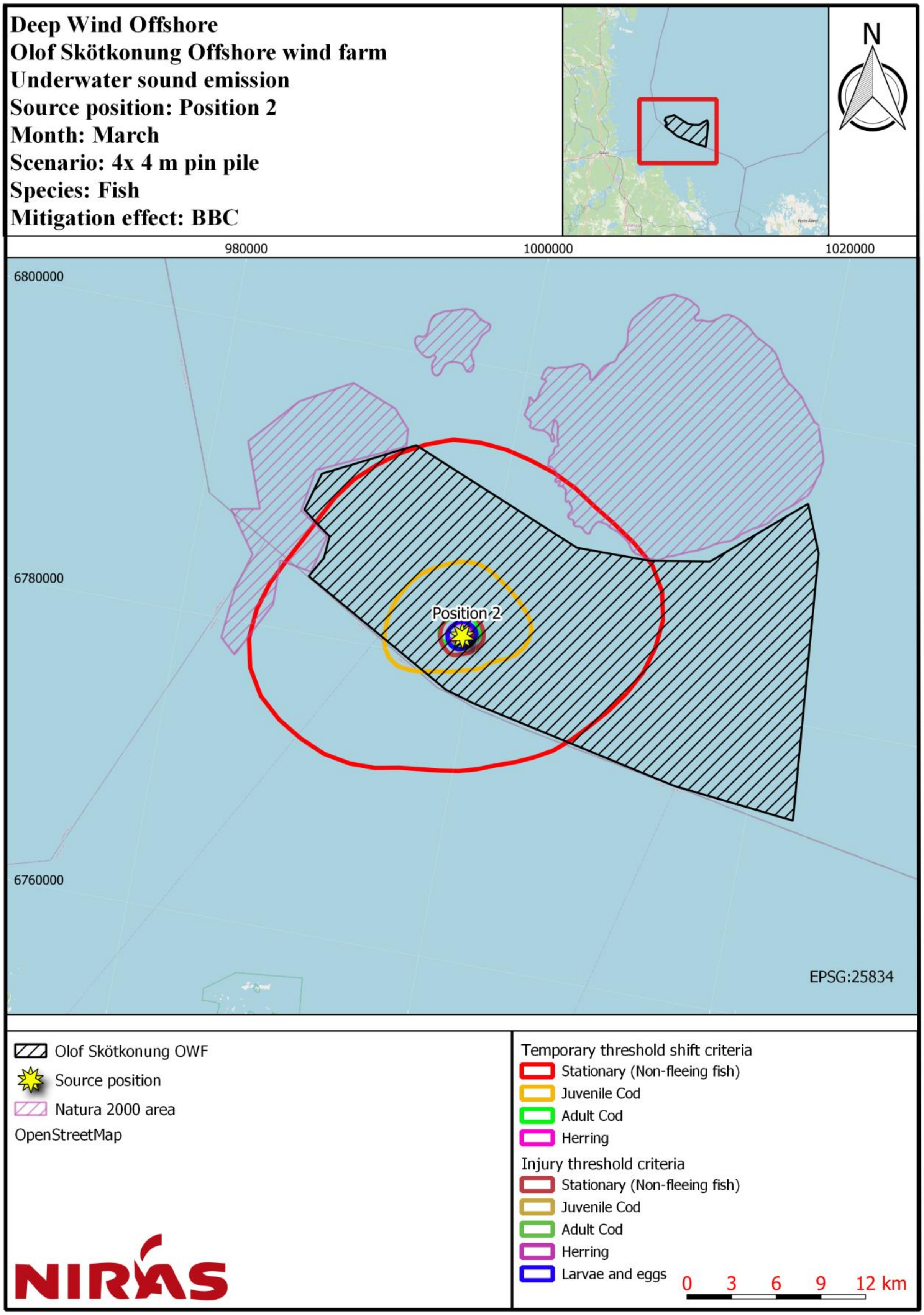



*Figure 8.24: Noise contour map for fish TTS and Injury with BBC mitigation effect; Position 2.*

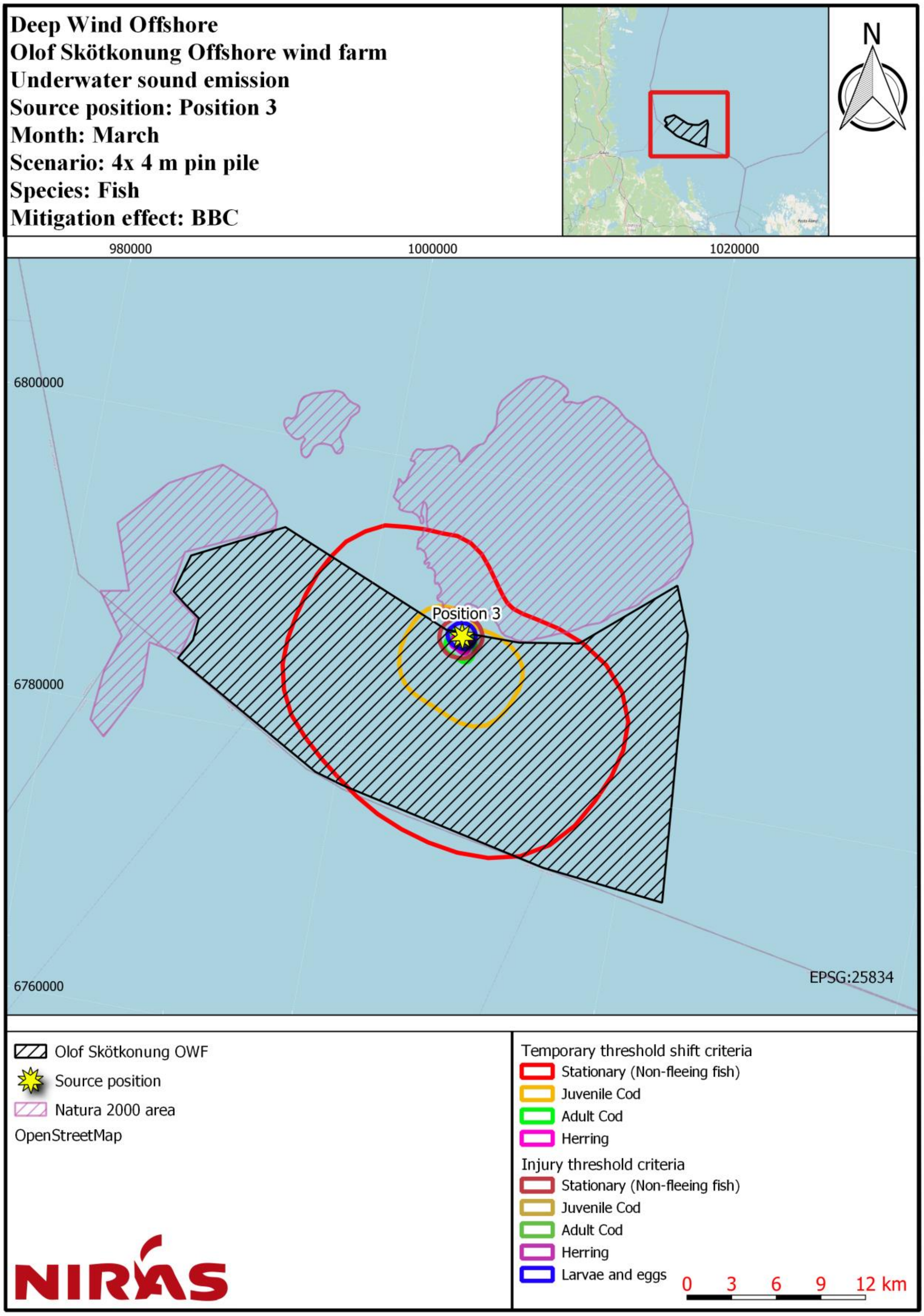



*Figure 8.25: Noise contour map for fish TTS and Injury with BBC mitigation effect; Position 3.*

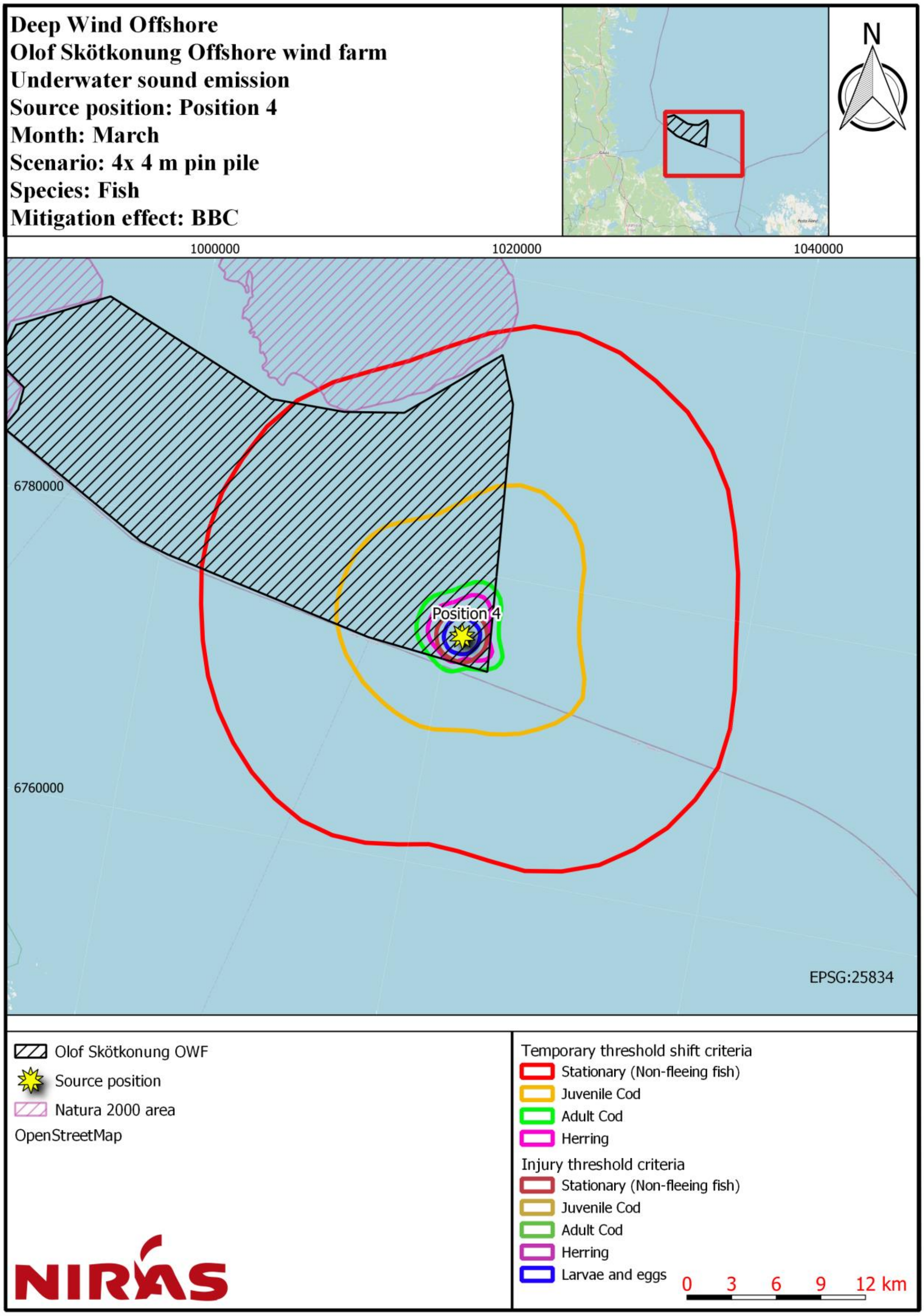



*Figure 8.26: Noise contour map for fish TTS and Injury with BBC mitigation effect; Position 4.*

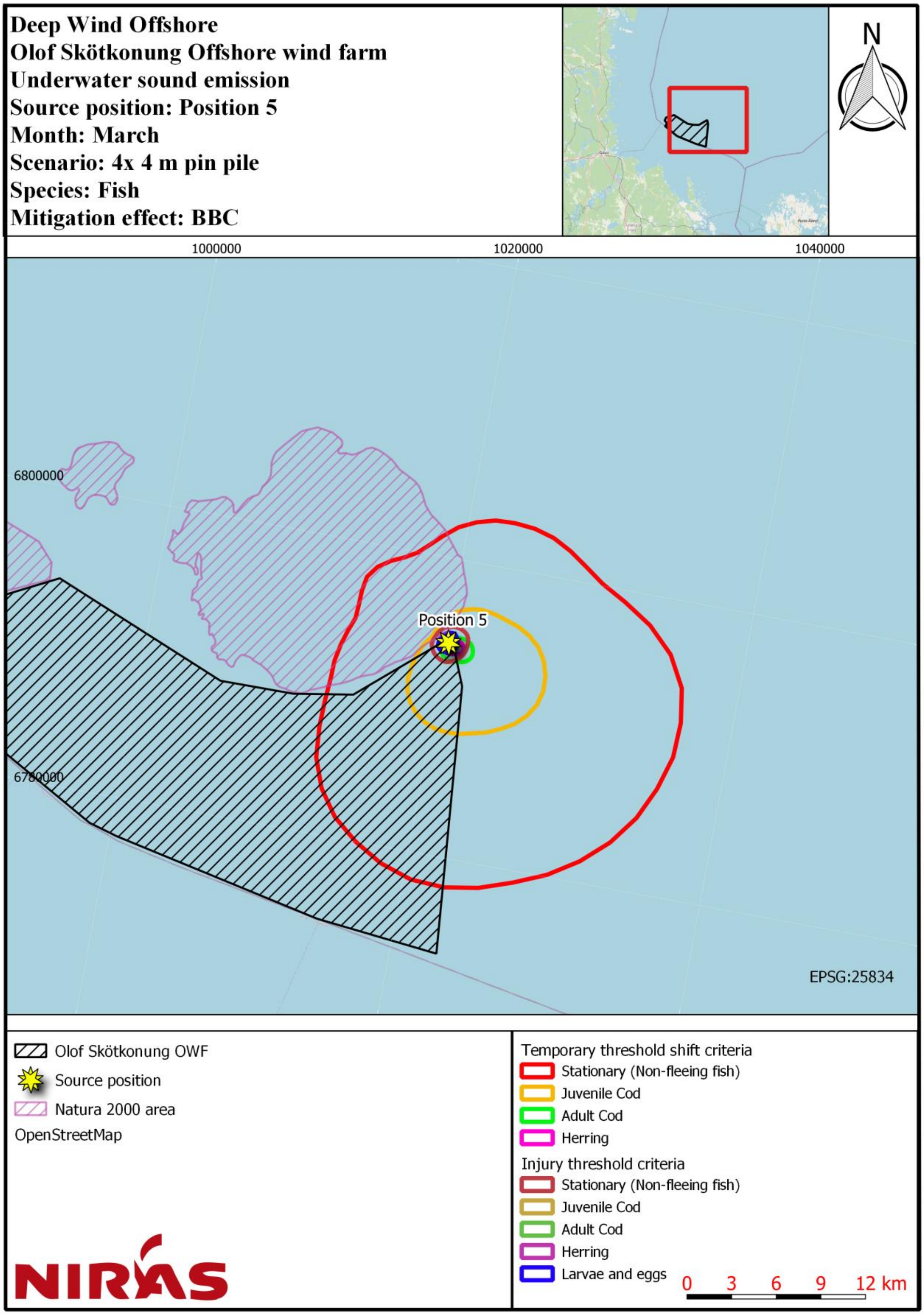



*Figure 8.27: Noise contour map for fish TTS and Injury with BBC mitigation effect; Position 5.*

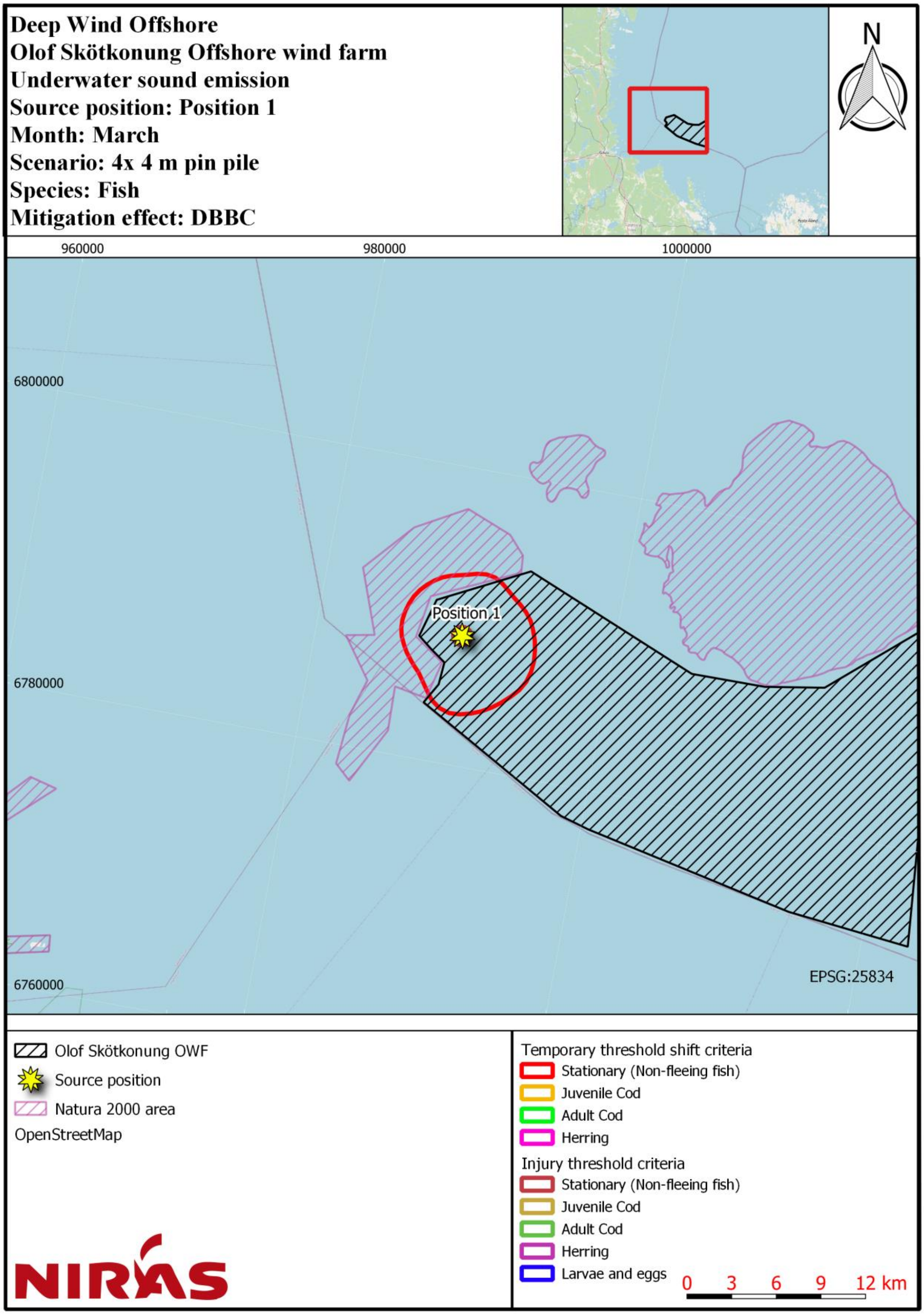



*Figure 8.28: Noise contour map for fish TTS and Injury with DBBC mitigation effect; Position 1.*

