Ran
Offshore Wind Farm

Underwater noise prognosis

Geophysical survey

NIRAS A/S

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Executive Summary

Ran Vindpark AB is planning geophysical survey activities in relation to the planning of the Ran offshore wind farm (OWF), located in the Swedish part of the Baltic Sea. The investigation area covers the OWF site. Geophysical survey activities produce underwater noise, of which certain activities have the potential to disturb and harm marine fauna. NIRAS has been tasked with preparation of an underwater noise prognosis for these activities, to act as input for an impact assessment for marine mammals.

The potential for underwater noise impact was evaluated for the proposed geophysical survey activities:

1. Multibeam echosounder (MBES),
2. side scan sonar (SSS),
3. sub-bottom profiler (SBP),
4. airgun,
5. sparker (UHRS)
6. Magnetometer

The acoustic impact of activity type MBES, SSS and Magnetometer was assessed based on available literature, while underwater sound propagation modelling was undertaken for activity type SBP, UHRS, and Airgun.

A 3D acoustic environmental model, based on available online data sources, as well as client input, for bathymetry, sediment, salinity, temperature and sound speed, was created in QGIS and NIRAS TRANSMIT (MATLAB toolbox). Worst case hydrographic conditions, represented by historical data for the month of March, was used. Underwater sound propagation modelling was carried out in dBSea 2.3.6, for activities SBP, UHRS, and Airgun, using the 3D acoustic environmental model, as well as a source model derived from available literature and NIRAS experience. Sound propagation was calculated in a 25 x 0.5 m range-depth grid in 45-90 directions from each source (4 - 8° resolution). Number of directions were increased for model positions near land masses. Resulting sound propagation losses were processed in NIRAS SILENCE (MATLAB toolbox) to determine impact ranges to relevant marine mammal threshold criteria.

For marine mammals, 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 attending 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 severe 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.

Marine mammals included in the prognosis are harbour porpoise (*Phocoena phocoena*) and earless seals (here grey seal (*Halichoerus grypus*) and ring seal (*Phoca hispida*)) with threshold criteria for PTS and TTS, as well as behaviour reaction.

Impact ranges for PTS and TTS describe the minimum distance from the source a marine mammal must at least be, prior to onset of survey activities, in order to avoid the respective impact. It therefore does not represent a

constant distance the animals must maintain, but a safe starting distance, beyond which the threshold criteria are unlikely to be exceeded. For marine mammals, fleeing behaviour is included.

Impact ranges for behaviour, describes the specific distance, up to which, the behavioural threshold criteria are likely to be exceeded, when survey activities are operating at maximum intensity.

Results are presented in numeric form in Table 1.1 – Table 1.2 for harbour porpoise and seal respectively.

Table 1.1: Impact ranges for harbour porpoise.

Position	**Harbour porpoise (VHF): Threshold criteria impact ranges**				
	PTS		**TTS**		**Behaviour**
	Impulsive	Non-impulsive	Impulsive	Non-impulsive	Impulsive
Innomar Medium 100 (SBP) – distances relative to vessel					
1	-	< 100 m	-	< 100 m	1450 m
2	-	< 100 m	-	< 100 m	1600 m
3	-	< 100 m	-	< 100 m	1500 m
GeoSource 200-400 – distances relative to vessel					
1	< 100 m	-	190-700	-	1750 m
2	< 100 m	-	225-875	-	2200 m
3	< 100 m	-	250-775	-	1850 m
Sercel mini GI 60 in3 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	550 m
2	< 100 m	-	< 100 m	-	550 m
3	< 100 m	-	< 100 m	-	575 m
All sources active (combined)					
1	< 100 m	< 100 m	250-725 m	< 100 m	1800 m
2	< 100 m	< 100 m	225-875 m	< 100 m	2200 m
3	< 100 m	< 100 m	275-850 m	< 100 m	1850 m

For harbour porpoise, underwater sound propagation modelling results show impact on the behaviour at up to 2.2 km distance from the survey. It should be noted that this behaviour criterion is only considered valid for impulsive noise sources (Tougaard, 2021), however as no threshold criteria have been established by science for non-impulsive sources, the impulsive criterion is used as a proxy.

For PTS and TTS, results show no impact beyond 100 m range for PTS, and up to 875 m for TTS, for the proposed geophysical survey activities.

Table 1.2: Impact ranges for seals.

Position	Seals (PCW): Threshold criteria impact ranges				
	PTS		**TTS**		**Behaviour**
	Impulsive	Non-impulsive	Impulsive	Non-impulsive	-
Innomar Medium 100 (SBP) – distances relative to vessel					
1	-	< 100 m	-	< 100 m	-
2	-	< 100 m	-	< 100 m	-
3	-	< 100 m	-	< 100 m	-
GeoSource 200-400 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	-
2	< 100 m	-	< 100 m	-	-
3	< 100 m	-	< 100 m	-	-
Sercel mini GI 60 in3 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	-
2	< 100 m	-	< 100 m	-	-
3	< 100 m	-	< 100 m	-	-
All sources active (combined)					
1	< 100 m	< 100 m	< 100 m	< 100 m	-
2	< 100 m	< 100 m	< 100 m	< 100 m	-
3	< 100 m	< 100 m	< 100 m	< 100 m	-

For earless seals, underwater sound propagation modelling results show no impact beyond 100 m range for TTS and PTS, for the proposed geophysical survey activities. The survey vessel itself, producing more low frequency content than the survey equipment, is therefore likely to define the behavioural impact of the survey.

Contents

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	
World Ocean Atlas 2023	WOA23	
Sound Exposure Propagation loss	EPL	
National Marine Fisheries Service	NMFS	
Maximum over-depth	MOD	

1. Introduction and objectives

Ran Vindpark AB is planning geophysical survey activities in relation to the planning of the Ran offshore wind farm (OWF), located in the Swedish part of the Baltic Sea. The investigation area covers the OWF site. NIRAS has been tasked with preparation of an underwater noise prognosis for the geophysical survey activities, as input for an environmental impact assessment for marine mammals.

The report is structured as outlined below.

Chapter	Content
2	Project description
3	Definitions: A brief introduction to terms and metrics used throughout the report
4	Marine mammal threshold criteria for auditory impact
5	Ambient underwater noise study
6	Underwater noise prognosis for geophysical survey

2. Project description

Ran Vindpark AB is planning to establish an offshore wind farm, Ran, in the Baltic Sea east of Gotland. The Ran wind farm is located in Swedish territorial waters, approximately 12 km east of the east coast of Gotland (Figure 2.1). The water depth in the area varies between approximately 40 and 85 meters.

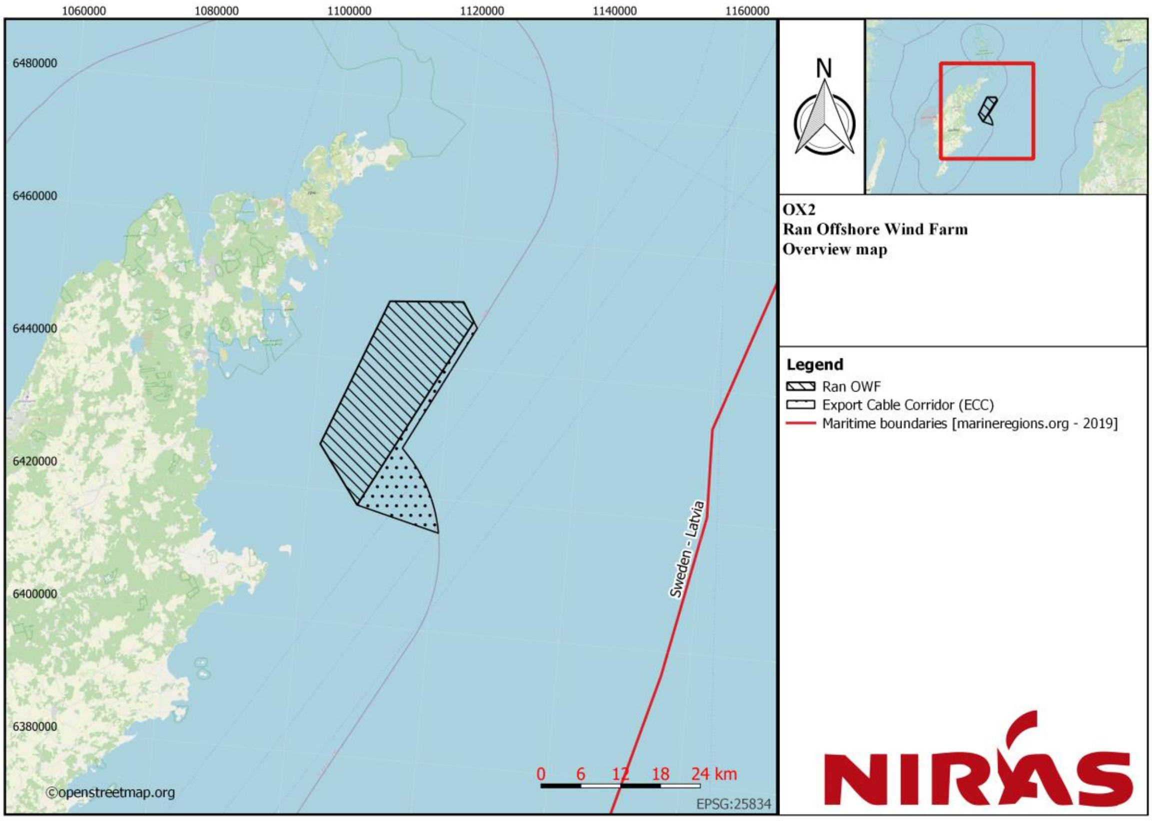

Figure 2.1: Overview of the planned Ran OWF project area.