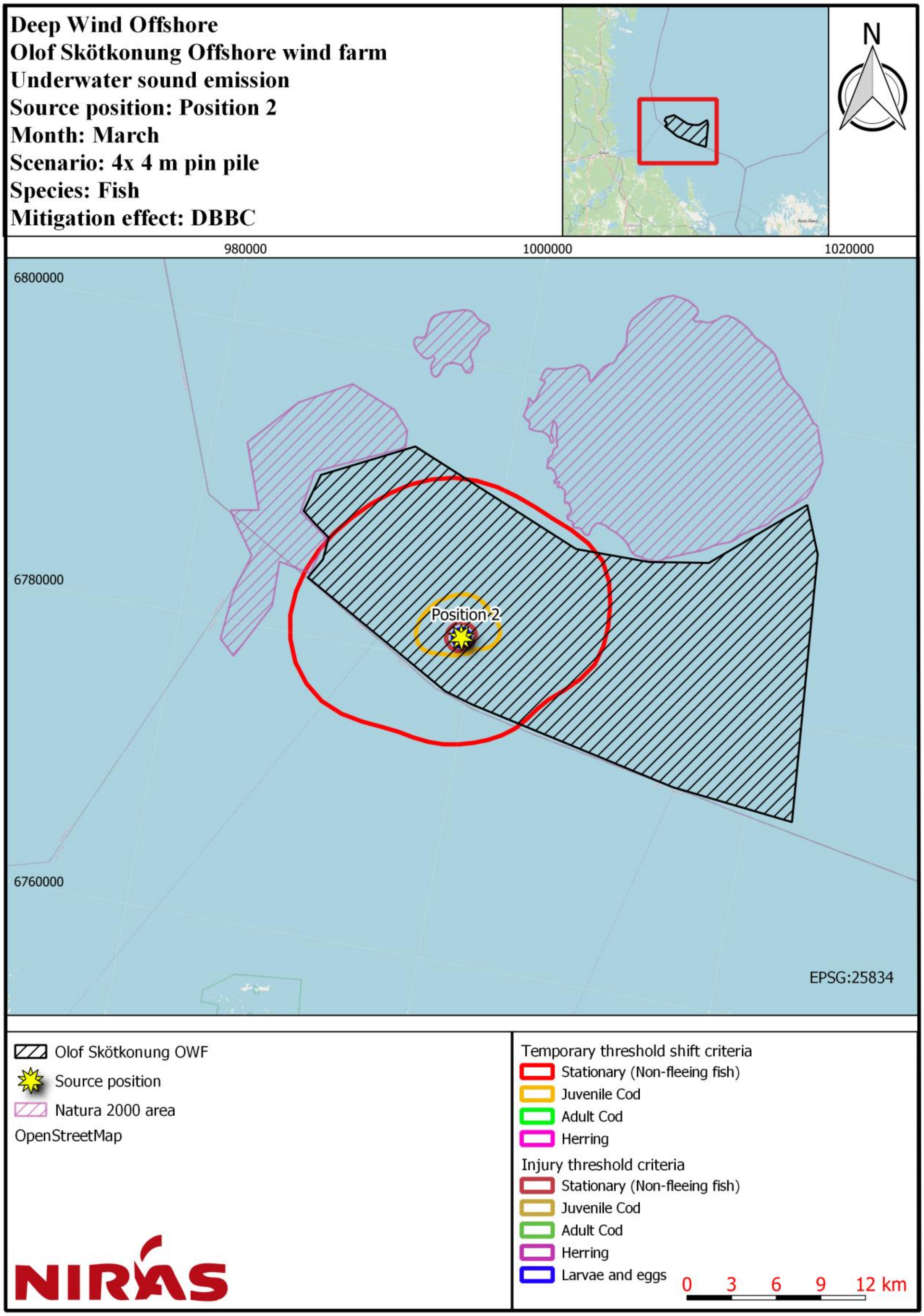



*Figure 8.29: Noise contour map for fish TTS and Injury with DBBC mitigation effect; Position 2.*

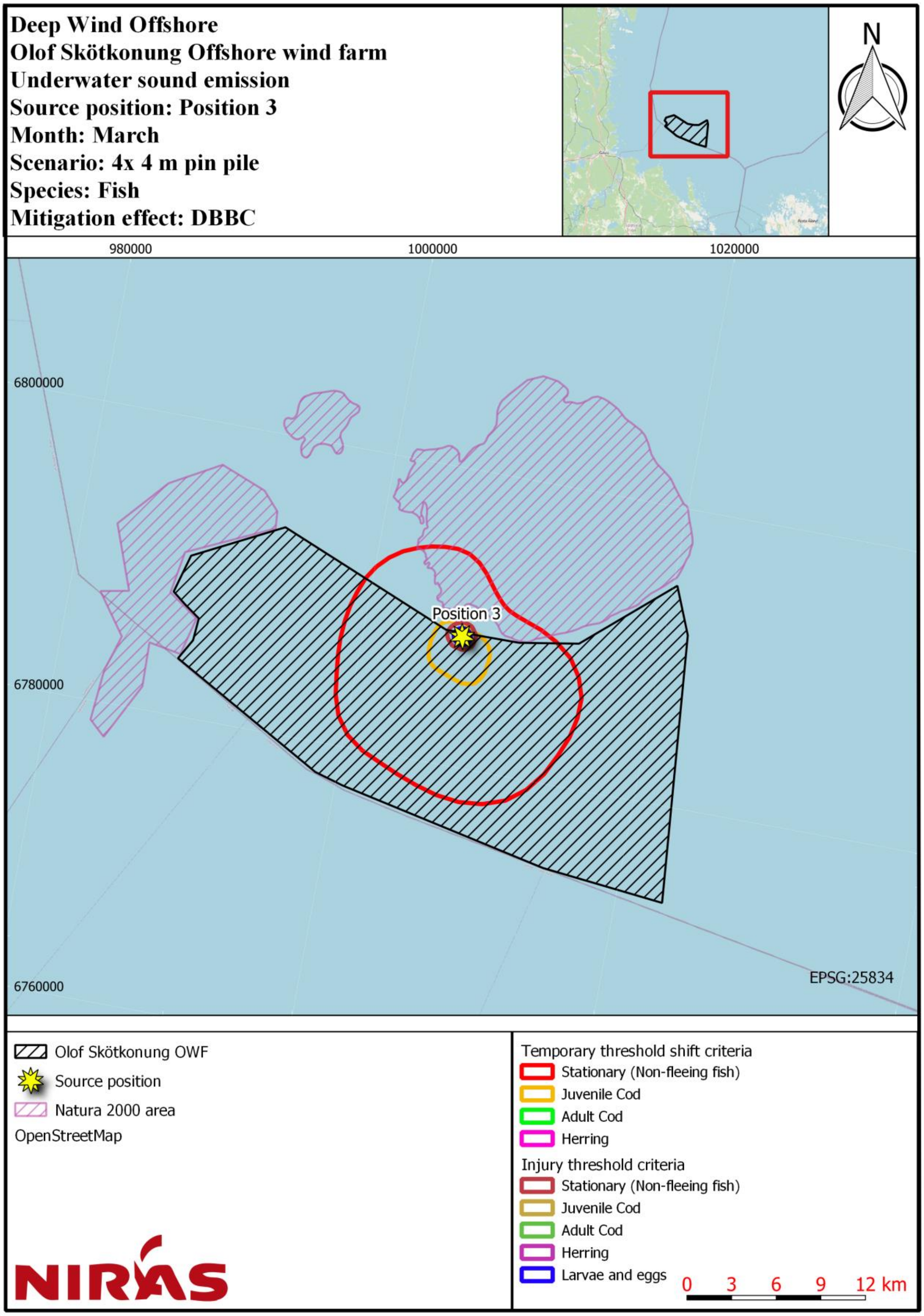



*Figure 8.30: Noise contour map for fish TTS and Injury with DBBC mitigation effect; Position 3.*

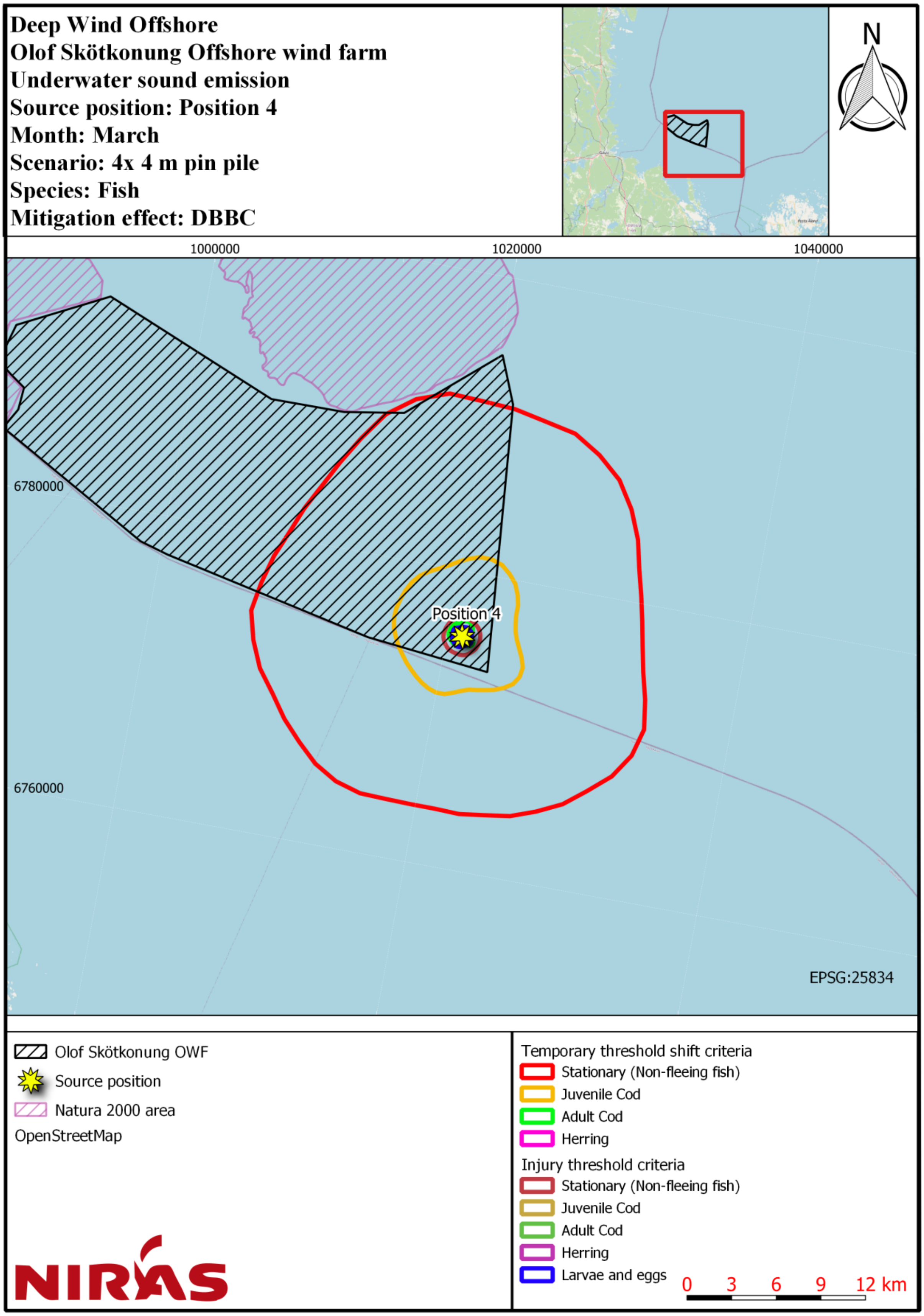



*Figure 8.31: Noise contour map for fish TTS and Injury with DBBC mitigation effect; Position 4.*

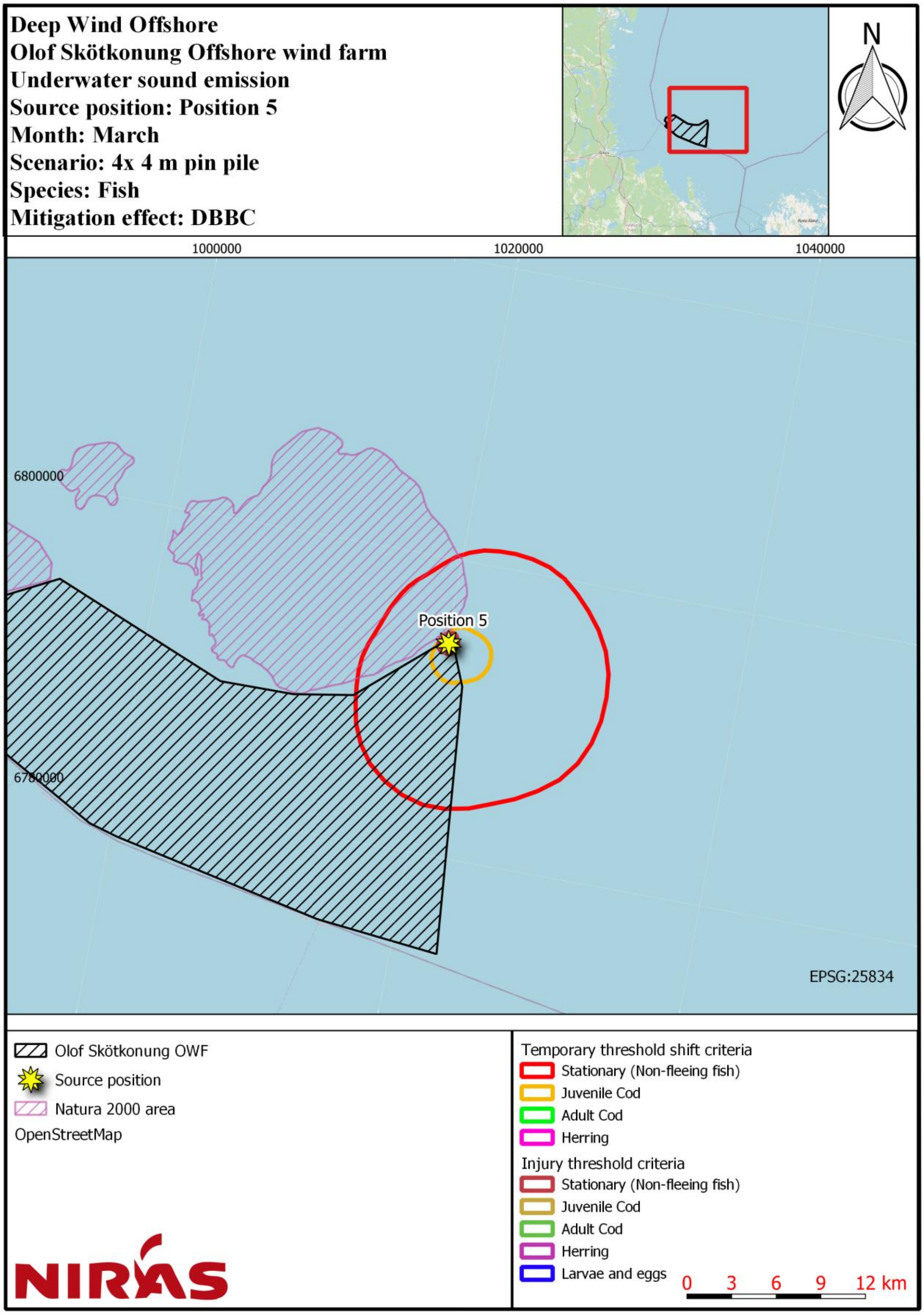



*Figure 8.32: Noise contour map for fish TTS and Injury with DBBC mitigation effect; Position 5.*

### 8.8.2. Mitigated impact ranges for marine mammal threshold criteria

For marine mammals, PTS and TTS threshold criteria are based on the frequency weighted $L_{E,cum,24h,xx}$ [dB re. 1 μPa²s], where "xx" refers to the species specific weighting function. Species specific fleeing behaviour as outlined in section 5.2 is assumed.

Threshold criteria for behaviour reaction is based on the frequency weighted $L_{p,125ms,xx}$ [dB re. 1 μPa].

Resulting impact ranges are provided in Table 8.9, and affected area for behaviour in Table 8.10.

For behaviour reaction in harbour porpoise, also the overlapping area with nearby Natura 2000 areas is listed in Table 8.11.

*Table 8.9: Impact ranges for marine mammal threshold criteria, with mitigation measures*

| | Impact range for marine mammal threshold criteria | | | | |
|---|---|---|---|---|---|
| **Position** | PTS | | TTS | | Behaviour |
| | Porpoise (VHF) | Seal (PCW) | Porpoise (VHF) | Seal (PCW) | Porpoise (VHF) |
| 4-legged jacket foundation with 4 m diameter pin piles, BBC, March | | | | | |
| 1 | < 200 m | < 200 m | < 200 m | < 200 m | 7.4 km |
| 2 | < 200 m | < 200 m | < 200 m | < 200 m | 8.7 km |
| 3 | < 200 m | < 200 m | < 200 m | < 200 m | 7.8 km |
| 4 | < 200 m | < 200 m | < 200 m | < 200 m | 8.7 km |
| 5 | < 200 m | < 200 m | < 200 m | < 200 m | 8.8 km |
| 4-legged jacket foundation with 4 m diameter pin piles, DBBC, March | | | | | |
| 1 | < 200 m | < 200 m | < 200 m | < 200 m | 5.0 km |
| 2 | < 200 m | < 200 m | < 200 m | < 200 m | 5.8 km |
| 3 | < 200 m | < 200 m | < 200 m | < 200 m | 6.3 km |
| 4 | < 200 m | < 200 m | < 200 m | < 200 m | 6.6 km |
| 5 | < 200 m | < 200 m | < 200 m | < 200 m | 6.4 km |

*Table 8.10: Area affected for behaviour threshold criteria in marine mammals.*

| Position | Affected area (behaviour in harbour porpoise) [km²] |
|---|---|
| 4-legged jacket, BBC, March | |
| 1 | 116 |
| 2 | 161 |
| 3 | 121 |
| 4 | 213 |
| 5 | 155 |
| 4-legged jacket, DBBC, March | |
| 1 | 62 |
| 2 | 88 |
| 3 | 72 |
| 4 | 119 |
| 5 | 80 |

*Table 8.11: Area of Natura 2000 site where sound levels exceed marine mammal behaviour threshold criteria.*

| Position | Natura 2000 site | Affected Natura 2000 area [$km^2$ / % of Natura 2000 area] |
|---|---|---|
| | 4-legged jacket, BBC, March | |
| 1 | Finngrundet-Västra banken | 30 $km^2$/ 36 % |
| 2 | - | 0 $km^2$/ 0 % |
| 3 | Finngrundet-Östra banken | 10 $km^2$/ 4 % |
| 4 | - | 0 $km^2$/ 0 % |
| 5 | Finngrundet-Östra banken | 24 $km^2$/ 10 % |
| | 4-legged jacket, DBBC, March | |
| 1 | Finngrundet-Västra banken | 13 $km^2$/ 16 % |
| 2 | - | 0 $km^2$/ 0 % |
| 3 | Finngrundet-Östra banken | 6 $km^2$/ 3 % |
| 4 | - | 0 $km^2$/ 0 % |
| 5 | Finngrundet-Östra banken | 11 $km^2$/ 5 % |

Noise contour maps for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect are shown in Figure 8.33 - Figure 8.37.

Noise contour maps for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect are shown in Figure 8.38 - Figure 8.42.

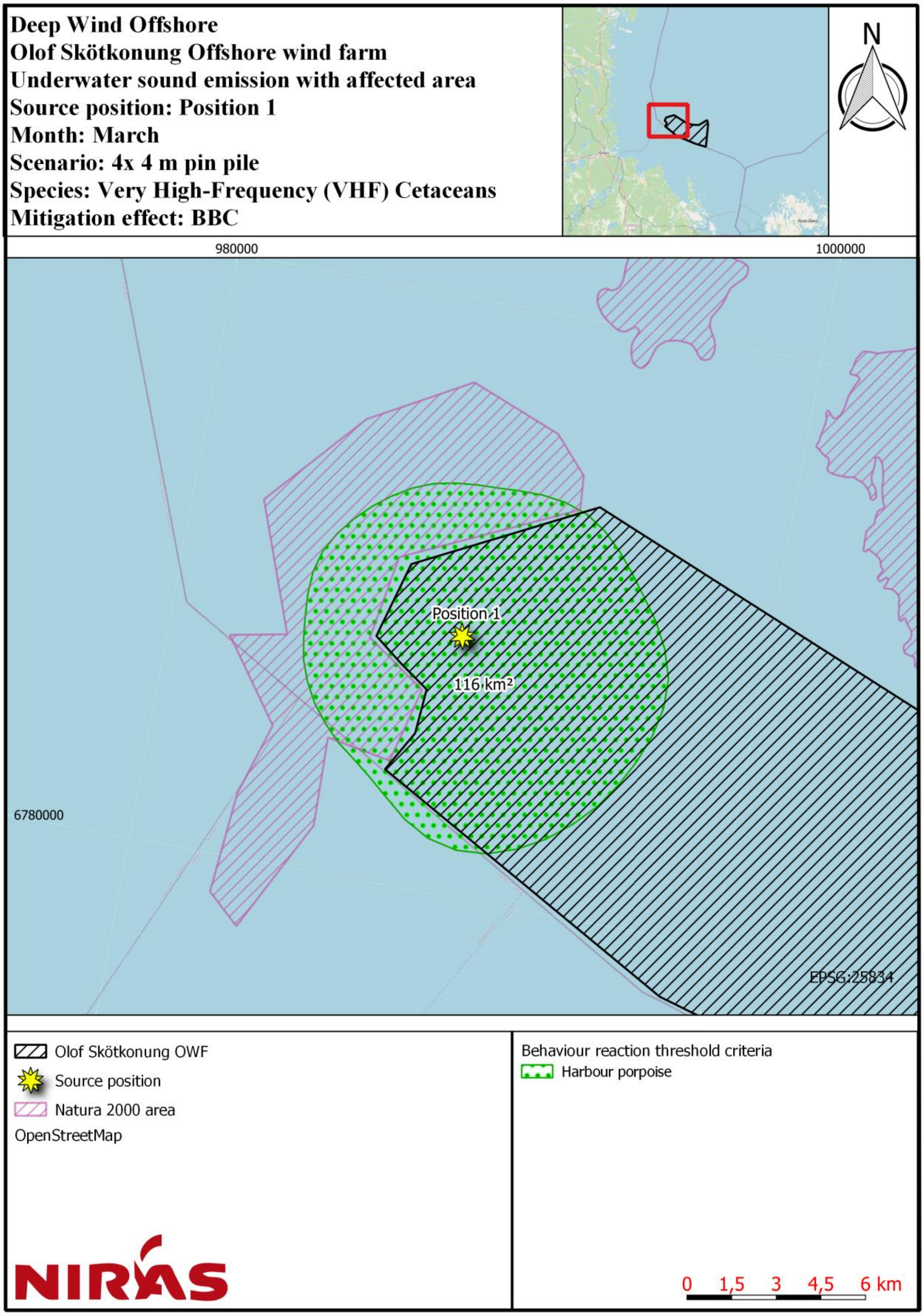



*Figure 8.33: Noise contour map for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect; Position 1.*

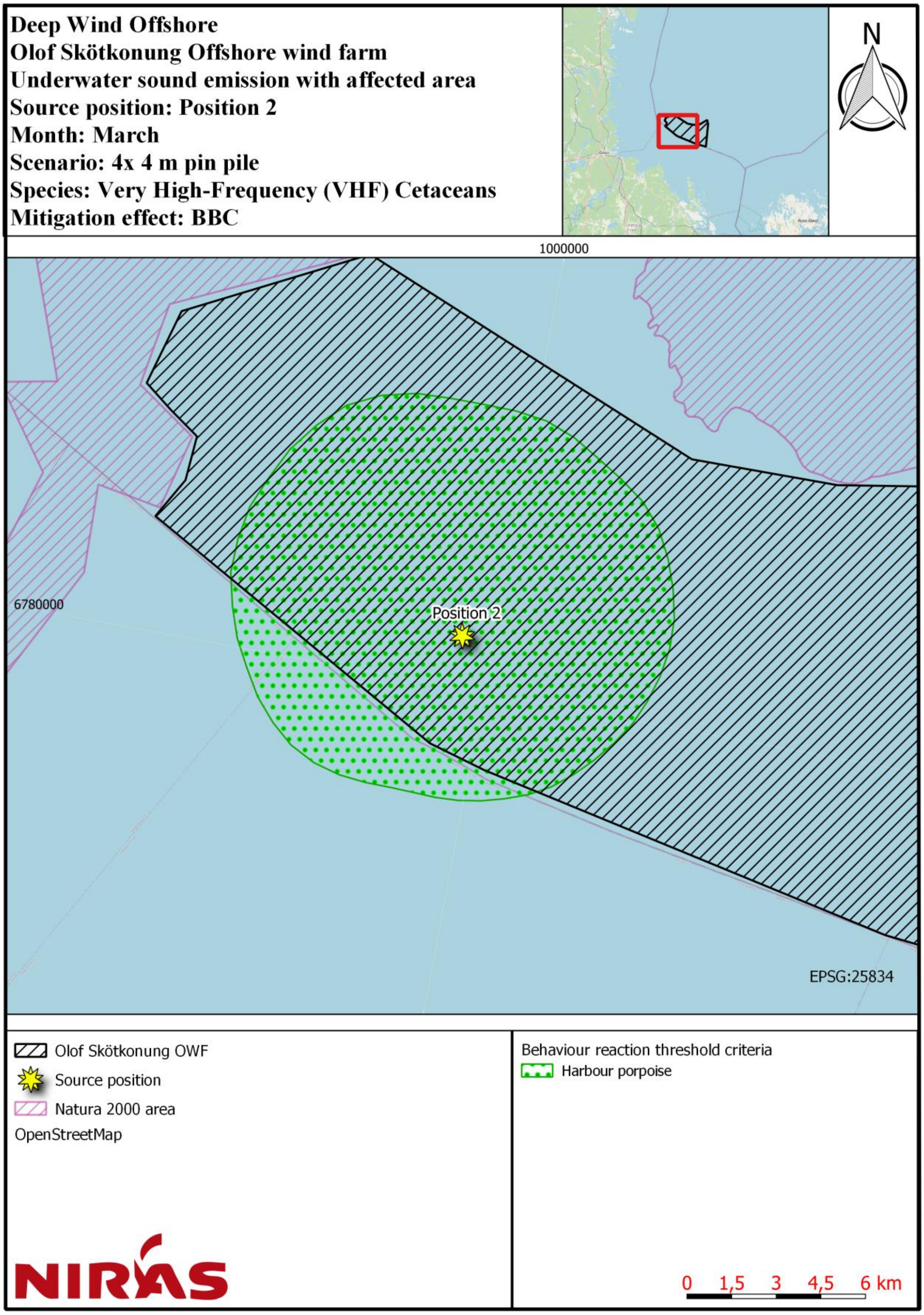



*Figure 8.34: Noise contour map for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect; Position 2.*

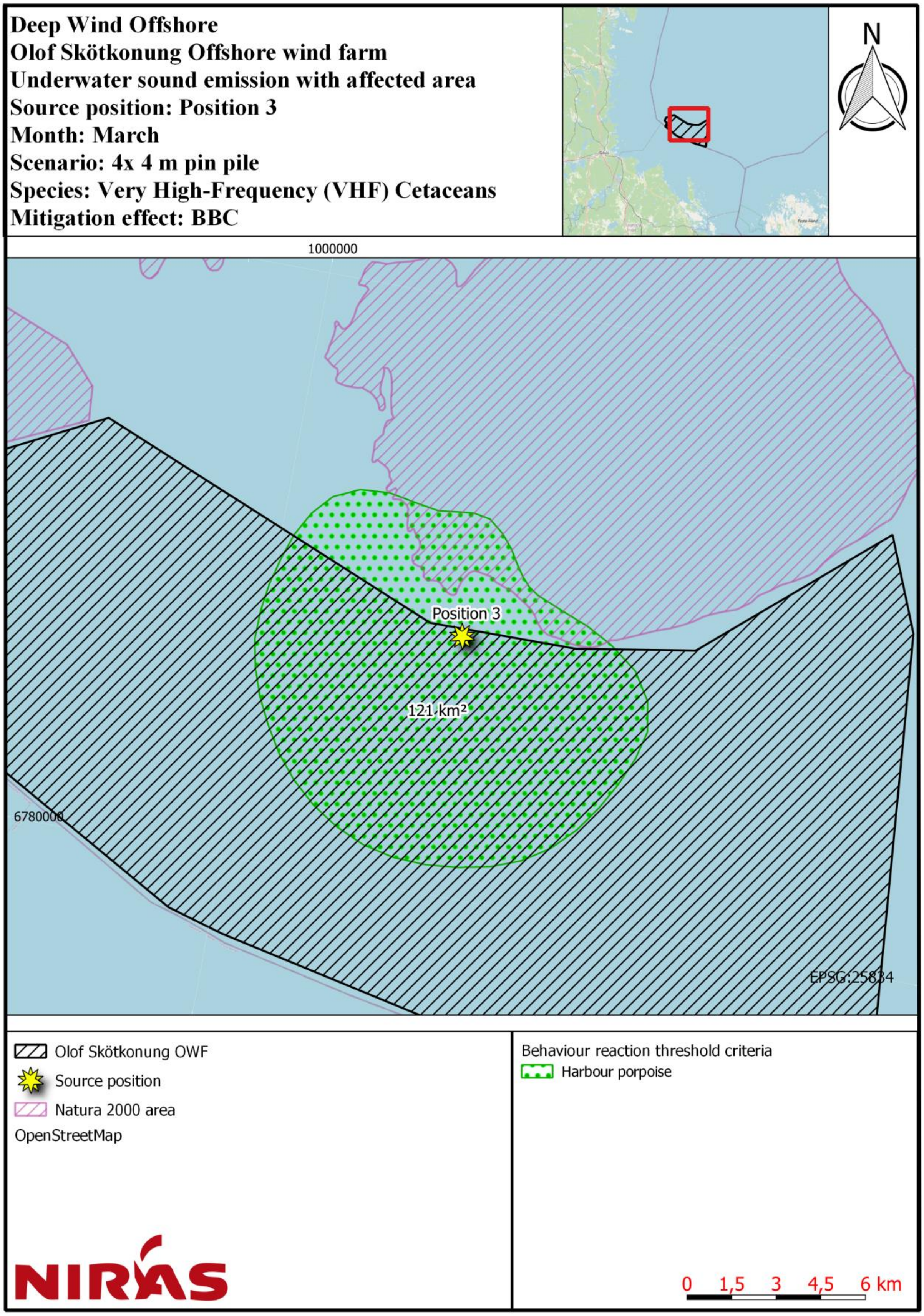



*Figure 8.35: Noise contour map for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect; Position 3.*

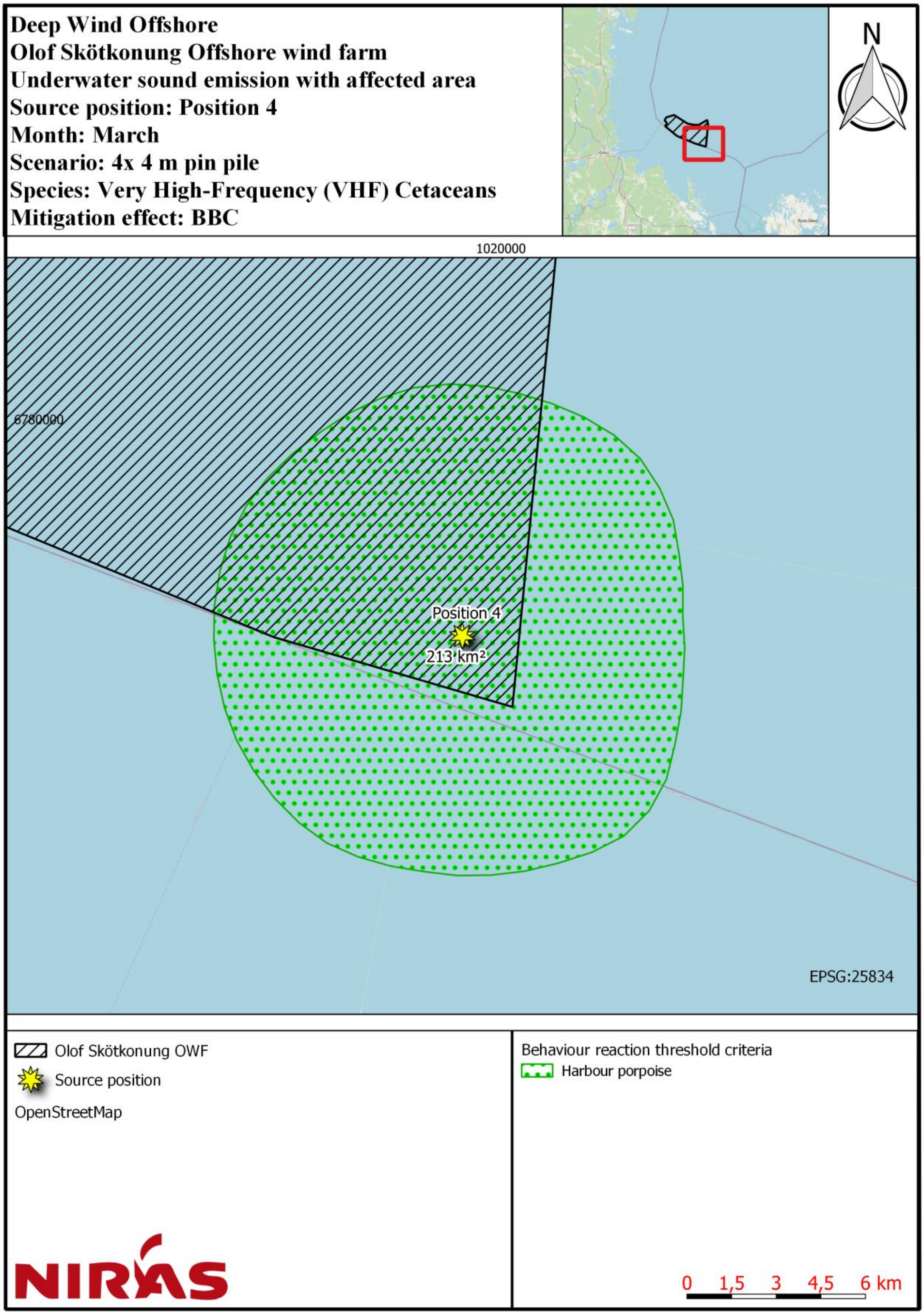



*Figure 8.36: Noise contour map for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect; Position 4.*