The area for the wind farm is approximately 327 km2 and when fully developed, the park will include 90-121 wind turbines with a maximum total height of 310 meters. The wind farm is expected to have an installed capacity of approximately 1.8 GW and is expected to generate around 8 TWh of renewable electricity per year.

2.1. Description of Activities

Underwater noise emission is expected to occur as a result of the geophysical survey activities, where the physical properties of the seabed within the OWF site are investigated.

Geophysical investigations are typically characterised by non-invasive acoustic techniques. By analysing the reflections of sound waves emitted towards the seafloor and sediment layers, the sediment layer composition, as well as pockets of natural resources, can be determined. Investigations that map the bathymetry and objects on or imbedded in the seabed, such as unexploded ordnance (UXO), are also considered part of the geophysical investigations.

3. 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).

3.1. 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):

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

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).

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

Equation 2

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

3.2. 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 duration of an entire survey from start to end, or it can be a single noise event like an airgun pulse. The SEL is normalized to 1 second and is defined in (Martin, et al., 2019) through Equation 3.

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

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

$$L_{E,p} = L_p + 10 * \log_{10}(T)$$ 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).

3.3. Cumulative Sound Exposure level

For moving sources in combination with moving receivers, the $L_{E,cum,t}$ is calculated using the approach presented in (Tougaard, 2016). The survey vessel speed, and its direction relative to a moving receiver is used to calculate the $L_{E,cum,t}$ for a given receiver. In Equation 5, the distance between the source and receiver at the ith pulse, r_i, is given for a specific piece of survey equipment. This is based on a starting position of the marine mammal relative to the source, defined by the on-axis distance, l_0, corresponding to the transect line, and the off-axis distance, d_0, corresponding to the perpendicular distance from the transect line. Δt_i is the time in seconds between the first pulse and the ith , while v_{ship} and $v_{receiver}$ is the ship and receiver moving speed respectively, in m/s.

$$r_i = \sqrt{\left(l_0 - ((i-1)\cdot \Delta t_i)\cdot v_{ship}\right)^2 + (d_0 + ((i-1)\cdot \Delta t_i)\cdot v_{receiver})^2}$$ Equation 5

By summing the pulses from the entire survey, within a 24h window, given the propagation loss for the survey area, Equation 6 gives the resulting $L_{E,cum,24h}$.

$$L_{E,cum,24h} = 10 * \log_{10}\left(\sum_{i=1}^{N} 10^{\left(\frac{L_{S,E} - X*\log_{10}(r_i) - A*(r_i)}{10}\right)}\right)$$ Equation 6

Where N is the total number of pulses for that piece of survey equipment, $L_{S,E}$ is the source level at 1 m distance, X and A describe the sound exposure propagation losses (EPL), $N_{PL,E}$, for the specific project site. For surveys using multiple equipment types, the contribution from each source is first normalized into 1 sec. SEL based on firing frequency, and then added.

The parameters used in Equation 5 and Equation 6, related to the source level, firing frequency, movement speed and source direction must be based on best available knowledge. The EPL parameters (X and A) must be determined through advanced sound propagation modelling, in which all relevant site-specific environmental parameters are considered.

3.4. Source level

Two representations for the acoustic output of a sound emitting source 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.

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 impulsive noise sources.

3.5. 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 7 (NOAA, 2018).

$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right)\ [dB] \qquad \text{Equation 7}$$

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 3.1.

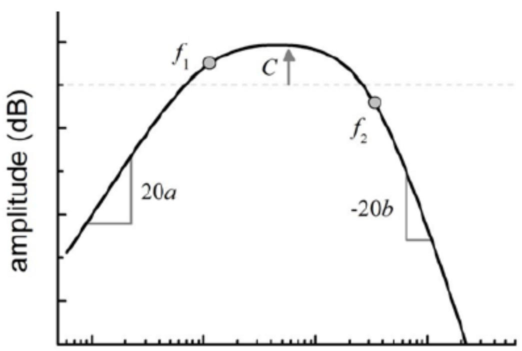

Figure 3.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).

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 7 are defined for the hearing groups and the values are presented in Table 3.1.

Table 3.1: 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 3.1 into Equation 7. The resulting spectra for the four hearing groups are shown in Figure 3.2.

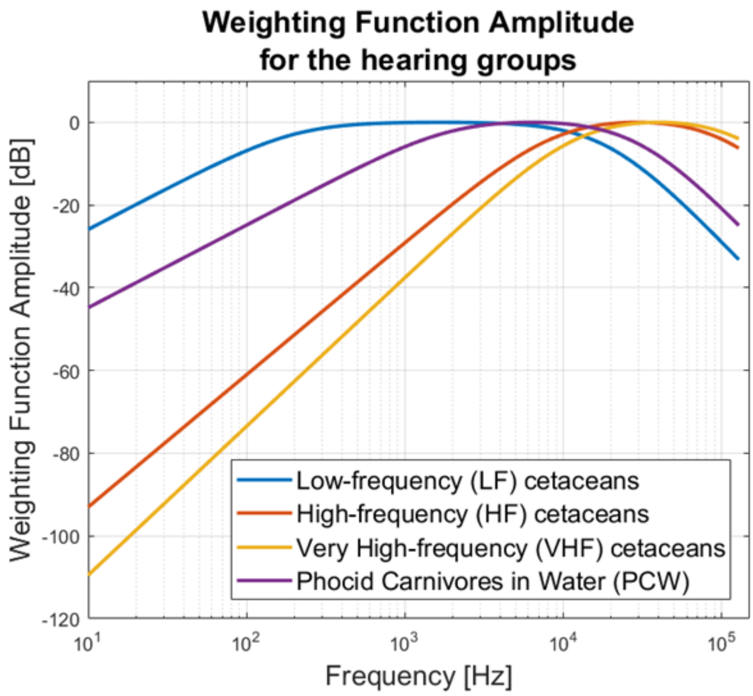

Figure 3.2: The weighting functions for the different hearing groups.

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)).

4. Underwater Noise Threshold Criteria

In Sweden, underwater noise from geophysical survey activities is handled by the authorities on a project-by-project basis. In order to provide a prognosis of impact, best available scientific knowledge from (NOAA, 2018), (Tougaard, 2021), (Energistyrelsen, 2023) is instead used in this project.

Two sets of threshold criteria are typically considered in evaluating the impact of underwater noise, based on the impulsiveness of the noise source. Following the definition of impulsive vs. non-impulsive noise sources in (NOAA, 2018), the terms are considered as follows:

- 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 are 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.

For geophysical survey activities, it is not always clear if a source behaviour is impulsive or non-impulsive. While equipment types, such as airguns and explosives are unquestionably impulsive in nature, arguments can be made in both directions for other equipment types.

The impulsiveness of individual activities is reflected upon in the evaluation of each activity. For cumulative assessment, when all survey equipment is active simultaneously, it is considered likely that non-impulsive threshold criteria are more suitable than impulsive threshold criteria, which may be overly conservative. If the combined noise emission is dominated heavily by an activity which is clearly defined as impulsive, it would however stand to reason that impulsive threshold criteria might be more appropriate.

4.1. Threshold criteria for marine mammals

Based on the newest scientific literature, species specific frequency weighted $L_{E,cum,24h}$ threshold values (NOAA, 2018), (Southall, et al., 2019) for TTS and PTS are used, Table 4.1. For avoidance behaviour, $L_{p,125ms,VHF} = 103\ dB\ re.1\ \mu Pa$ (Tougaard, 2021) is used for harbour porpoise.

Table 4.1: 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	
Harbour 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	-

5. 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.

No site specific measurements of ambient noise for the Ran OWF area were carried out. For the Baltic Sea however, the ICES continuous underwater noise dataset (ICES, 2018), presents the underwater noise levels in the Baltic 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 available 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 5.1 - Figure 5.3, for the frequency bands 63 Hz, 125 Hz and 500 Hz respectively. In addition to the 2018 ICES 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 5.4.

The ICES maps show that the ambient noise levels vary significantly with season, and with frequency. The levels at 63 Hz and 125 Hz are higher than those at 500 Hz and 2 kHz. Noise levels also vary by season, with a tendency of higher levels in the colder months/seasons. The latter is attributed to the hydrography, whereby the sound propagation in the Baltic Sea during the warmer months has higher sound attenuation properties.

What is also visible from the maps, is that variations spatially tend to correlate with shipping traffic, illustrated in Figure 5.5. 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 lanes greatly influence the overall ambient noise level inside and outside the project 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.

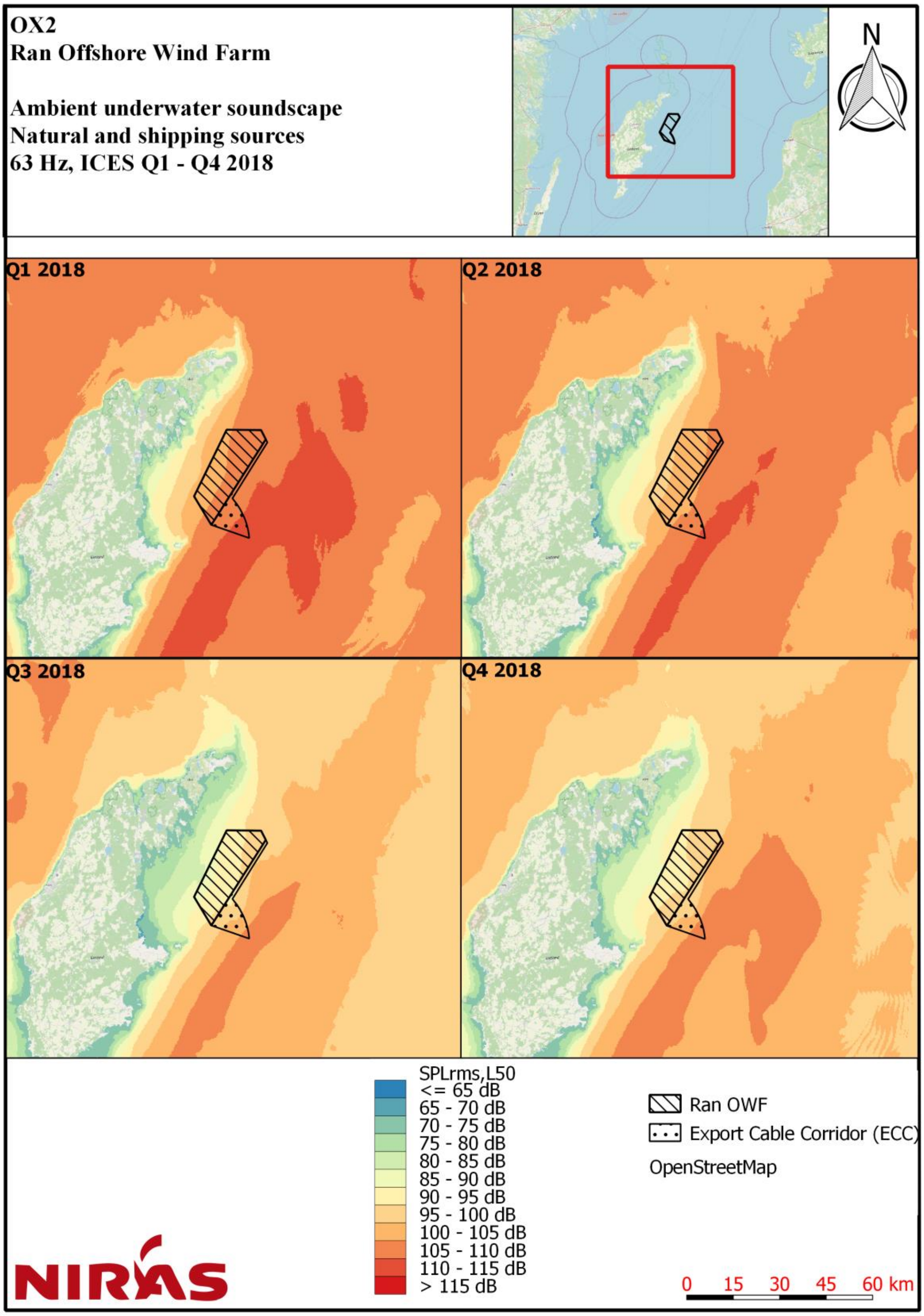

Figure 5.1: ICES soundscape map for 63 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,63Hz}$ $[dB\ re.1\mu Pa^2]$.

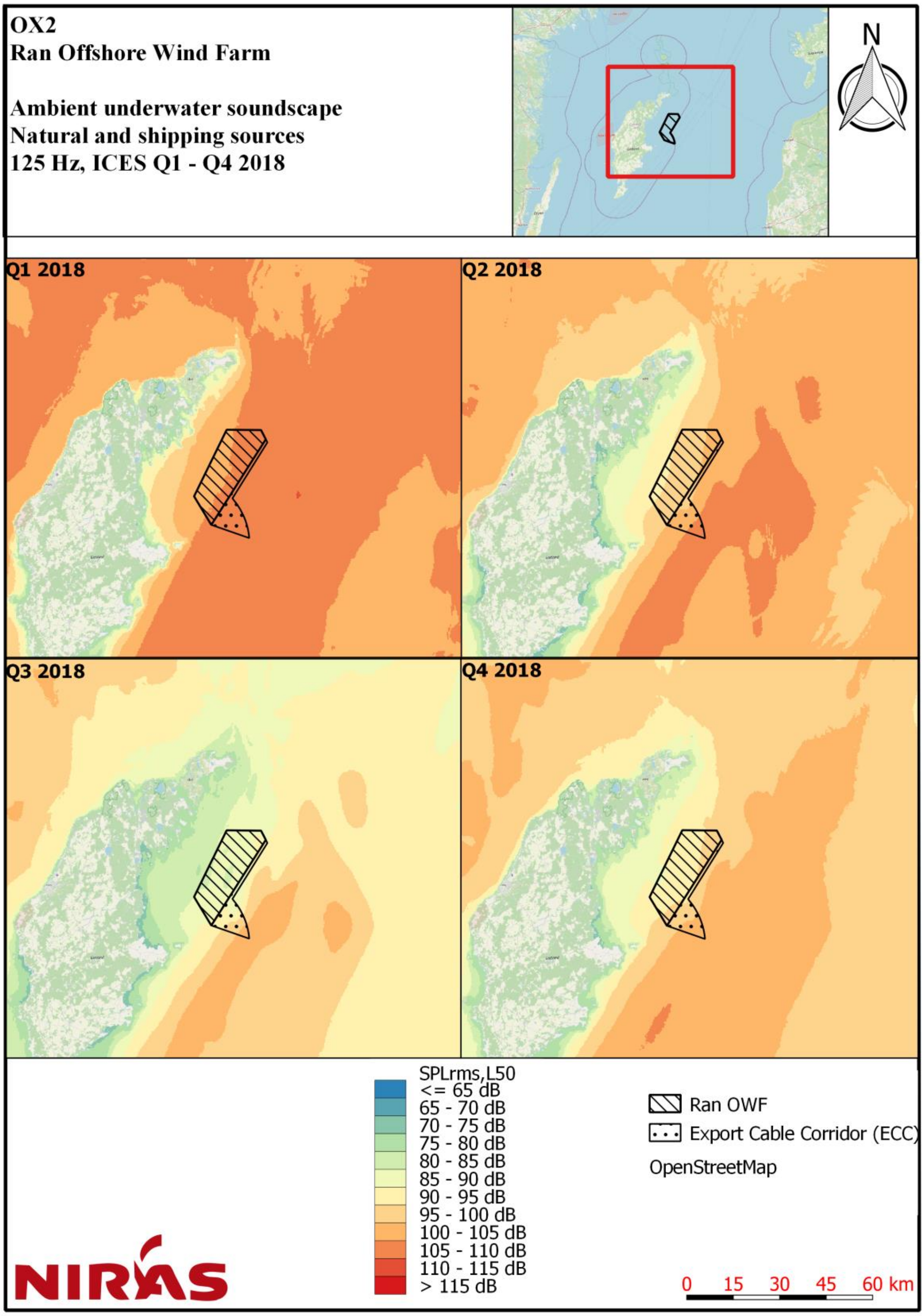

Figure 5.2: ICES soundscape map for 125 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,125Hz}$ $[dB\ re.1\mu Pa^2]$.