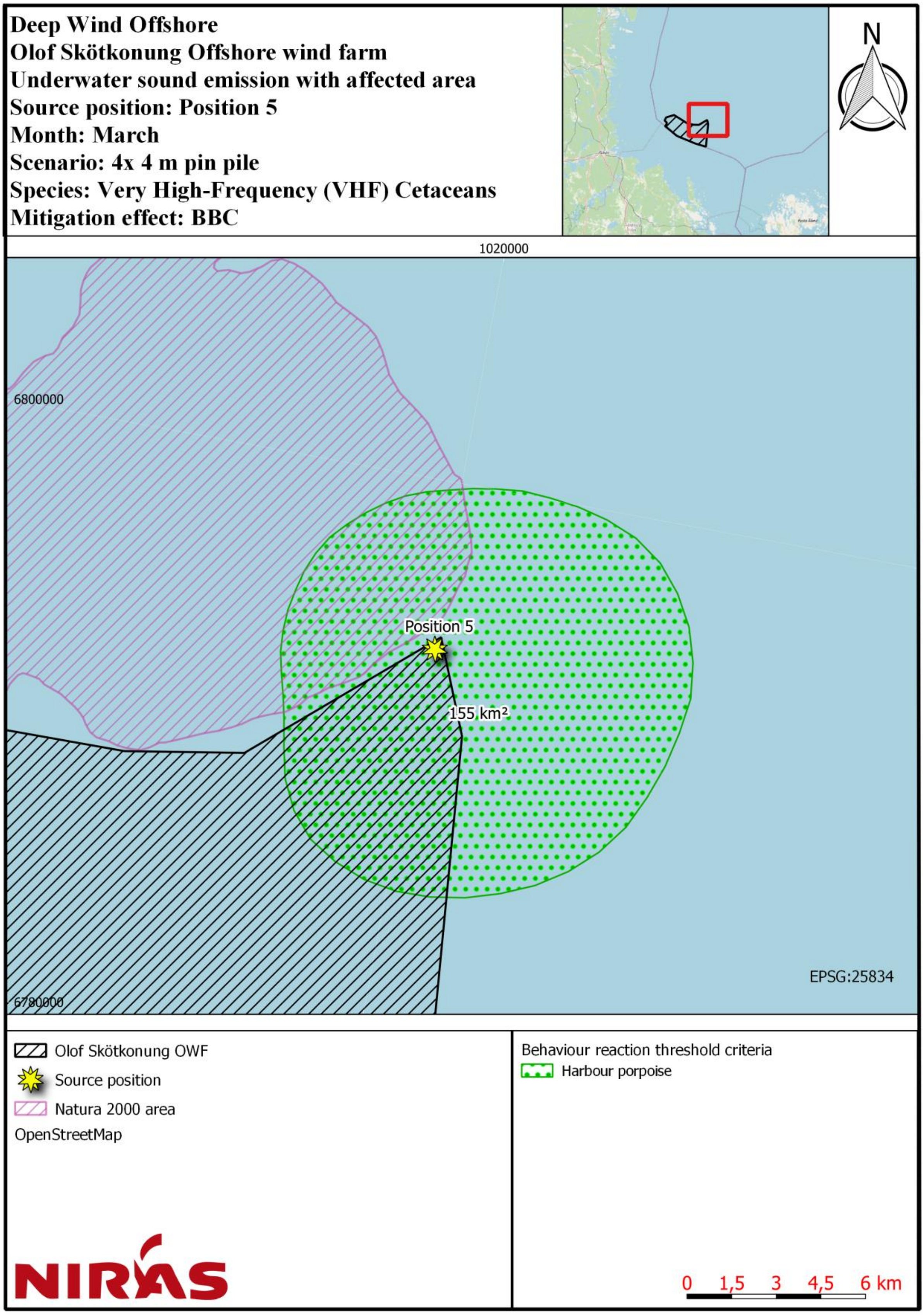



*Figure 8.37: Noise contour map for very high frequency (VHF) cetaceans behaviour with BBC mitigation effect; Position 5.*

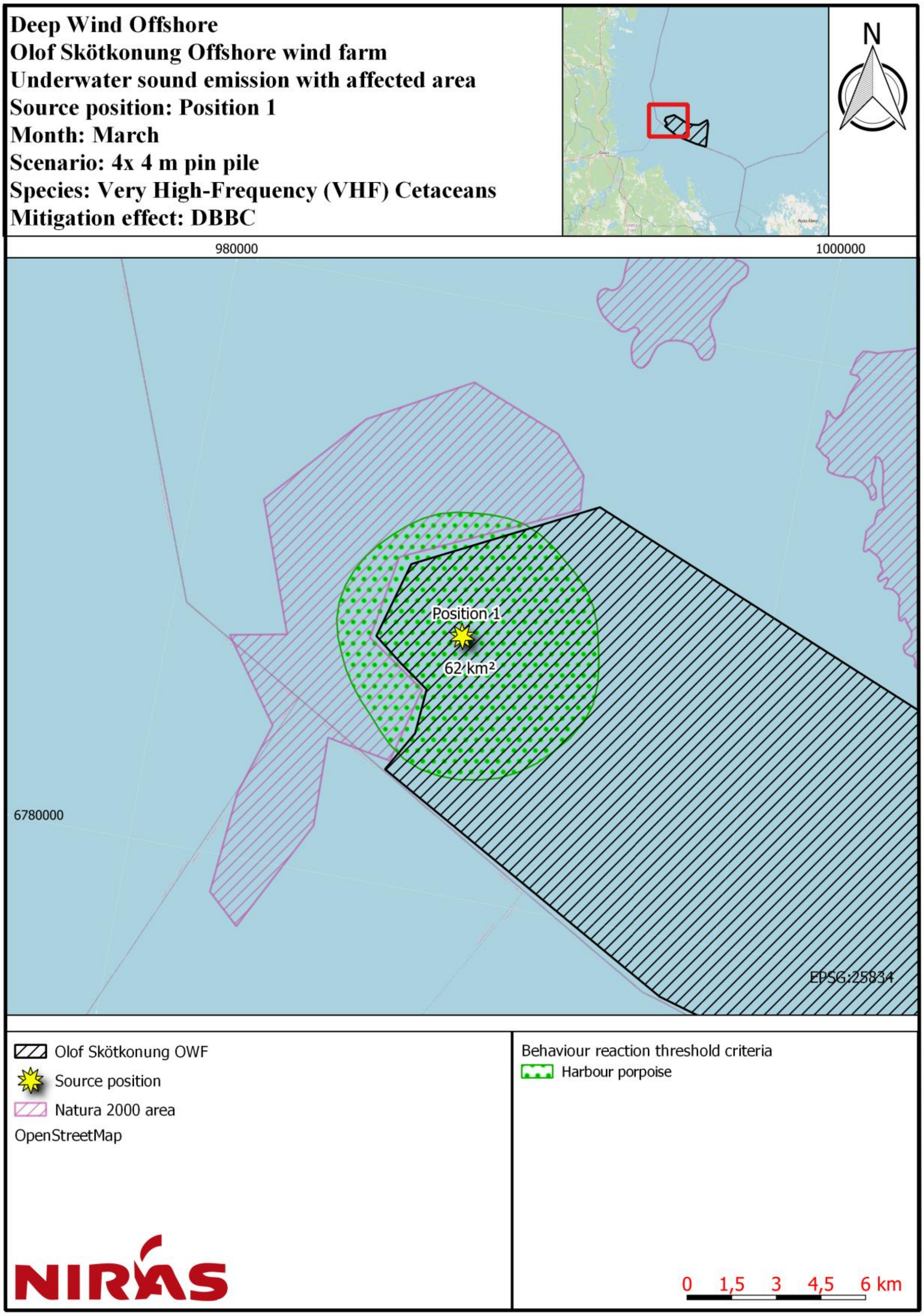



*Figure 8.38: Noise contour map for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect; Position 1.*

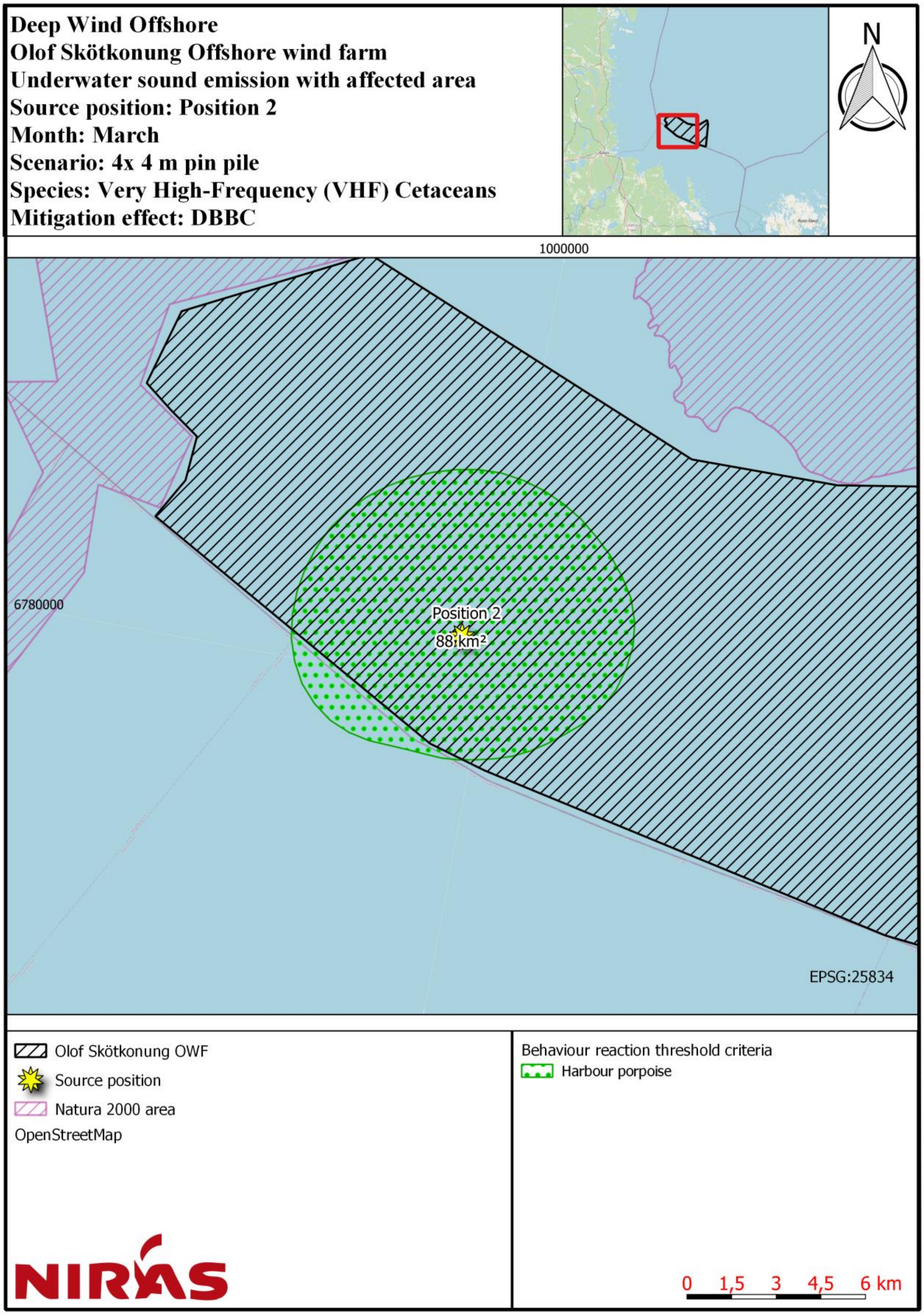



*Figure 8.39: Noise contour map for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect; Position 2.*

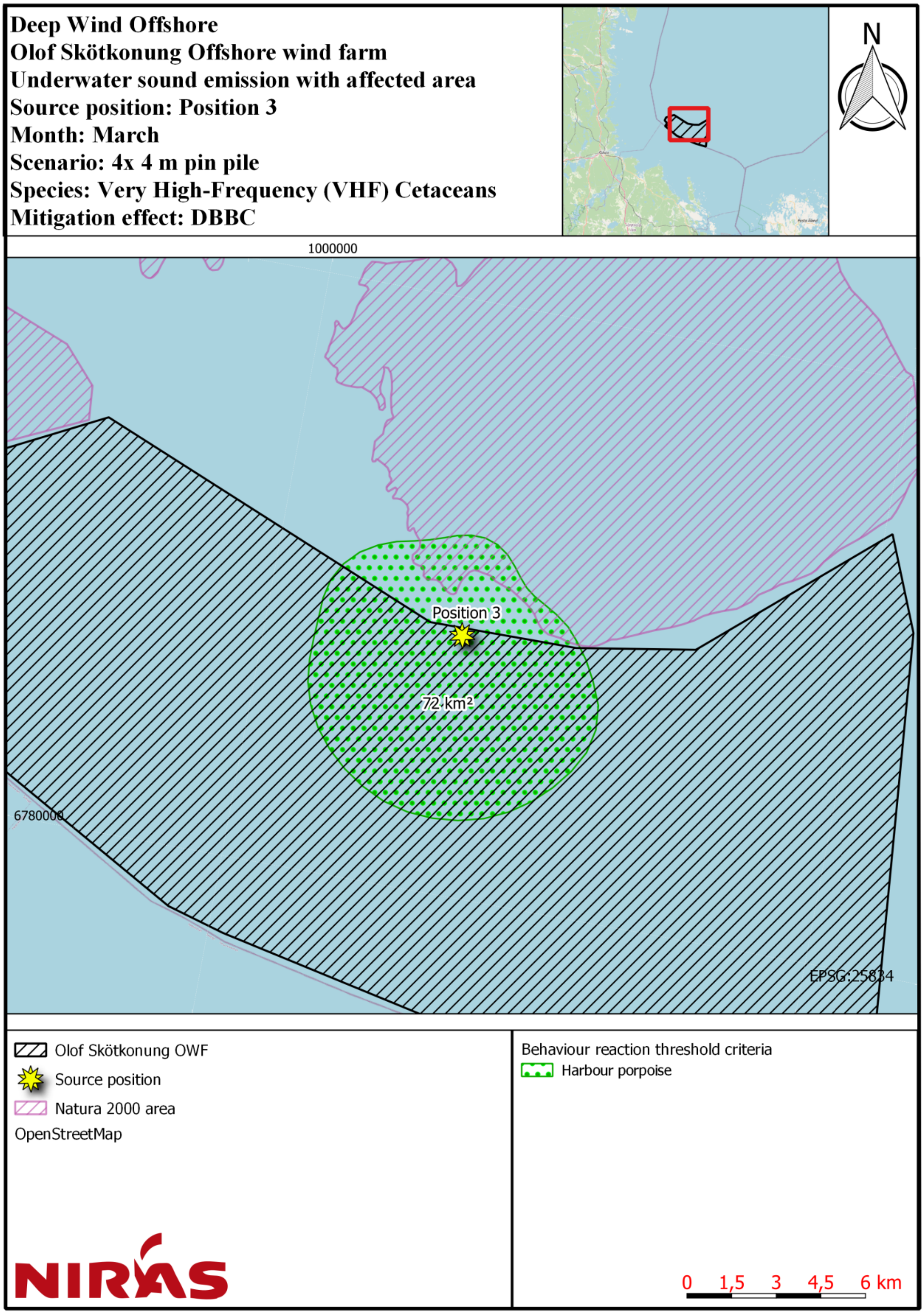



*Figure 8.40: Noise contour map for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect; Position 3.*

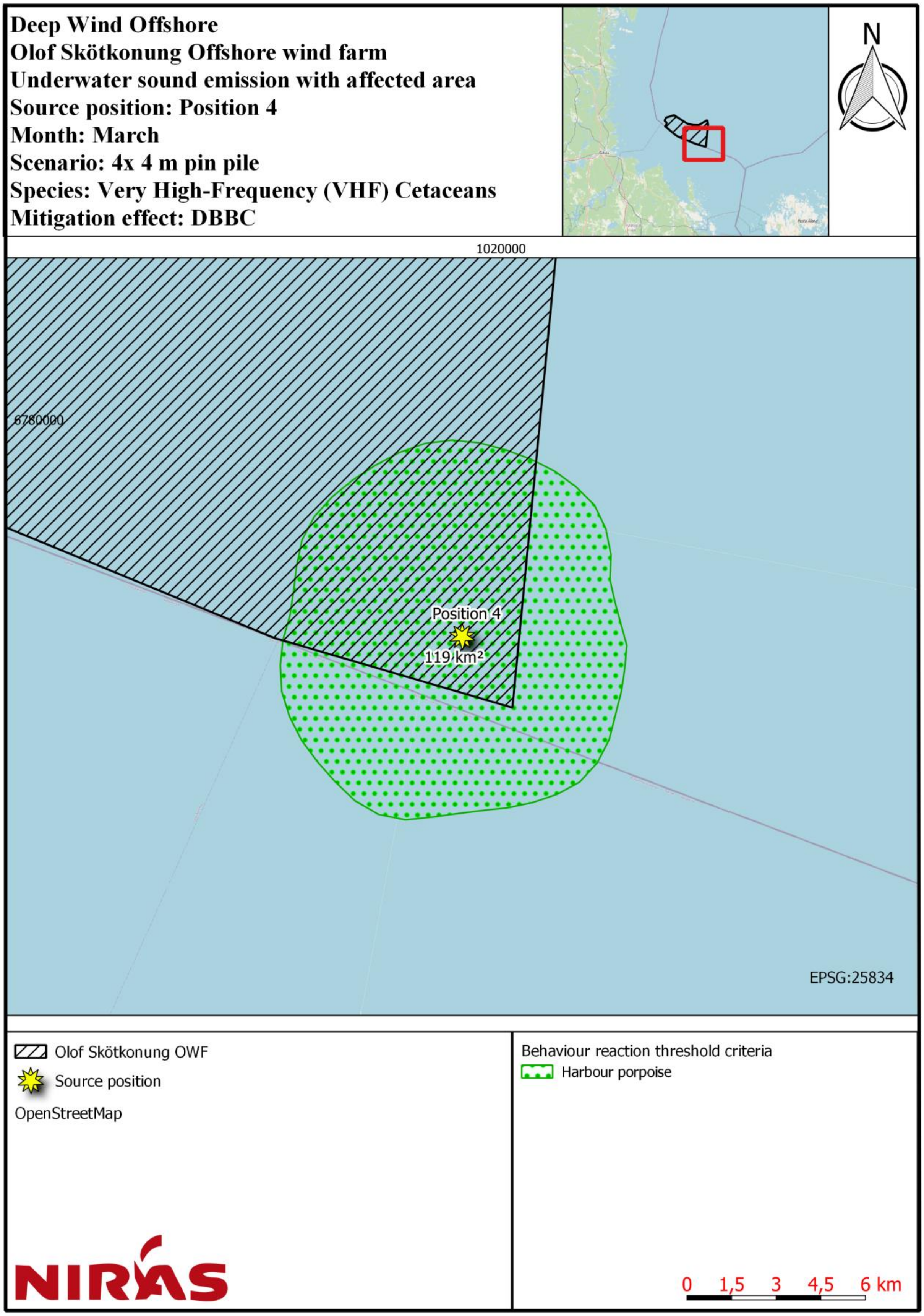



*Figure 8.41: Noise contour map for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect; Position 4.*