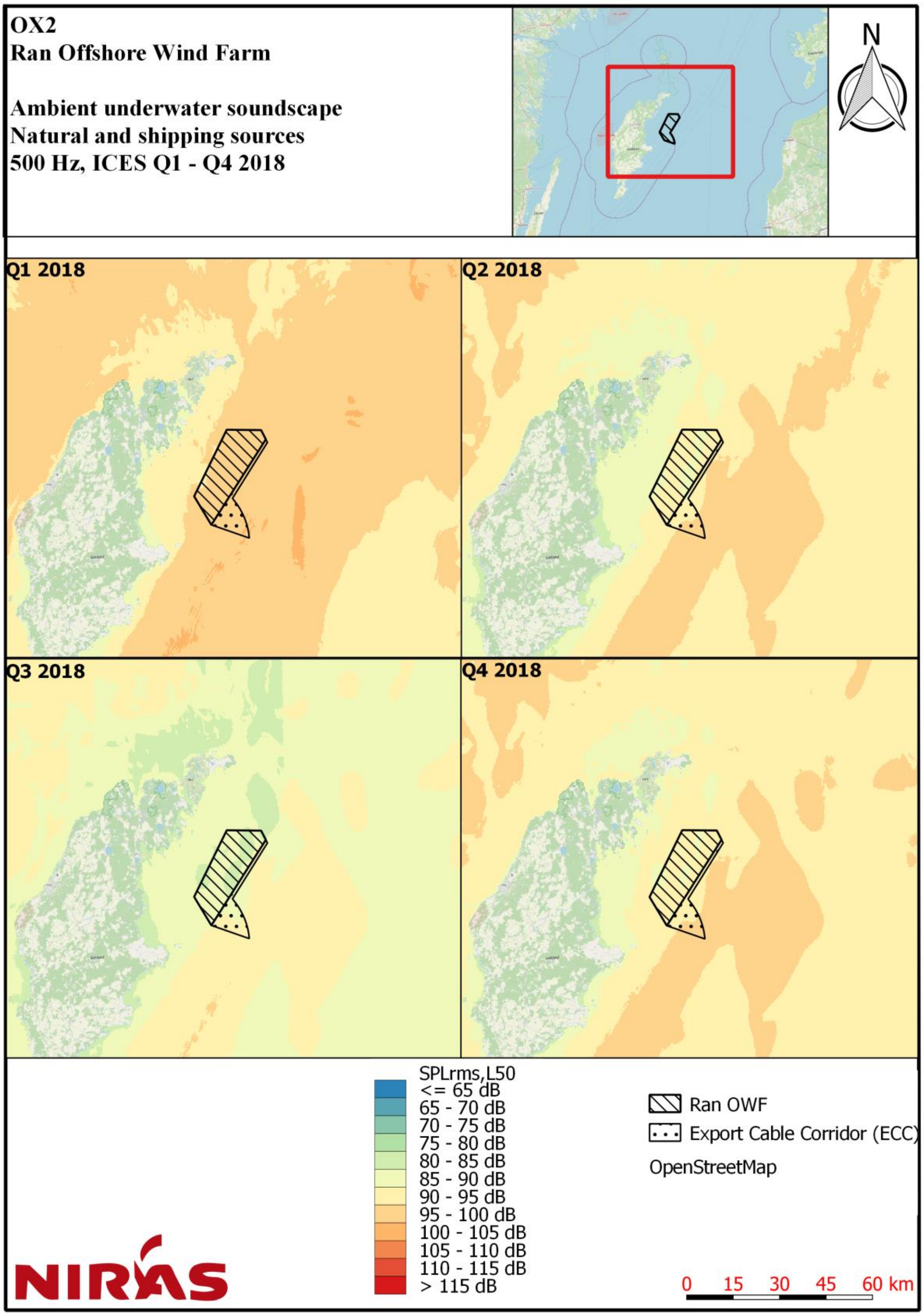

Figure 5.3: ICES soundscape map for 500 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,500Hz}$ $[dB\ re.1\mu Pa^2]$.

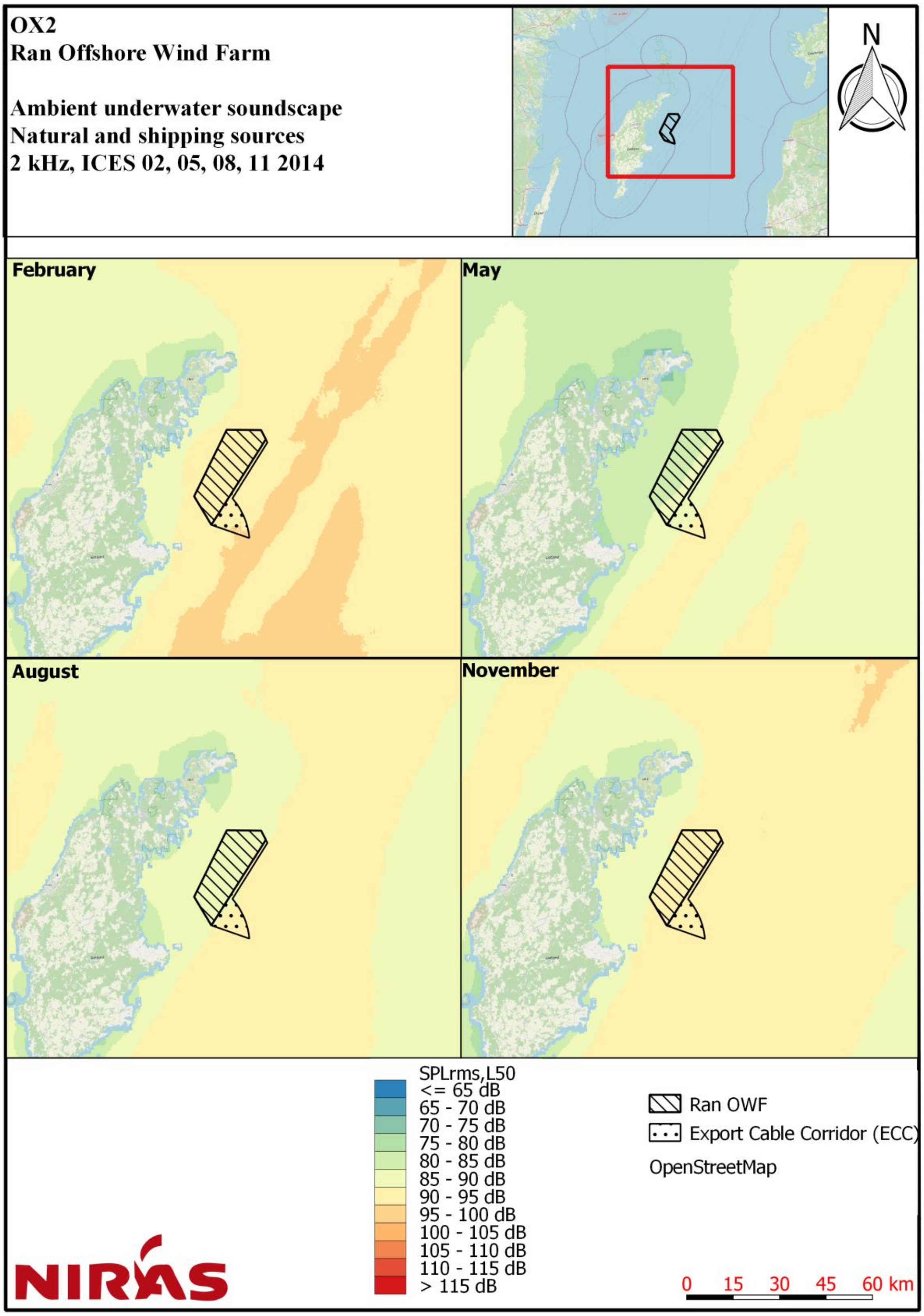

Figure 5.4: ICES soundscape map for 2 kHz, Feb, May, Aug, Nov 2014, 50th percentile $SPL_{rms,2kHz}$ $[dB\ re.1\mu Pa^2]$.

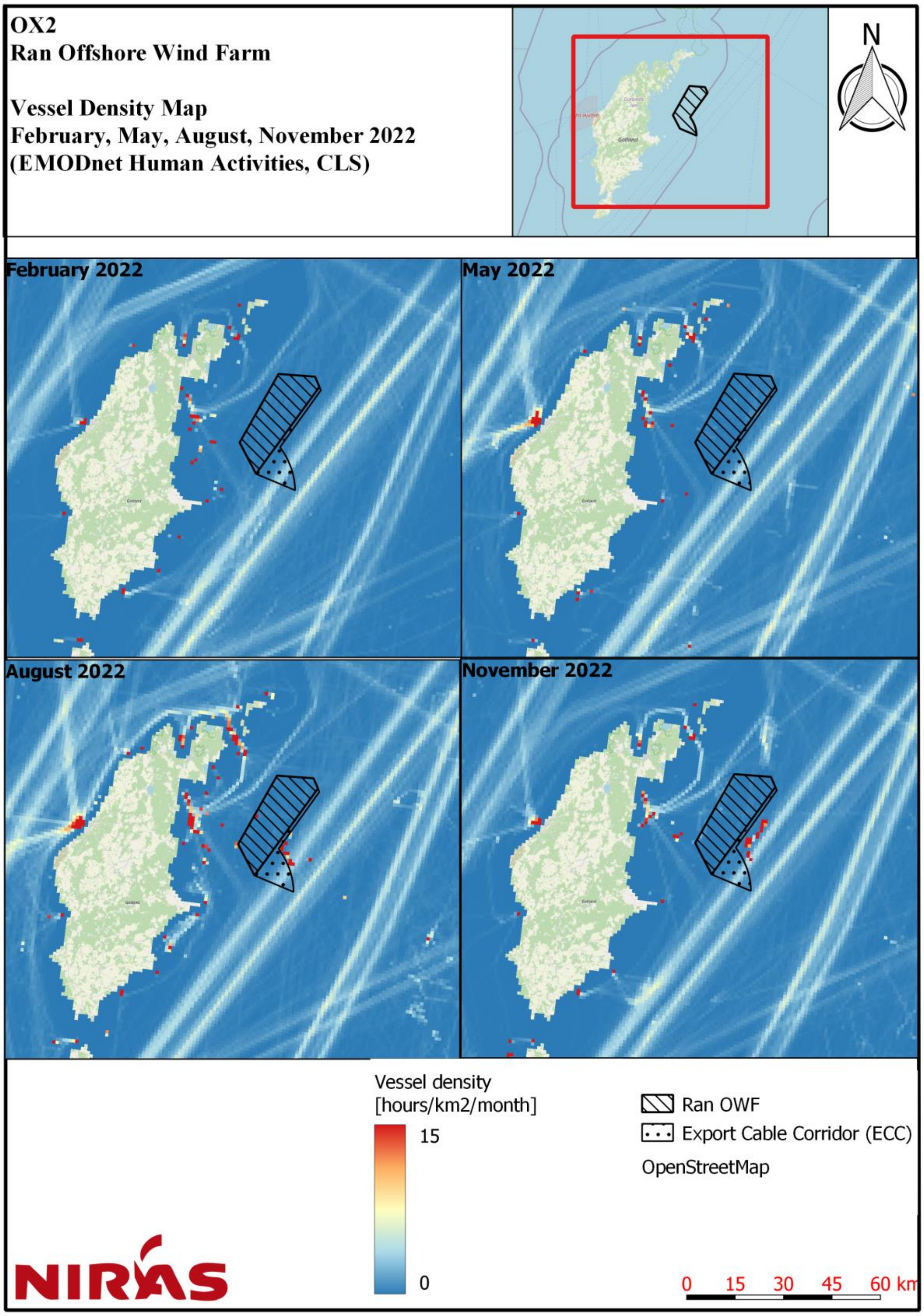

Figure 5.5: Vessel density map from 2022, from EMODnet (EMODnet, CLS, 2022) based on AIS data from CLS.