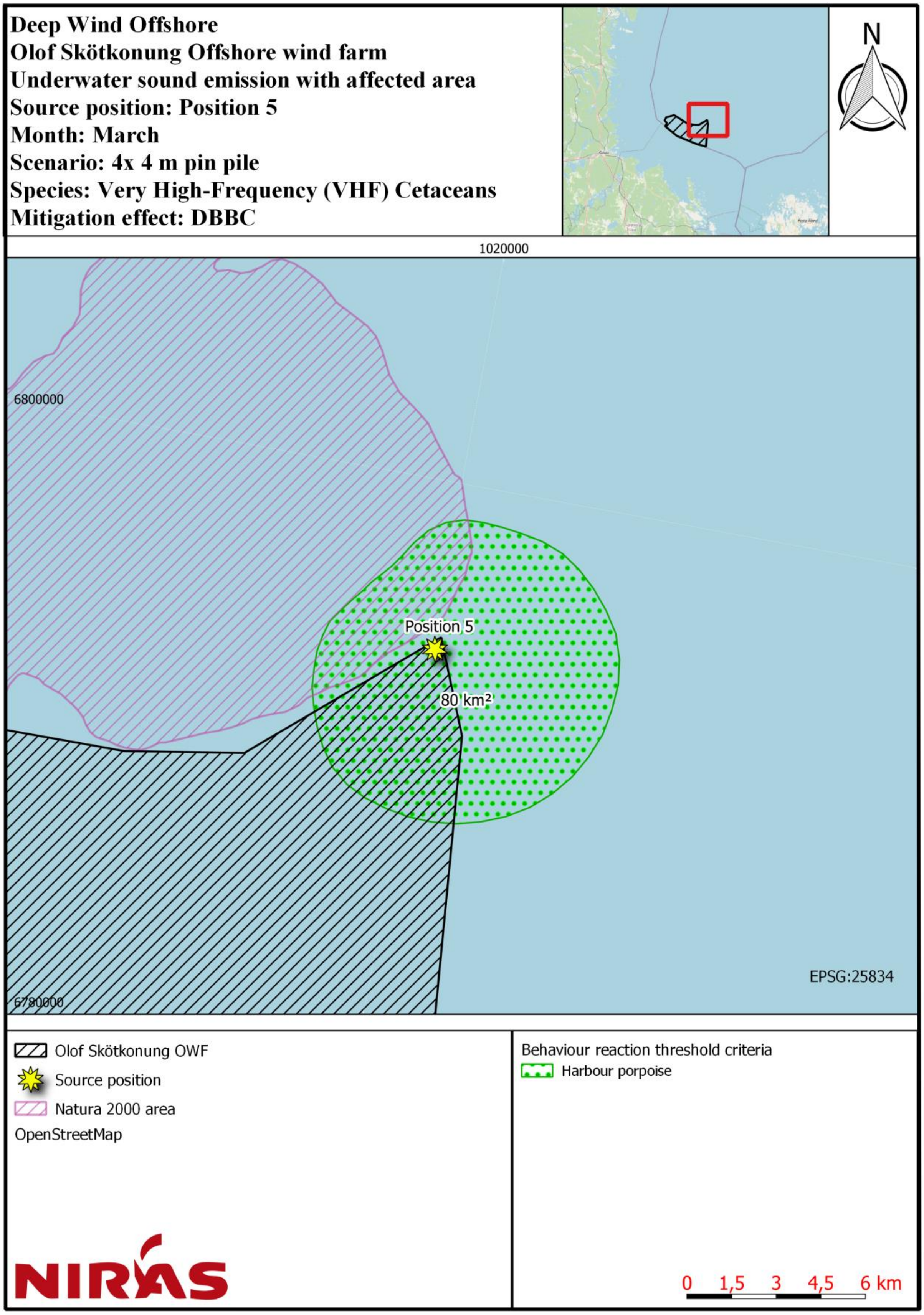



*Figure 8.42: Noise contour map for very high frequency (VHF) cetaceans behaviour with DBBC mitigation effect; Position 5.*

# 9. Underwater noise evaluation for operation phase

Underwater noise from offshore wind turbines comes primarily from two sources: mechanical vibrations in the nacelle (gearbox etc.), which are transmitted through the tower and radiated into the surrounding water; and underwater radiated noise from the service boats in the wind farm. In a review by Tougaard (2020), measurements of underwater noise from existing operational wind turbines are presented, whereby measured underwater noise levels are evaluated as a function of wind speed and turbine size. For monopiles, the review considers measurements from 0.55 MW – 3.6 MW turbines. For other foundation types (GBF, jacket and tripod), only singular measurements are available. Since the underwater noise radiated during operation will depend on the radiating structure (the foundation), its shape, material and size will matter. The turbine technologies (direct drive vs. gear box), will also have an impact on the radiated operational underwater noise. However, the limited available operational noise data does not allow for such differences to be resolved. The trendline proposed in Tougaard (2020), not taking foundation type or size into account, is therefore considered with caution (Figure 9.1). The trend line shows a size dependency, with source level increasing by a factor of 14 dB per factor 10 in turbine nominal capacity (Tougaard, et al., 2020).

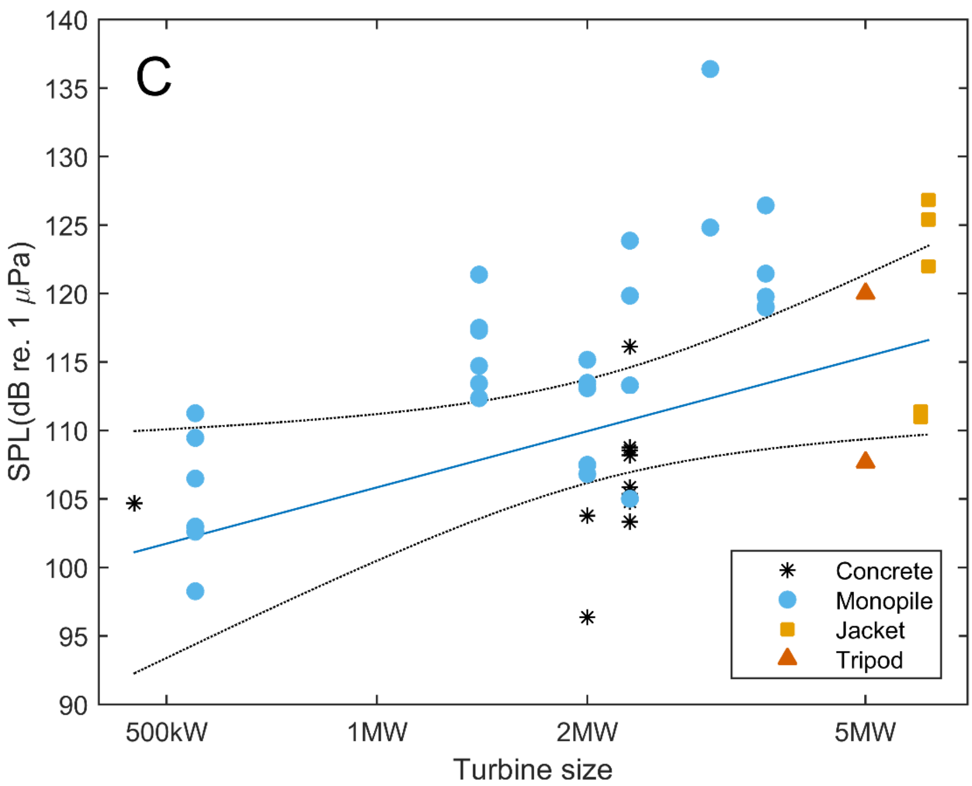



*Figure 9.1: Relationship between measured broadband underwater noise and turbine size compiled from available literature sources. Measurements have been normalized to a distance of 100 m from the turbine foundation and a wind speed of 10 m/s. From (Tougaard, et al., 2020).*

There is a strong dependency between wind speeds and radiated noise levels (Figure 9.2). At the lowest wind speeds, below the cut-in, there is no noise from the turbine. Above cut-in, there is a pronounced increase in the noise level with increasing wind speed, until the noise peaks when nominal capacity is reached in output from the turbine. Above this point, there is no further increase with wind speed and perhaps even a slight decrease.

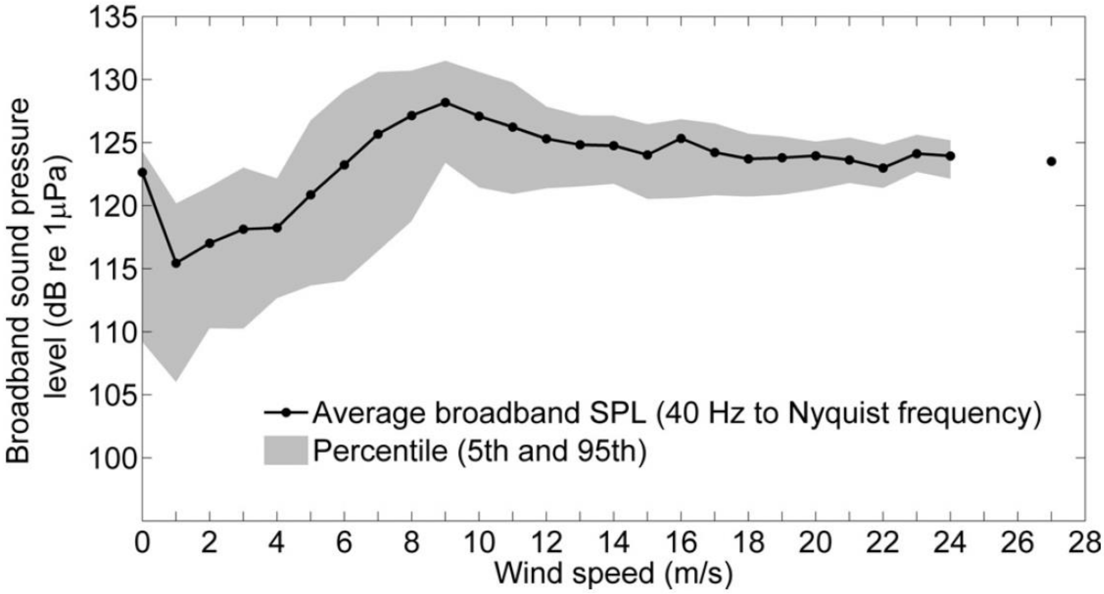



*Figure 9.2: Relationship between wind speed and broadband noise level, measured about 50 m from the turbine (3.6 MW Siemens turbine at Sheringham Shoal). Maximum production of the turbine is reached at about 10 m/s, above which the production is constant. Figure from (Pangerc, et al., 2016).*

All measurements of turbine underwater noise show the noise to be entirely confined to low frequencies, below a few kHz and with peak energy in the low hundreds of Hz. One spectrum of a typical mid-sized turbine is shown in Figure 9.3, where pronounced peaks are visible in the spectrum in the 160 Hz and 320 Hz bands.

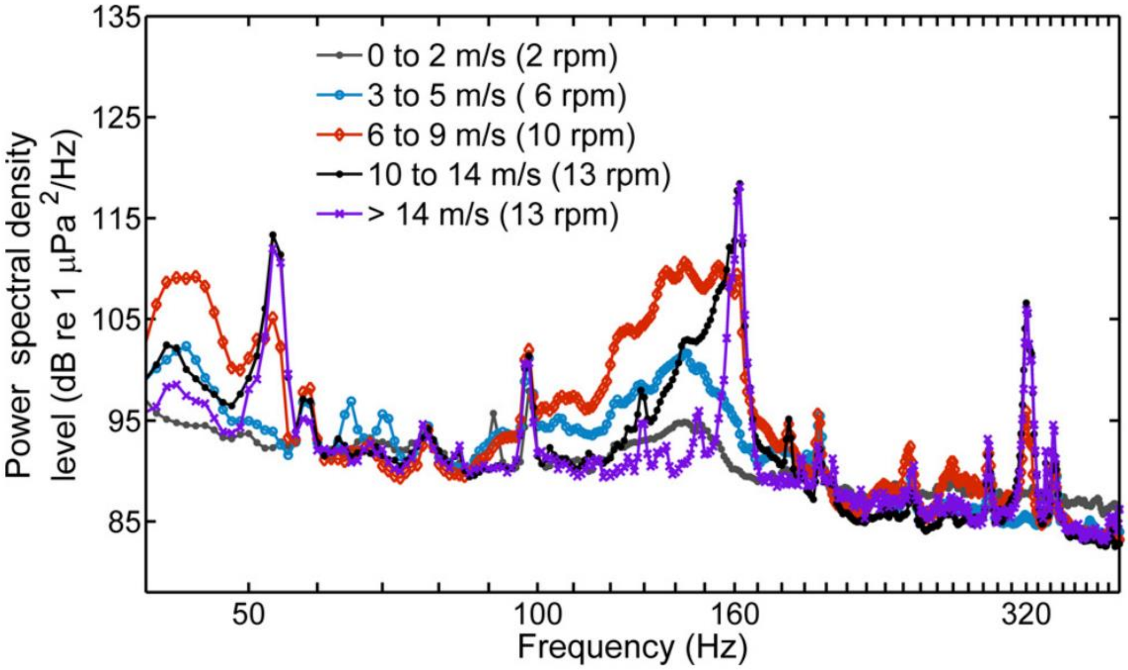



*Figure 9.3: Example of frequency spectra from a medium sized turbine (3.6 MW, Gunfleet Sands) at different wind speeds. Levels are given in 10 Hz intervals. Measurements were obtained about 50 m from the turbine. Measurements from (Pangerc, et al., 2016).*

Despite the inherent uncertainties with respect to type and size of turbines to be used in the project it is considered likely that the turbine noise will be comparable to what has been measured from other turbines. However, it should be considered with caution. Based on the data in Figure 9.1, a number of observations should be mentioned. First, significant variation in measured sound levels for individual turbine sizes on same foundation type, up to 20 dB is noticed. Second, the trendline (blue) representing the best fit of all data points, is not assessed to provide an accurate fit for any given turbine size. This presents a challenge in terms of reliably predicting source levels within the covered turbine size range in Figure 9.1 (0.4 MW – 6.15 MW), and to an even greater extent for turbine sizes outside this range. For Olof Skötkonung OWF, turbine sizes are expected to have a size of 20 MW. This would represent a 6 fold increase compared to the available empirical data for monopiles. Given the uncertainties present in the empirical data, any extrapolation of such magnitude is considered to be provide a very uncertain source level prediction.

An additional source of uncertainty in prediction is the type of turbine. All but one of the turbines, from which measurements are available, are types with gearbox, a main source of the radiated noise. Only one measurement is available for a turbine with a direct drive (Haliade 150, 6 MW) (Elliott, et al., 2019), which is a type increasingly being installed in new projects. The limited data suggests that noise levels from the direct drive turbine are more broadband in nature than from types with gear box.

Despite the above mentioned uncertainties, a calculation for PTS, TTS and behaviour reaction threshold criteria is carried out below, based on the blue trendline in Figure 8.1 as well as the scaling and frequency considerations presented in (Tougaard, et al., 2020). It should be kept in mind, that there are significant uncertainties with the estimated impact range due to the lack of scientific data supporting such a calculation.

For a 20 MW turbine, the sound level at 100 m, would be $SPL_{rms} = 124\,dB\,re\,1\mu Pa$, based on the extrapolation of the blue trendline. The primary frequency would be ~160 Hz, with secondary frequency at 320 Hz, approximately 10 dB below the primary (Tougaard, et al., 2020).

A conservative approach would set the unweighted 160 Hz level to $SPL_{rms} = 124\,dB\,re\,1\mu Pa$ and for 320 Hz, $SPL_{rms} = 114\,dB\,re\,1\mu Pa$.

Seals and harbour porpoise however are not equally good at hearing all frequencies. As described in further detail in section 4.5, frequency weighting functions are used to predict impact ranges more accurately for the individual species. For seal, the frequency weighting for Phocid Carnivores in Water (PCW) is used, and for harbour porpoise, Very High Frequency Cetacean (VHF). In Figure 4.2, the frequency dependent correction values are listed, from which the following correction values (number of dB to be subtracted from unweighted levels) can be observed for seal and harbour porpoise.

- For seal:
  - -20 dB at 160 Hz, and
  - -15 dB at 320 Hz.
- For harbour porpoise:
  - -65 dB at 160 Hz, and
  - -55 dB at 320 Hz.