6. Underwater noise prognosis for geophysical survey

Geophysical survey activities have the potential to cause avoidance response, TTS, and PTS in marine mammals (Madsen, et al., 2006).

Proposed survey equipment is first evaluated for its potential to have adverse effects on marine mammals (section 6.1). In the evaluation of the different equipment types, the following groups of equipment are considered:

A. Equipment has insignificant underwater noise emission for marine mammals:
   -> no further evaluation takes place.
B. Equipment has significant underwater noise emission, but sound propagation modelling is not feasible:
   -> evaluation is based on either literature or equation based calculation.
C. Equipment has significant underwater noise emission and sound propagation modelling is feasible:
   -> evaluation is based on sound propagation modelling.

For equipment in group A or B, the impact is determined directly in the evaluation. For group C equipment, sound propagation modelling is carried out, with the following components:

- A source model, charactering the noise source, and the emission of noise into the water column (section 6.2).
- An environmental model, charactering the marine environment and its acoustic properties (section 6.3).
- A sound propagation model, through which the source and environmental model is used to determine the sound propagation (section 6.3.4).

Results are reported as impact ranges for marine mammals, in numerical form in section 6.5.

6.1. Equipment evaluation

There is no final list of survey equipment models and operational parameters available for the survey activities, however a representative list is considered for use in the prognosis, see Table 6.1, based on experience from previous surveys, and information from the client.

Table 6.1: Geophysical survey equipment models and operational parameters. Note that actual equipment models to be used have not yet been selected, and the listed models and operation parameters are used as representative equipment, based on experience from previous surveys. Source parameters are chosen conservatively where no information was supplied by Ran Vindpark AB.

Type	Equipment model	Source Level, L_s [dB re 1 µPa · m]	Primary Frequency Range (kHz)	Pulse Length	Beam Width	Sound exposure source level, $L_{S,E}$ [dB re 1 $\mu Pa^2 m^2 s$]	Duty cycle over a 24 hour period
Sub-bottom profiler (SBP)	Innomar Medium 100	247 dB	1-150	0.07 – 2 ms	2°	213 dB	40 Hz
Sparker (UHRS)	GeoSource 200-400	216 dB (@1000 J)	0.05-4	2 ms	60° (1 kHz) 30° (2 kHz) 15° (4 kHz)	189 dB	4 Hz
Airgun	Sercel mini GI 5 – 60 in^3	228 dB	0-0.5	3.6 ms	Omni	197 dB	1 Hz
Multi-beam echosounder (MBES)	Reson SeaBat T50-R	190 - 220 dB	190-420	0.3 - 10 ms	2° @ 200 kHz 1° @ 400 kHz	170 - 200 dB	50 Hz
Side scan sonar (SSS)	Edgetech 4200	210 dB	100+400 300+600 300+900	<20 ms (100kHz) <12 ms (300kHz) <10 ms (400kHz) <5 ms (600kHz) <3 ms (900kHz)	1.50° (100 kHz) 0.50° (300 kHz) 0.40° (400 kHz) 0.26° (600 kHz) 0.20° (900 kHz)	193 dB (100 kHz) 191 dB (300 kHz) 190 dB (400 kHz) 187 dB (600 kHz) 185 dB (900 kHz)	15 Hz
Magnetometer*	-	-	-	-	-	-	-

6.1.1. Parametric SBP (Innomar Medium 100)

The Innomar Medium 100 creates a very detailed profile of the uppermost part of the seabed, typically the uppermost 20 m below the seabed. It emits two high frequency pulses, called the primary frequencies, with both pulses typically in the frequency range of 100 – 120 kHz. The frequency separation between the two pulses dictates the secondary frequency, created inside the water column as the difference between the two primary frequencies: $f_{sec} = f_{pri2} - f_{pri1}$ $[Hz]$.

The source level of the Innomar Medium 100 is listed as $SL = 247\ dB\ re. 1\mu Pa\ @1m$. It is a complex sound source as the sound emission is heavily focused towards the seabed. The horizontal emission of underwater noise is therefore significantly lower than the source level would indicate, compared to the emission directly downward into the seabed.

In a sound source verification study for geophysical survey activities in the Danish North Sea (Pace, et al., 2021), acoustic measurements were carried out for the Innomar Medium 100. In the study, the sound level was recorded in the horizontal direction at distances ranging from 10s of meters to 750 m. In Figure 6.1, all measured data points in the horizontal direction are presented as the individual pulse SEL, along with a logarithmic curve fit. The trend indicates a source level of 193 dB and a rapid decay of approximately 37 dB/decade in the horizontal direction.

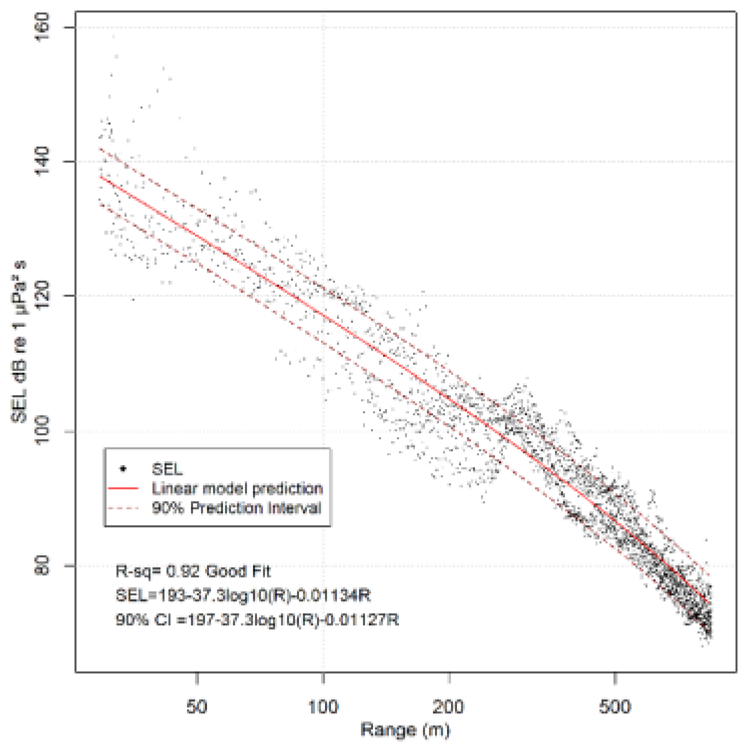

Figure 6.1: Sound Exposure Level measurements and curve fit for Innomar Medium 100, during a sound source verification study in the North Sea (Pace, et al., 2021).

The curve fit obtained from these measurements, should however be considered with a degree of caution, and should not be considered generally applicable. The environmental conditions affect the sound propagation. In order to use the measurement data in a different setting or environment, it is necessary to compensate for the environment where it was obtained, and to develop an equivalent source model that, given the same environment, performs in line with the measurements. NIRAS constructed a digital 3D acoustic model in dBSea, representing the actual survey environment, based on the information supplied in the report along with best available knowledge. In this model, an equivalent omnidirectional point source was designed, mimicking the measured data. The equivalent model can then be used in any other marine environment, however recognizing that the model is an approximation of the equipment behaviour, more so than an actual source model. It is therefore also recognized that this introduces an uncertainty into the sound propagation model. It is however considered the best-possible approach given the lack of an actual source model, which would require detailed source level and frequency measurements, as well as detailed frequency specific directivity measurements.

Based on the evaluation above, the Innomar Medium 100 is considered a "group C" equipment type, and should be evaluated through sound propagation modelling.

6.1.2. Sparker (GeoSource 200-400)

The "GeoSource 200-400" from Geo Marine Survey Systems, is a multi-tip electrode sparker, discharging energy through a number of electrodes arranged in a uniformly spaced planar grid, creating a downward focused acoustic pulse. The directivity at primary frequencies, where most of the source energy is located, is provided in Table 6.1.

The dominant frequency content for the emitted acoustic signals is between 250 Hz to 3.25 kHz. Although being downward focused, the directivity is limited, and significant sound energy will be emitted in the horizontal direction. Thus, the noise source has the potential to cause long impact ranges.

In a sound source verification study for geophysical survey activities in the Danish North Sea (Pace, et al., 2021), acoustic measurements were carried out for a 360 tip sparker system (assessed to be equivalent to the proposed GeoSource 200-400). In the study, the sound level was recorded in the horizontal direction at distances ranging from 10s of meters to 2 km. In Figure 6.2, all measured data points in the horizontal direction are presented as the individual pulse SEL, along with a logarithmic curve fit. The trend indicates a source level of 168 dB and a decay of approximately 14.5 dB/decade in the horizontal direction.