The sound levels, as experienced by seal and harbour porpoise, from a single turbine in operation would therefore amount to:

- For seal:
  - @160Hz, 100 m distance: $SPL_{rms,PW} = 104\ dB\ re\ 1\mu Pa$
  - @320Hz, 100 m distance: $SPL_{rms,PW} = 99\ dB\ re\ 1\mu Pa$
  - "Broadband", 100 m distance: $SPL_{rms,PW} = 105\ dB\ re\ 1\mu Pa$
- For harbour porpoise
  - @160Hz, 100 m distance: $SPL_{rms,VHF} = 59\ dB\ re\ 1\mu Pa$
  - @320Hz, 100 m distance: $SPL_{rms,VHF} = 59\ dB\ re\ 1\mu Pa$
  - "Broadband", 100 m distance: $SPL_{rms,VHF} = 62\ dB\ re\ 1\mu Pa$

For seal, no behaviour threshold is currently supported by literature, and it is therefore not possible to compare the sound level at 100 m with a behavioural threshold. For harbour porpoise, a behavioural threshold criteria of $SPL_{rms,125ms,VHF} = 103\ dB\ re\ 1\mu Pa$, is however provided in (Tougaard, 2021). Noticing, that the single turbine level at 100 m is 41 dB below the behavioural threshold value, it is unlikely that the harbour porpoise will react to the noise from one operating turbine. Even when summing the contributions of all nearby turbines, assuming a conservative 13 dB/decade based on the propagation loss from unmitigated pile driving determined in section 8.5, the nearest 9 turbines would add less than 5 dB in any position to this level, and further turbines, even less. An extremely conservative 10 dB addition to the sound field, from all turbines combined, will still mean that the sound level is 31 dB below the behavioural threshold value. It is therefore assessed that even for the conservative scenario, behavioural reaction is considered unlikely.

Adding 10 dB (to include noise from nearby turbines) would bring the broadband sound levels at 100 m up to $SPL_{rms,PCW} = 115\ dB\ re\ 1\mu Pa$ for seal, and $SPL_{rms,VHF} = 72\ dB\ re\ 1\mu Pa$ for harbour porpoise. Calculating the cumulative noise dose for a seal located at a constant distance of 100 m from a turbine foundation within the wind farm area, over a 24 hour period, would result in cumulative sound exposure level, $SEL_{cum,24h,PCW} = 115 + 10 \cdot log_{10}(86400) \cong 154\ dB\ re.1\mu Pa^2 s$. Given a threshold criteria for onset of TTS in seal for continuous noise of $SEL_{cum,24h,PW} = 183\ dB\ re.1\mu Pa^2 s$, the impact over a 24 hour duration is 29 dB lower than the TTS onset criteria. With a 29 dB margin to the TTS threshold criteria, auditory injures are unlikely to occur.

For harbour porpoise, the calculation gives an $SEL_{cum,24h,VHF} = 72 + 10 \cdot log_{10}(86400) \cong 121\ dB\ re.1\mu Pa^2 s$. This is 32 dB below the threshold criteria for TTS. With a 32 dB margin to the TTS threshold criteria, auditory injures are unlikely to occur.

Most fish detect sound from the infrasonic frequency range (<20 Hz) up to a few hundred Hz (e.g. Salmon, dab, and cod) whereas other fish species with gas-filled structures in connection with the inner ear (e.g. herring) detect sounds up to a few kHz. The main frequency hearing range for fish is therefore overlapping with the frequencies, produces by operational wind turbines (below a few hundred Hz). There are no studies defining fish behavioural response threshold for continuous noise sources, and the scientific data addressing TTS from such noise sources is very limited. The only studies providing a TTS threshold value for fish is from experiments with goldfish. Goldfish is a freshwater hearing specialist with the most sensitive hearing in any fish species. All of the species locally occurring in the project area have a less sensitive hearing, compared to the goldfish (Popper, et al., 2014), and using threshold for goldfish will lead to an overestimation of the impact. Empirical data for several of the fish species without a connection between the inner ear and the gas-filled swim bladder showed no TTS in responses to long term continuous noise exposure (Popper, et al., 2014). In a study by Wysocki et al. (2007), rainbow trout exposed to increased continuous noise (up to 150 dB re 1 µPa rms) for nine months in an aquaculture facility, showed no hearing loss nor any negative health effect. Therefore, it is assessed that TTS is unlikely to occur as a result of underwater noise from an operational offshore wind farm.

In summary, the underwater noise emission from operational wind turbines, depends on the turbine size, wind speed and whether it has a gearbox or is gearless (direct drive). While available literature indicates a correlation between turbine size and underwater noise levels, the available dataset is limited to 6.15 MW turbines, and shows significant variance in reported noise levels for the same turbine size. Extrapolation of the reported trend, to be used in assessing the underwater noise emission from future turbines of 20 MW, should therefore be used with caution.

## 9.1. Noise from service boats

In addition to the noise from the turbines themselves, the service boats and vessels within offshore wind farms are likely to be a source of underwater noise during the operational phase of the wind farm. However, the levels and temporal statistics of this noise source has not yet been sufficiently quantified or described. Without dedicated studies it is therefore not possible to quantify the contribution of service boats to the noise in the wind farm.

It is expected that both small and fast boats as well as larger, slower moving vessels will be used. Underwater noise from smaller boats has a noise level ranging 130-160 dB re 1 µPa@1meter (Erbe, 2013; Erbe, et al., 2016), while the underwater noise levels from larger vessels is up to 200 dB re 1 µPa@1 meter (Erbe & Farmer, 2000; Simard, et al., 2016; Gassmann, et al., 2017). Source levels may vary by 20-40 dB within a ship class due to variability in design, maintenance, and operation parameters such as speed (Simard, et al., 2016; Erbe, et al., 2019). Furthermore the underwater noise levels increase when the ship is maneuvered, such as when the ship goes astern, or thrusters are used to hold the ship at a certain position (Thiele, 1988). Ship noise contribute to the ambient underwater noise level from frequencies as low as 10 Hz to as high as several kHz, depending on ship size and speed (Haver, et al., 2021).

The Olof Skötkonung OWF area is located in an area with ship traffic (Figure 7.5) and the area is therefore expected already to be dominated by low-frequency ship noise. Based on data from the BIAS-project, the underwater noise level measured in the 63 and 125 Hz frequency band (indicators of ship noise) is modelled to be above 75 - 95 dB re 1uPa for both frequencies in the project area (50 % of the time) with highest levels in the eastern part of the area (see Figure 7.1 - Figure 7.4). It is clear that underwater noise from vessels in the nearby shipping lane, east of the project area already dominates the underwater noise soundscape within the OWF area.

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# Appendix 1

## Concurrent installation of multiple foundations

If more than one foundation were to be installed at the same time, the cumulative aspects for sound propagation must be considered. Two scenarios are considered: Simultaneous/partially overlapping and sequential installation.

Installation of two foundations simultaneously

If 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 dose received by a marine mammal or fish. For certain species, this would depend on their swim speed.

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 could potentially occur, whereby a marine mammal or fish 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 SEL with time. In this scenario, it is difficult to predict what $L_{E,cum,24h}$, the marine mammal or fish would receive over the span of the installations. Inversely, the closer the foundations, the lower the risk of trapping, but also the longer the threshold distances for PTS and TTS 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 can potentially result in increased behaviour distances. The interaction between wave fronts from two pile installations will however be a complex mix of positive and destructive interference patterns as the wave fronts collide. The resulting sound field would be impossible to predict but it is expected that avoidance behaviour could occur at increased distances, compared to those of a single pile installation.

Installation of two foundations sequentially

Installation of two foundations sequentially, where the second pile installation is started as soon as the former is completed, would result in more predictable effects on the underwater soundscape. In a closely spaced scenario, the marine mammals and fish 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.

For behaviour, 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, as the marine mammals and fish 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 and fish to return to the area.

# Appendix 2

## Temperature, salinity, and sound speed profiles

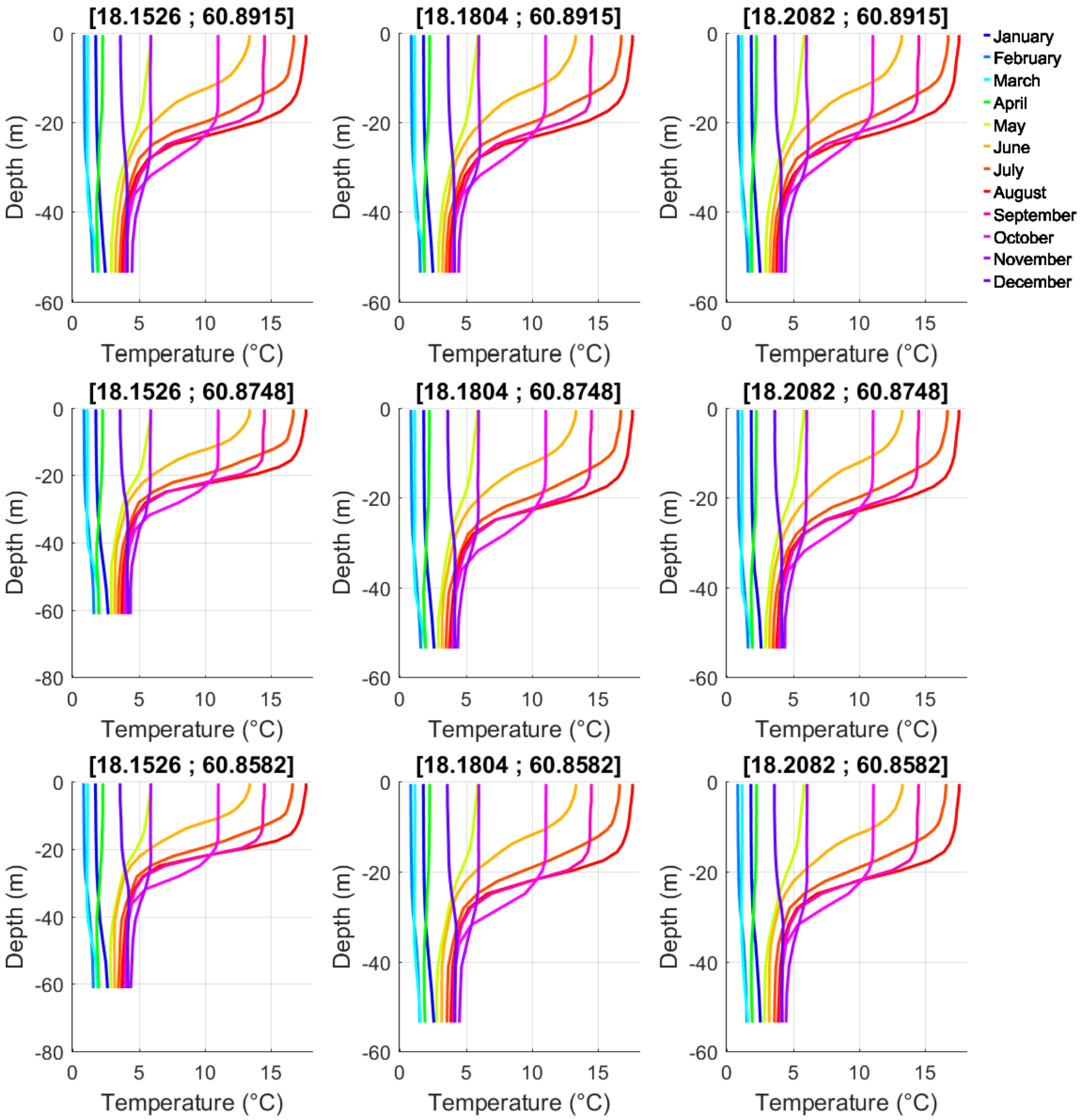


*Figure 10.1: Temperature profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.*

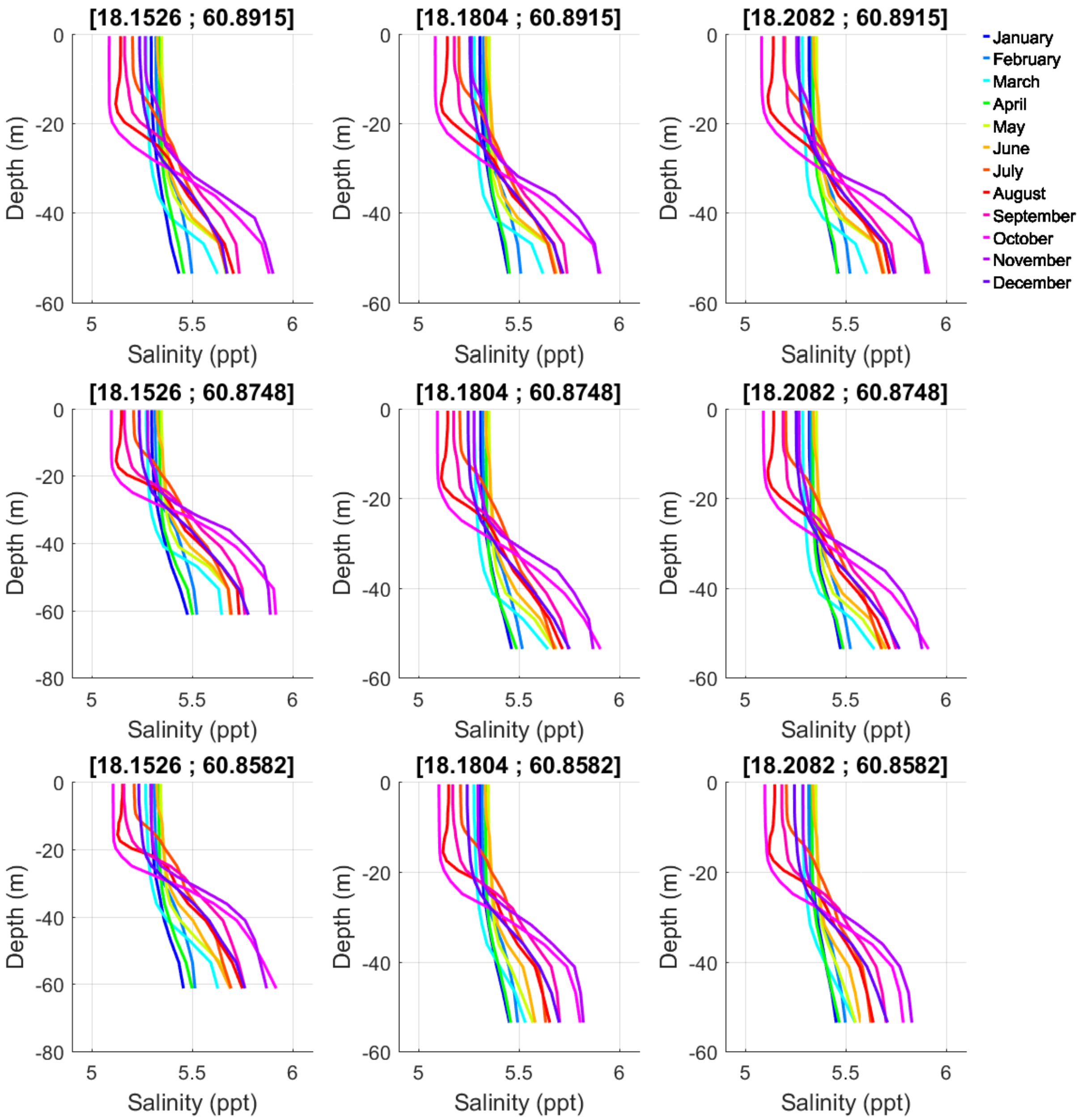


*Figure 10.2: Salinity profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.*

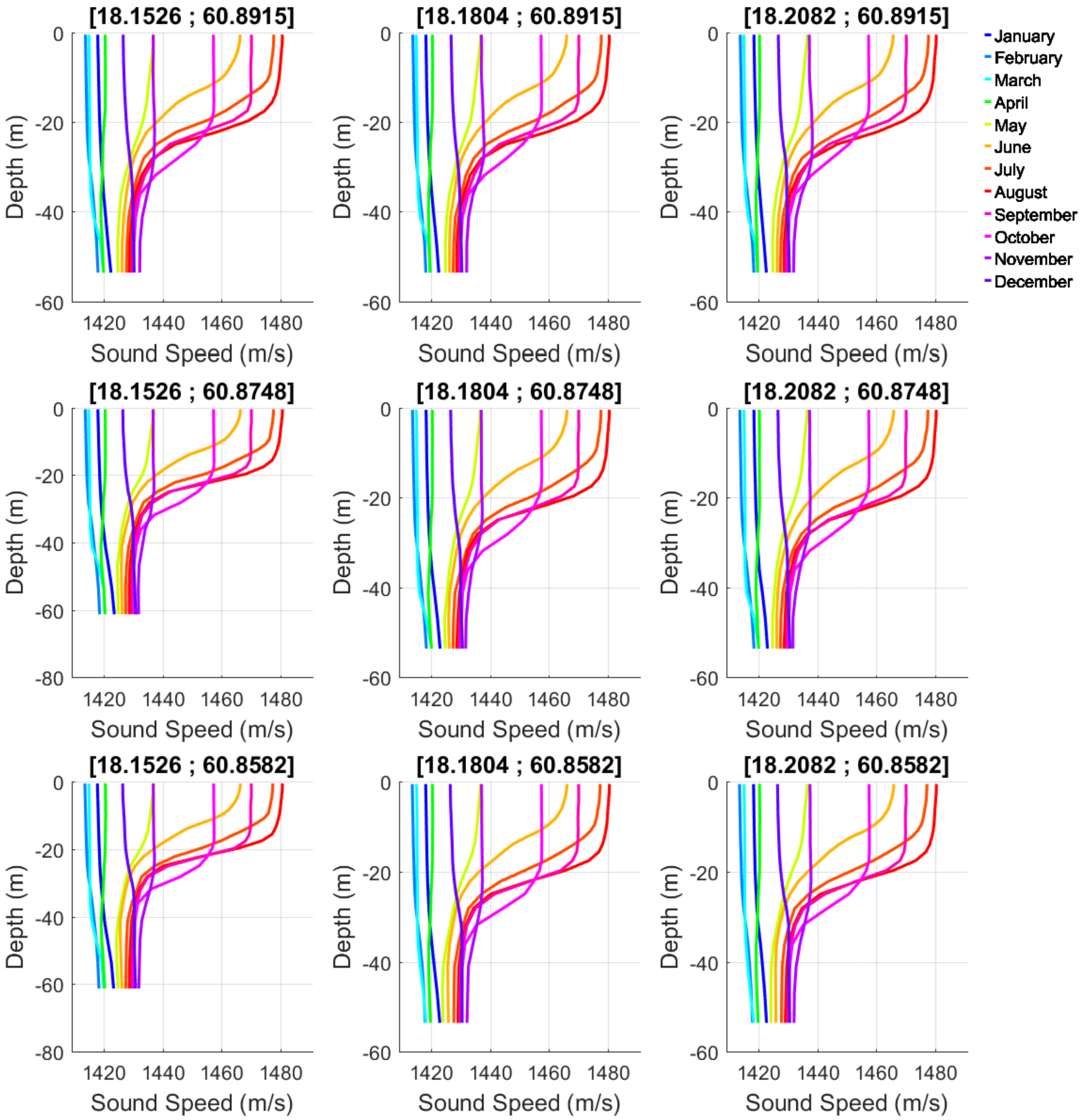


*Figure 10.3: Sound speed profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.*

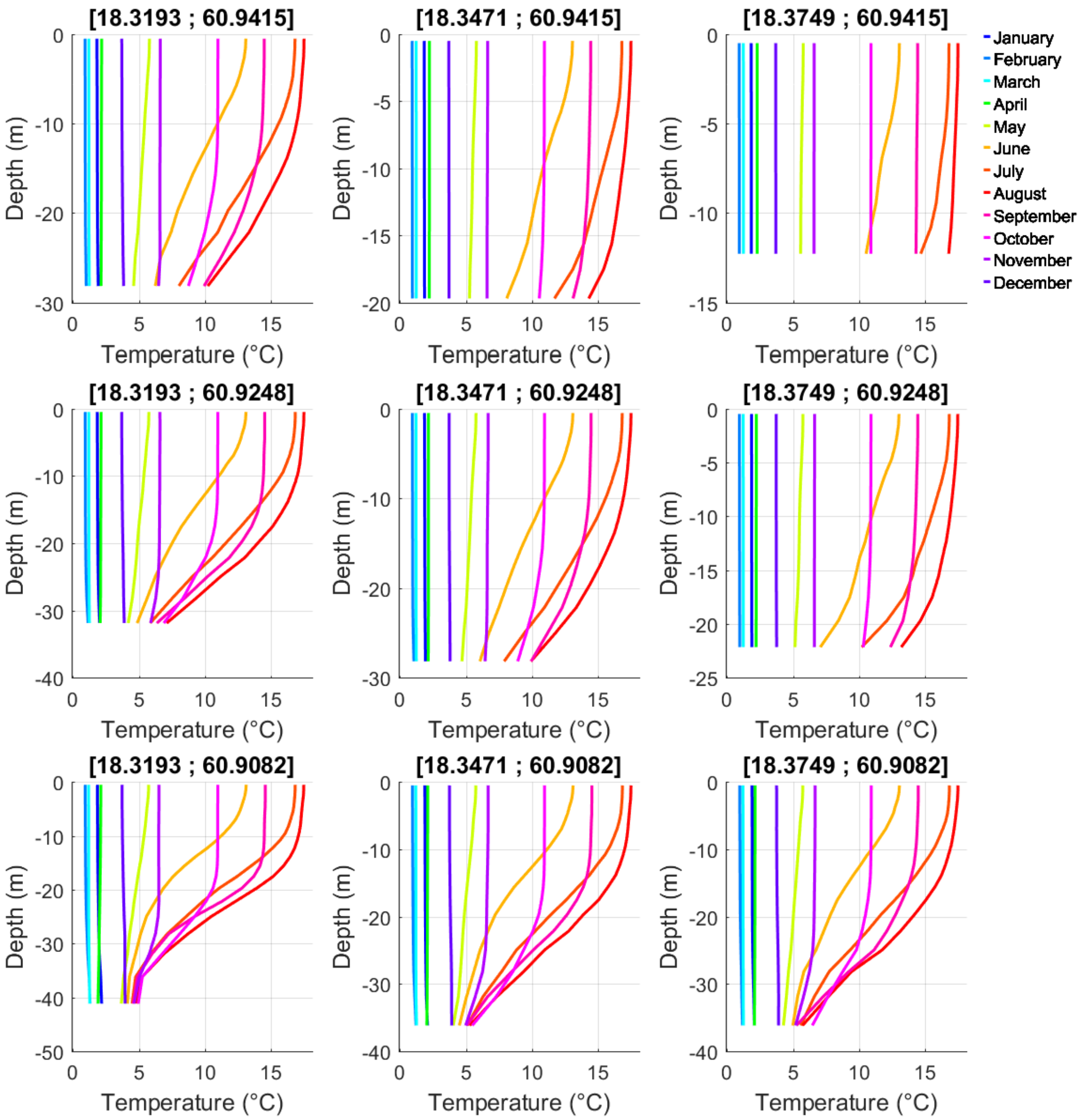


*Figure 10.4: Temperature profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.*

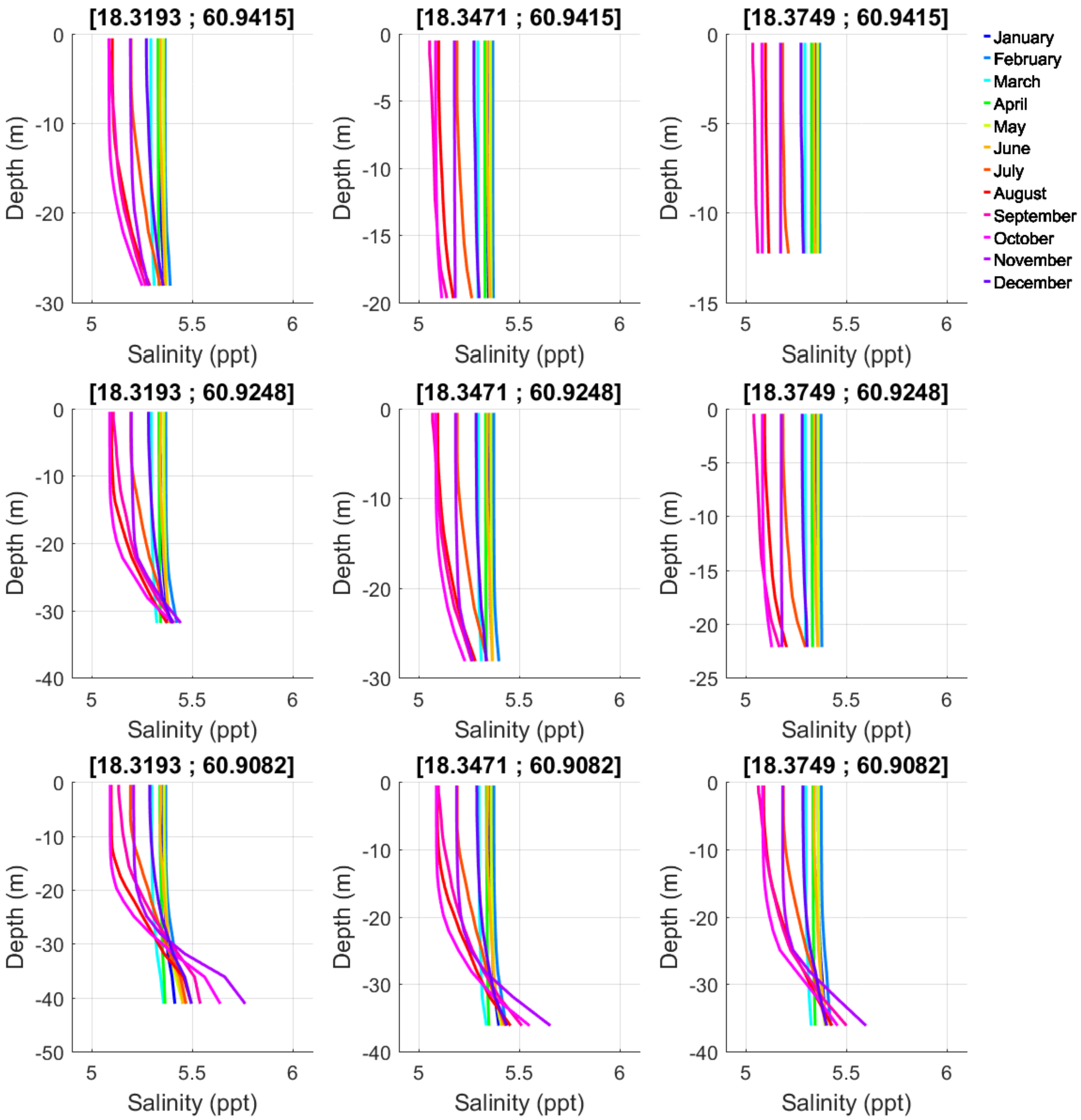


*Figure 10.5: Salinity profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.*

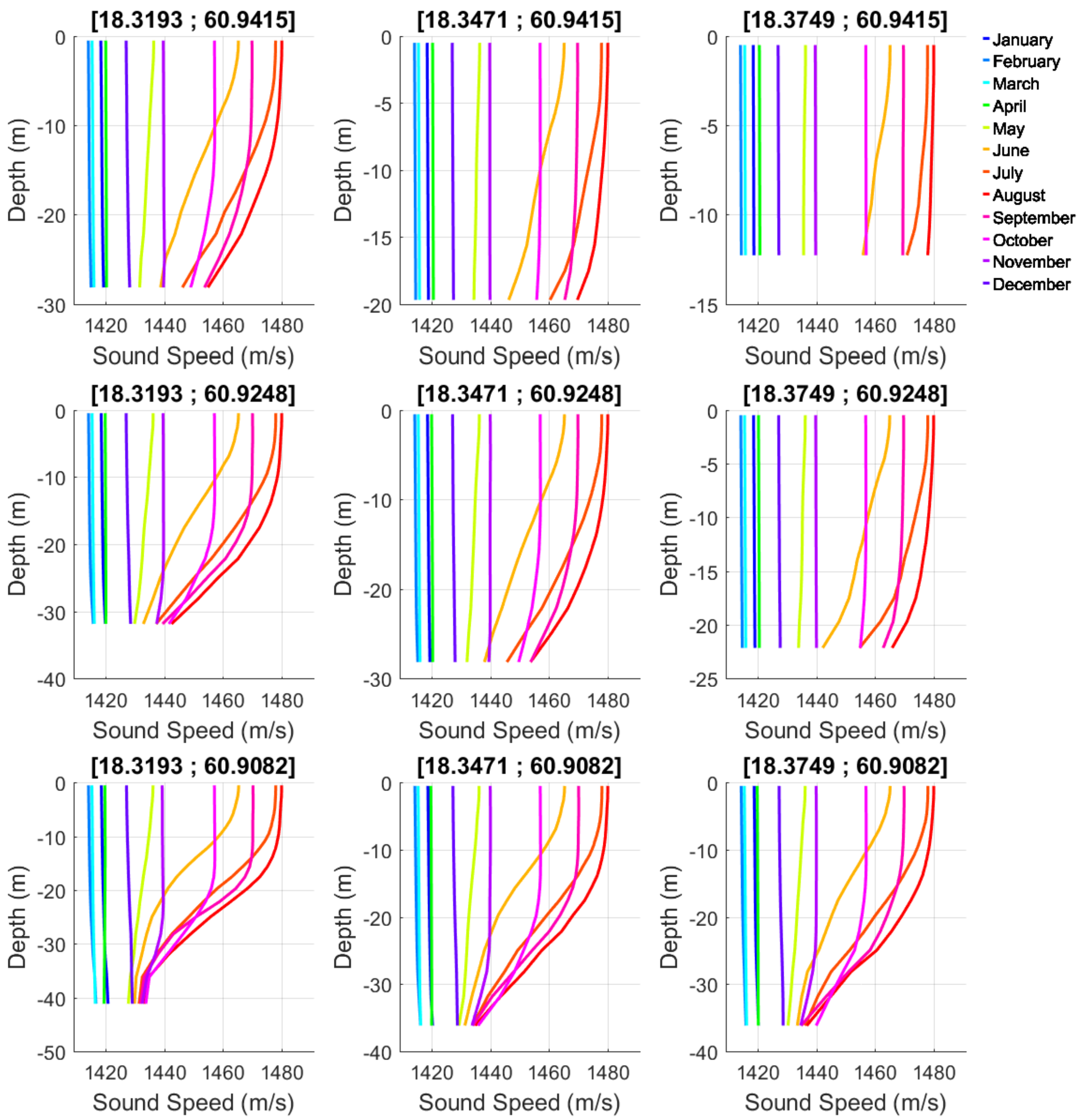


*Figure 10.6: Sound speed profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.*

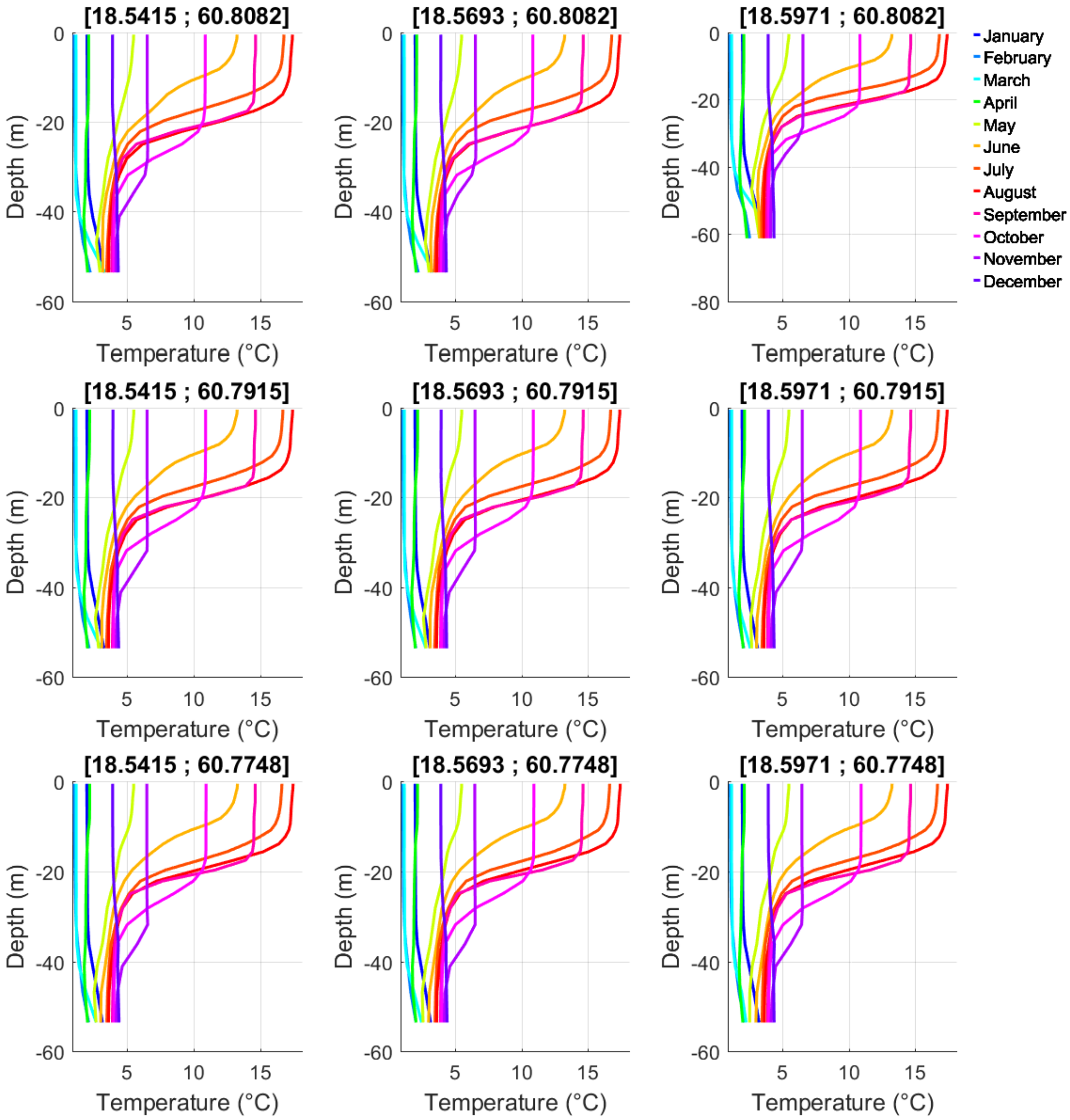


*Figure 10.7: Temperature profiles for the area around source position 4 for all months. Gridded layout reflects geographical location.*