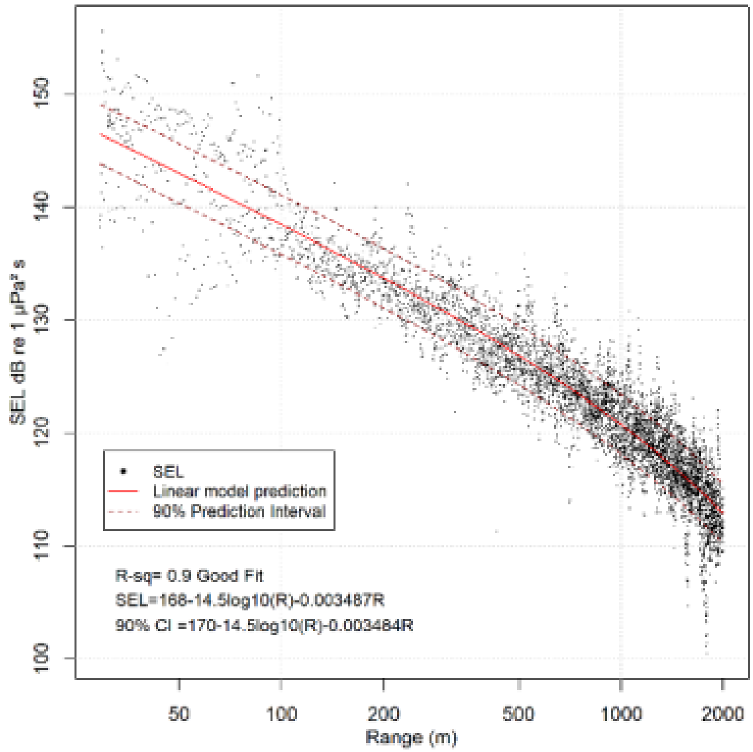

Figure 6.2: Sound Exposure Level measurements and curve fit for 360 tip sparker, during a sound source verification study in the North Sea (Pace, et al., 2021).

The curve fit obtained from these measurements, should however be considered with a degree of caution, and should not be considered generally applicable. As for the Innomar Medium 100, NIRAS developed an equivalent sound source model to represent the GeoSource 200-400 sparker, in the same way as described in section 6.1.1.

The GeoSource 200-400 sparker is considered a "group C" equipment type, and should be evaluated through sound propagation modelling.

6.1.3. Airgun (Mini GI 60 cu. inch)

A mini airgun of the model, Sercel Mini G 60 cu. inch, is used to investigate the sub-bottom layers of the seabed structure.

Airguns work by rapidly releasing compressed air, causing a release of a focused pressure pulse. A single-airgun configuration is omnidirectional and thereby emits underwater noise equally in all directions. Most of the energy from an airgun is located in the low frequency range, with the primary frequency content between 10 Hz – 1 kHz, and the highest energy level around 20 – 40 Hz. It is therefore below the primary hearing frequency range of harbour porpoise and seal. The low frequency nature of the source, however allows the sound to propagate with low propagation loss (PL) over distance, and combined with the impulsive nature of the source, and its high source level it still has the potential to cause adverse effects on marine life. As an omnidirectional point source, it can be implemented directly into an underwater sound propagation model.

The Sercel Mini G 60 cu. inch airgun is considered a "group C" equipment type, and should be evaluated through sound propagation modelling.

6.1.4. Multi-beam Echosounder (Reson SeaBat T50-R)

The Reson SeaBat T50-R MBES is a hydroacoustic device used for mapping the seafloor and collecting bathymetric data in marine environments. It employs the principles of sonar to measure the depth of the seabed and generate high-resolution bathymetric maps.

The transducer array is the primary component of the MBES. It consists of multiple individual transducers arranged in a fan-shaped or circular array. Each transducer emits a narrow beam of sound pulses in a downward direction and receives the echo reflected from the seafloor.

The frequencies emitted by the MBES are at least 200 kHz, which is outside the hearing ability of any marine mammals. Coupled with the strong downward directivity, this equipment type is unlikely to have any negative auditory effect on marine mammals. It is therefore considered a "Group A" equipment type, and is not considered further in this prognosis.

6.1.5. Side scan sonar (Edgetech 4200)

The Edgetech 4200 side scan sonar (SSS) is an underwater imaging system used for high-resolution imaging and mapping of the seafloor. Unlike multibeam echosounders (MBES) that primarily measure bathymetry, SSSs are designed to provide detailed visual representations of the seafloor surface and its features.

The transducer array in a SSS is responsible for transmitting and receiving acoustic signals. It typically consists of one or more transducers arranged in a line or an array configuration. Each transducer emits a narrow beam of sound waves perpendicular to the seafloor, covering a wide swath on either side of the sonar system.

The frequencies emitted by the SSS are typically at least 300 kHz, which is outside the hearing ability of any marine mammals. While the Edgetech 4200 also comes with the option of a 100 kHz frequency, it was agreed with Ran Vindpark AB not to use this setting, as it coincides with the frequency range where harbour porpoise is most sensitive to sound. Coupled with the strong downward directivity, and restricting the use of frequencies below 200 kHz, this equipment type is unlikely to have any negative auditory effect on marine mammals. It is therefore considered a "Group A" equipment type, and is not considered further in this prognosis.

6.1.6. Magnetometer

Marine magnetometers used in geophysical surveys for detecting buried objects such as UXOs are designed to identify variations in the magnetic field caused by the presence of ferromagnetic materials. These materials, including metallic objects like munitions, generate localized disturbances in the Earth's magnetic field, which can be detected and analyzed by the magnetometer system.

The magnetometer sensor is typically mounted on a specialized instrument platform, such as a towfish or a remotely operated vehicle (ROV). The platform is then towed at a constant altitude above the seafloor, typically a few meters, ensuring consistent proximity to the target area.

The magnetometer does not rely on acoustic output to function, and it therefore has no underwater noise emission. It is classified as a “Group A” equipment type and is not considered further in this prognosis.

6.1.7. Noise from survey vessels

In addition to the noise from the individual activities, the survey vessel is also likely to be a source of underwater noise during the survey execution. In (Pace, et al., 2021), the survey vessel underwater noise emission was measured, and reporting in 1/3 octave levels at 5 different distances from the vessel, with and without marine mammal frequency weighting applied, see Figure 6.3.

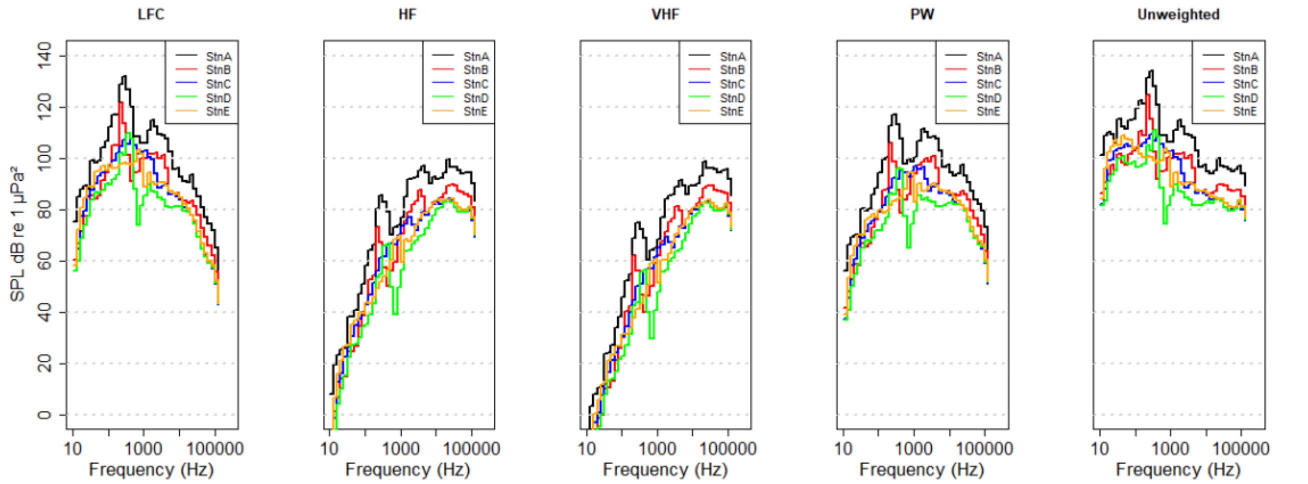

Figure 6.3: Weighted and unweighted 1/3 octave sound pressure level (SPL) measured at 5 different hydrophone distances (stnA is directly underneath the vessel path, stnB at 150 m distance, stnC at 540 m, stnD at 780 m and stnE at 2040 m). (Pace, et al., 2021).

From Figure 6.3, it is evident that noise levels are primarily low frequent, with most of the acoustic energy located below a few hundred Hz. For harbour porpoise (VHF-weighting), the measurements at station B (150 m distance) show 1/3 octave band levels below 90 dB in all bands, with broadband level below the threshold criteria for behaviour reaction, $L_{p,125ms,VHF} = 103 \text{ dB re. } 1 \text{ µPa}$.

Vessel noise is a continuous noise type, and is therefore evaluated by comparison with the non-impulsive TTS and PTS criteria. In Table 6.2, distances to PTS and TTS for each of the relevant species are provided, based on the measurement data in Figure 6.3, and assuming a 24 hour survey duration.

Table 6.2: PTS and TTS impact ranges from geophysical survey vessel noise.

Species	Swim speed [m/s]	Impact range [m]		
		PTS	TTS	Behaviour
		Non-impulsive	Non-impulsive	
Harbour porpoise (VHF)	1.5	< 10 m	< 100 m	< 150 m
Seal (PCW)	1.5	< 10 m	< 100 m	-

From this, it is evaluated that the survey vessel is categorized as “Group A,” and is not evaluated any further.

6.1.8. Summary of equipment evaluation

All proposed equipment types were evaluated for their potential to emit harmful levels of underwater noise, and three groups were defined:

- Group A equipment, for which their underwater noise emission is evaluated to be insignificant, was deemed appropriate for the MBES, SSS and magnetometer equipment types.
- Group B equipment, for which underwater noise emission may occur at harmful levels, but where sound propagation modelling is not deemed feasible, did not apply to any proposed equipment types.
- Group C equipment, for which significant underwater noise emission is likely, and sound propagation modelling should take place, included the parametric SBP, sparker, and airgun.

6.2. Source models

6.2.1. Parametric SBP (Innomar Medium 100) implementation

The Innomar Medium 100 source model is based on the approach described in section 6.1.1, using an omnidirectional equivalent point source. Source characteristics are shown in Figure 6.4, as both unweighted (blue), VHF (green) and PCW (red). It is reiterated that this is an equivalent point source model from a horizontal propagation perspective, and not an accurate representation of the sound source. It is therefore only to be used as a conservative model for calculating horizontal impact ranges for marine mammals.

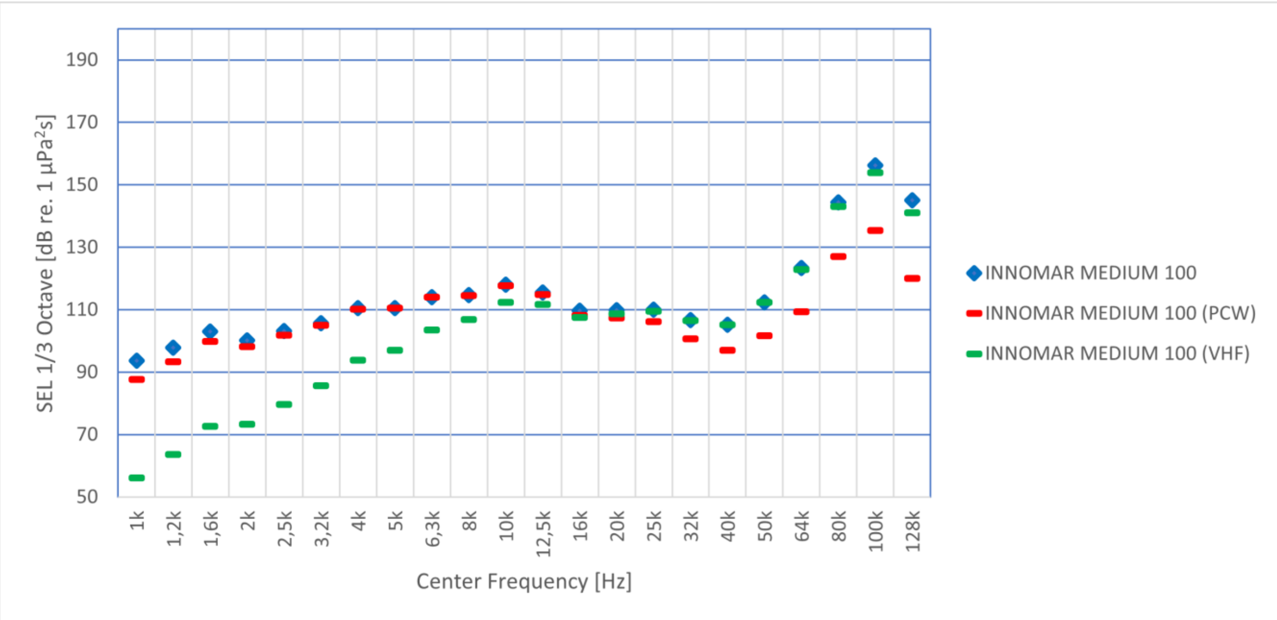

Figure 6.4: Equivalent omnidirectional point source model frequency spectrum for the Innomar Medium 100 parametric SBP. The source model is calibrated to fit measurement results from (Pace, et al., 2021).

The Innomar Medium 100 is mounted on the vessel, and is assumed operated at a 40 Hz pulse rate, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The Innomar Medium 100 is considered a non-impulsive source type, and impact range calculation is therefore based on the non-impulsive threshold criteria.

6.2.2. Sparker (GeoSource 200–400) implementation

The GeoSource 200-400 source model is based on the approach described in section 6.1.2, using an omnidirectional equivalent point source. Source characteristics are shown in Figure 6.5, as both unweighted (blue), VHF (green) and PCW (red). It is reiterated that this is an equivalent point source model from a horizontal propagation perspective, and not an accurate representation of the sound source. It is therefore only to be used as a conservative model for calculating horizontal impact ranges for marine mammals.

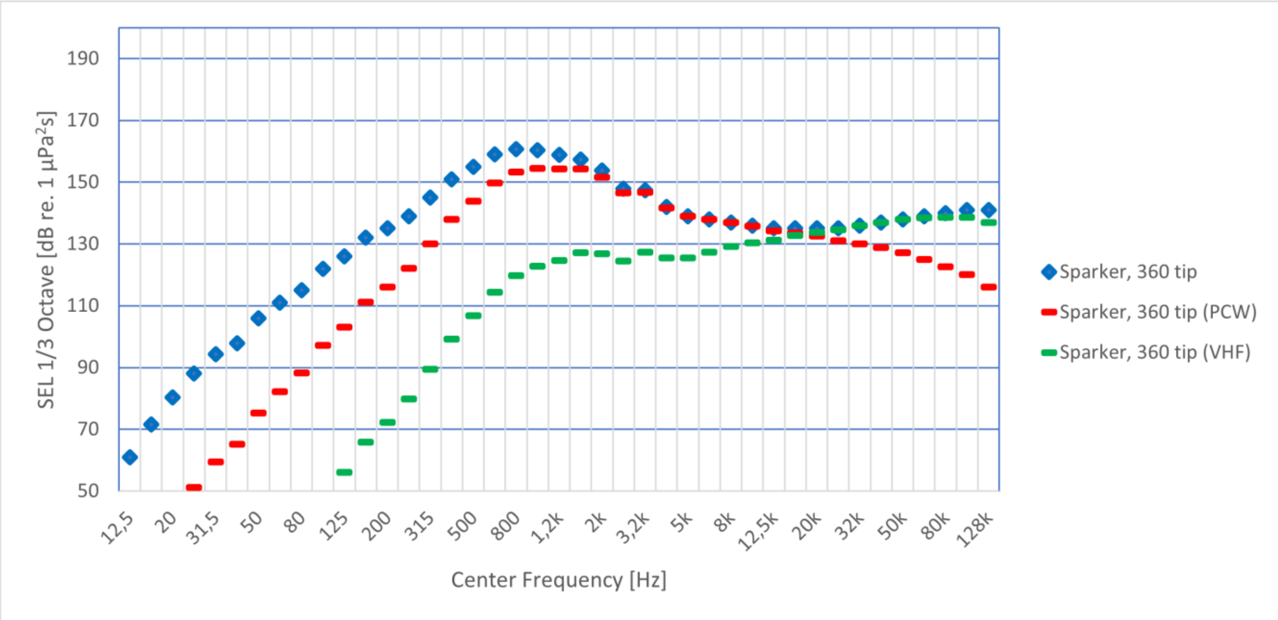

Figure 6.5: Equivalent omnidirectional point source model frequency spectrum for the GeoSource 200-400 sparker. The source model is calibrated to fit measurement results from (Pace, et al., 2021).

The GeoSource 200-400 is towed behind the survey, and is assumed operated at a 4 Hz pulse rate, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The GeoSource 200-400 is considered an impulsive source type, and impact range calculation is therefore based on the impulsive threshold criteria.

6.2.3. Airgun (Mini GI 60 cu. Inch) implementation

The Mini GI 60 cu. inch source model is based on the approach described in section 6.1.3, using an omnidirectional point source. Source characteristics are shown in Figure 6.6, as both unweighted (blue), VHF (green) and PCW (red).

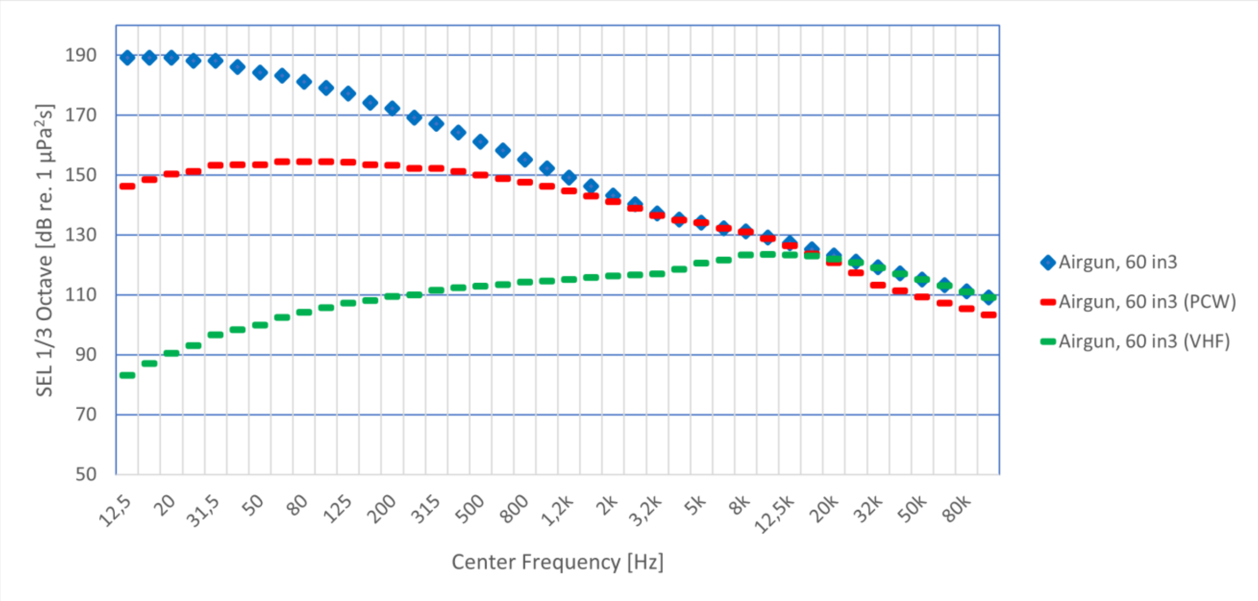

Figure 6.6: Equivalent omnidirectional point source model frequency spectrum for the Mini GI 60 cu. inch airgun. The source model is calibrated to fit measurement results from (Pace, et al., 2021).