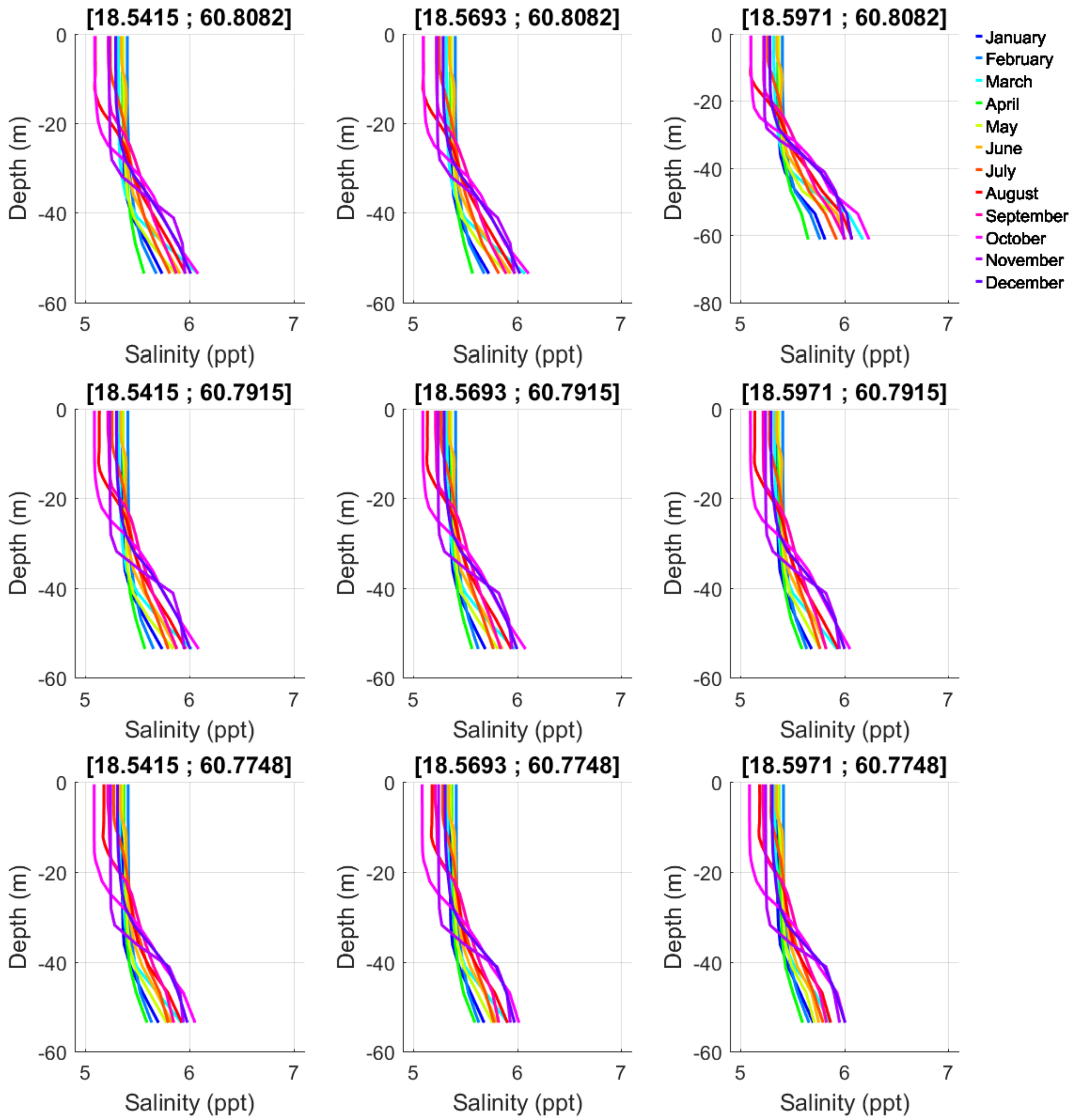


*Figure 10.8: Salinity profiles for the area around source position 4 for all months. Gridded layout reflects geographical location.*

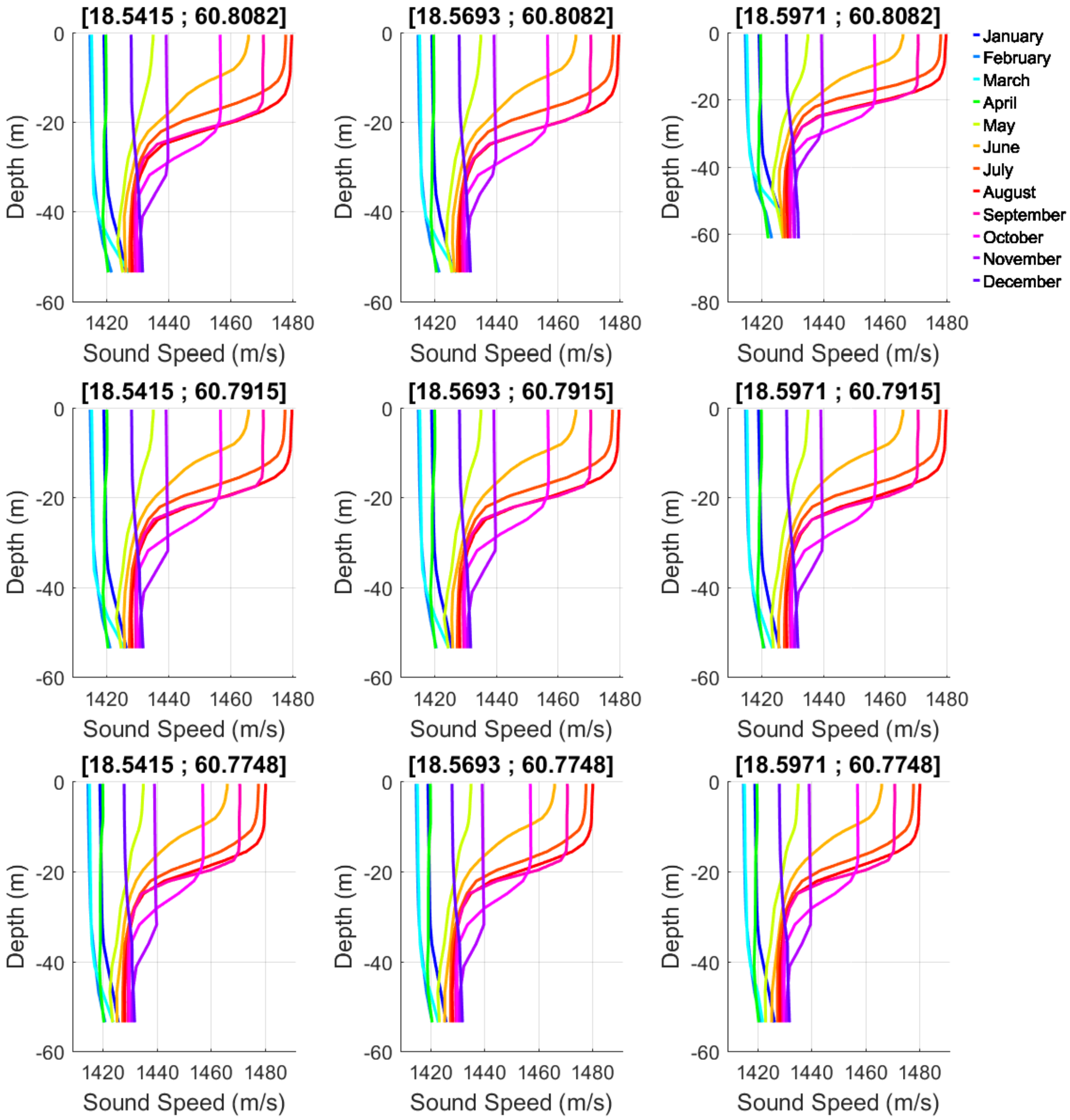


*Figure 10.9: Sound speed profiles for the area around source position 4 for all months. Gridded layout reflects geographical location.*

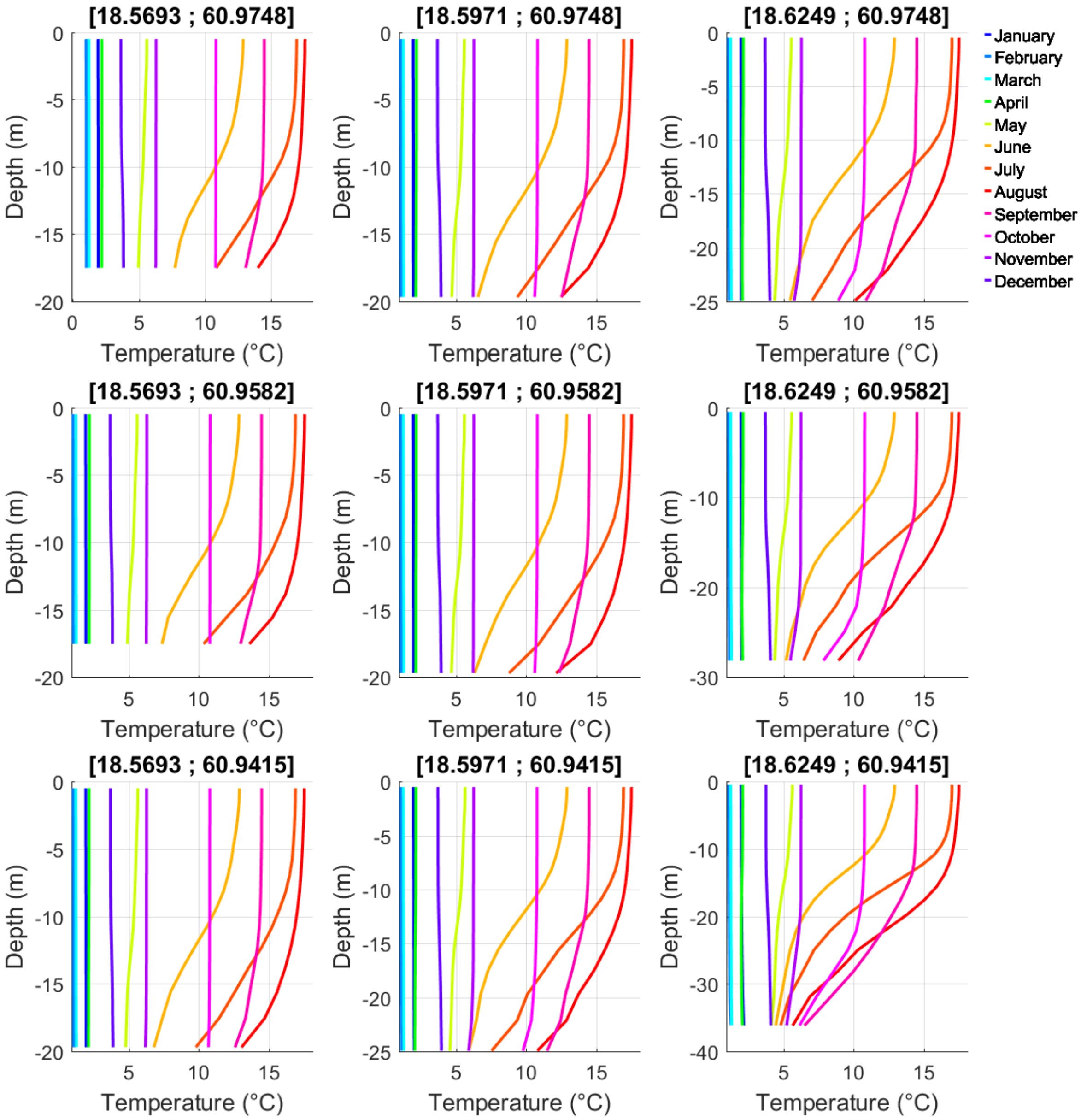


*Figure 10.10: Temperature profiles for the area around source position 5 for all months. Gridded layout reflects geographical location.*

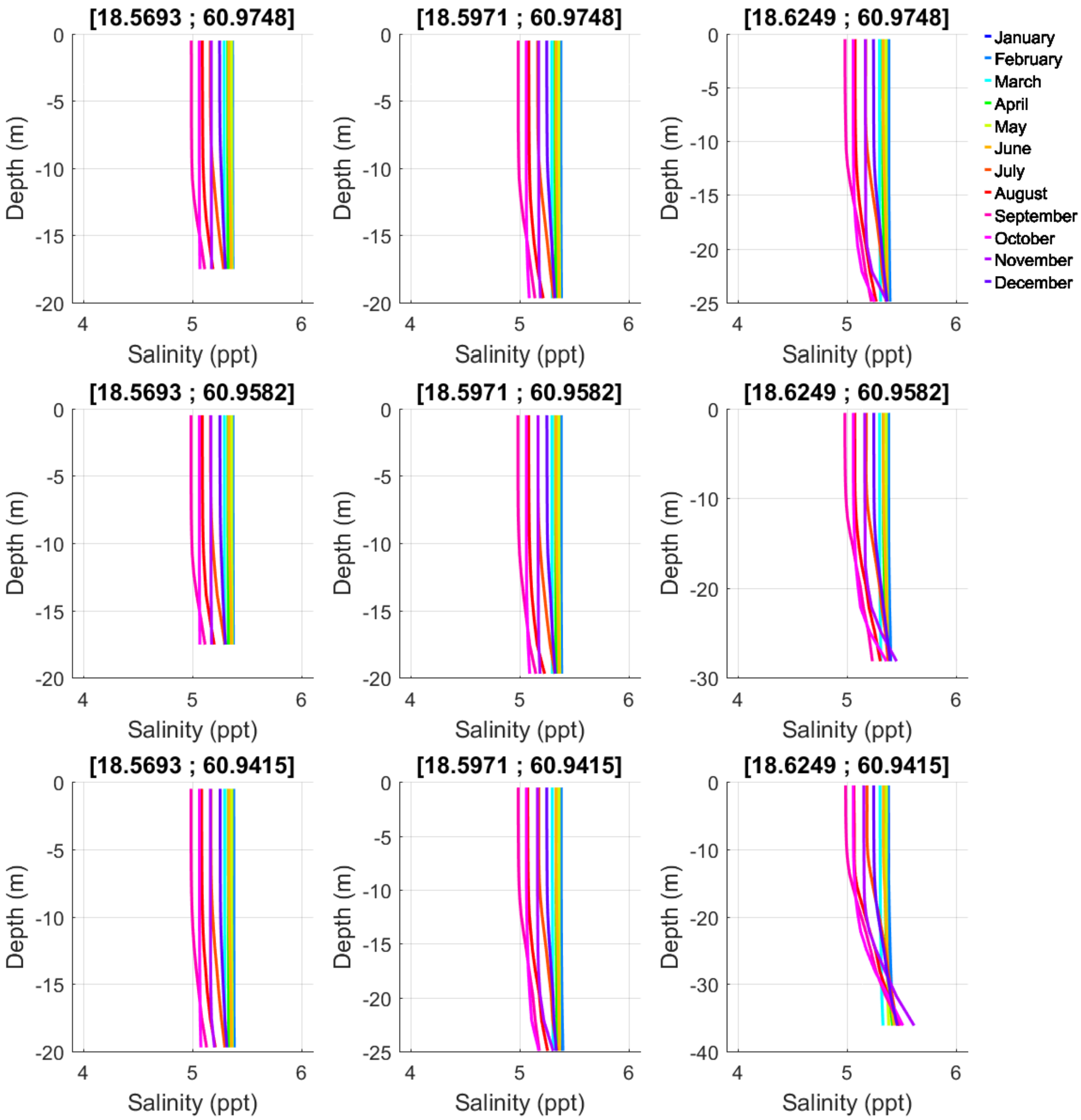


*Figure 10.11: Salinity profiles for the area around source position 5 for all months. Gridded layout reflects geographical location.*

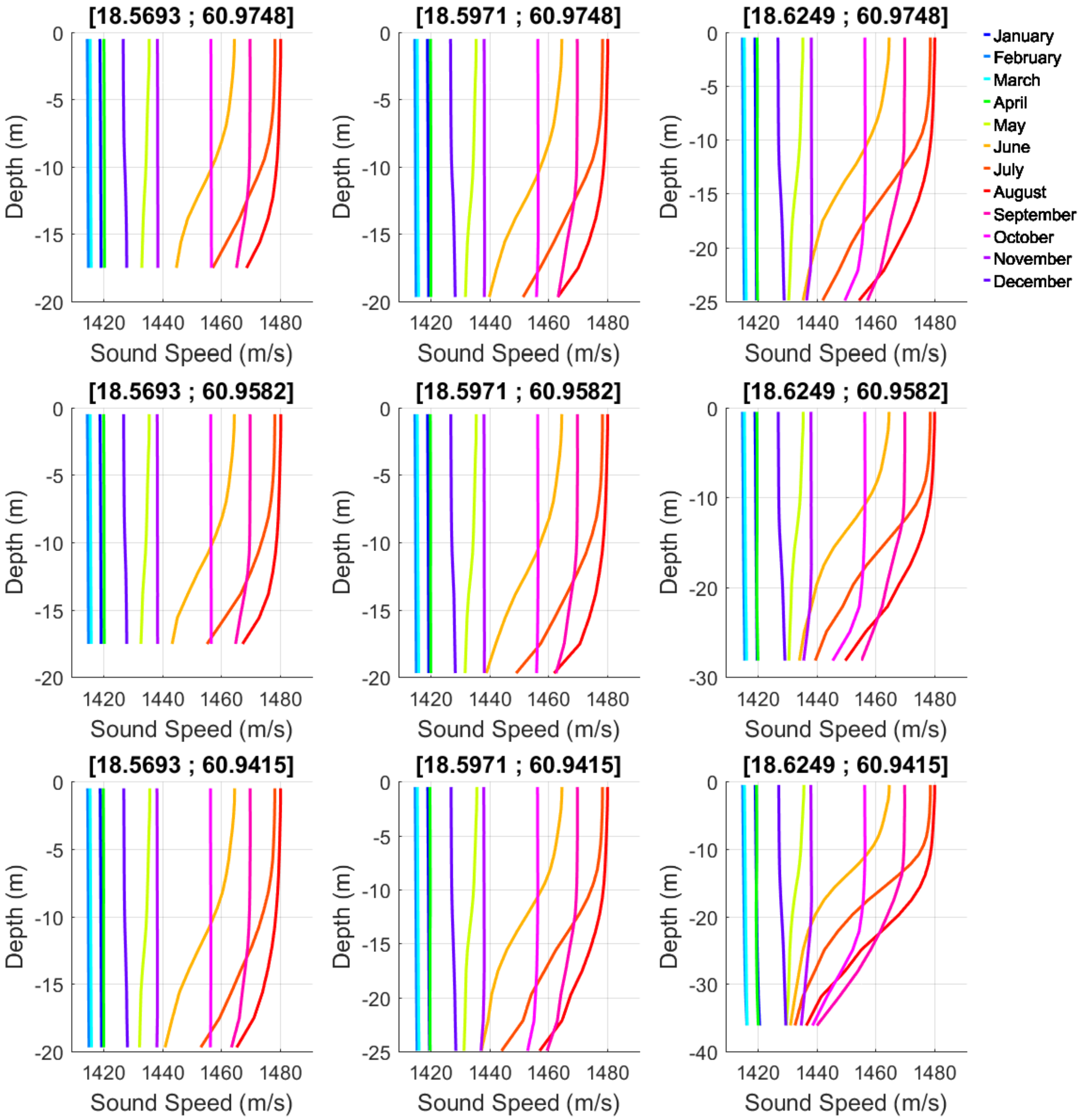


*Figure 10.12: Sound speed profiles for the area around source position 5 for all months. Gridded layout reflects geographical location.*