The Mini GI 60 cu. inch is towed behind the survey vessel, and is assumed operated at a 1 Hz pulse rate, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The Mini GI 60 cu. inch is considered an impulsive source type, and impact range calculation is therefore based on the impulsive threshold criteria.

6.2.4. Source positions

The project is in early stages of development, and final survey activities have not yet been determined. It was therefore agreed with Ran Vindpark AB to select a number of representative positions throughout the investigation area, so different sound propagation scenarios are covered. Areas where sound propagation most likely results in the longest impact ranges are identified, taking into account nearby marine mammal protection areas if relevant. The source positions are listed in Table 6.3, along with coordinates, and distances to relevant areas of interest. The positions are also shown in Figure 6.7.

Table 6.3: Source positions used for sound propagation modelling of underwater noise during geotechnical and geophysical surveys.

Position ID	Easting	Northing	EPSG	Nearby areas of interest
1	398492	6402915	25834	Nat2000 area "Gotska Sandön-Salvorev", ~23 km distance Coast of Gotland, ~15 km distance City of Herrvik, ~44 km distance
2	401769	6391340	25834	Nat2000 area "Gotska Sandön-Salvorev", ~34 km distance Coast of Gotland, ~33 km distance City of Herrvik, ~37 km distance
3	388503	6379078	25834	Nat2000 area "Gotska Sandön-Salvorev", ~49 km distance Coast of Gotland, ~20 km distance City of Herrvik, ~19 km distance

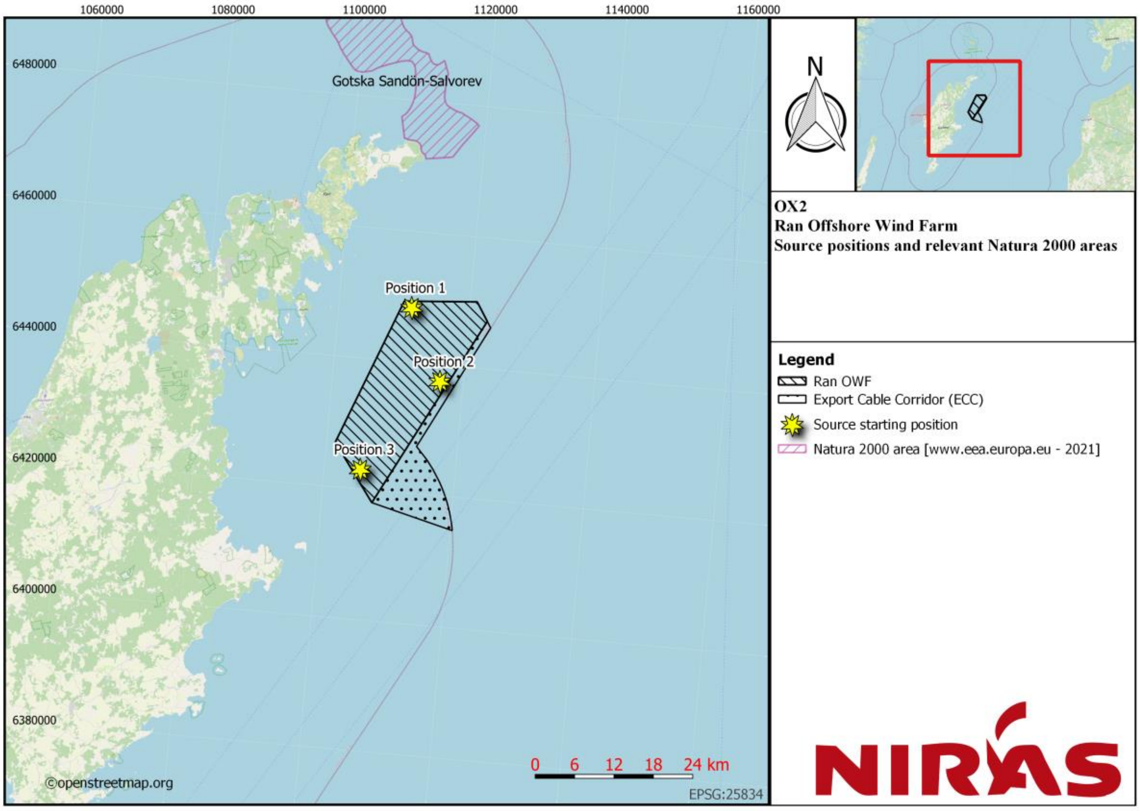

Figure 6.7: Source positions chosen for sound propagation modelling as well as nearby relevant Natura 2000 areas.

6.3. Environmental 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.

6.3.1. 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, it is necessary for the sound propagation model to extend 10 – 20 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 6.8, where darker colours indicate deeper areas, and lighter colours indicate more shallow water (EMODnet, 2021).

Figure 6.8: 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 6.4. A visualisation of the bathymetry model for the project area and surroundings is shown in Figure 6.9.

Table 6.4: Bathymetry model data sources.

Data source	Reference
Bathymetry (AREA 1)	(Emodnet, 2022)

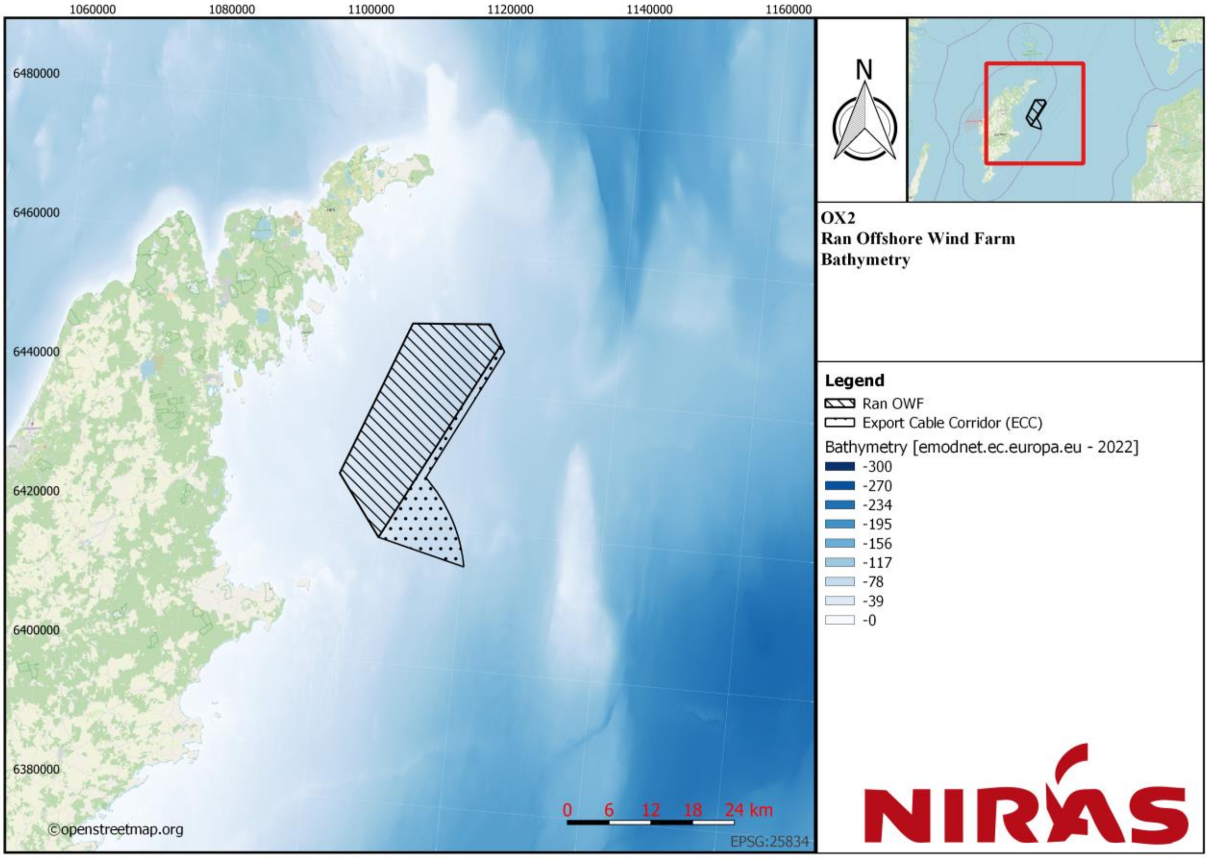

Figure 6.9: Bathymetry for the project area and surroundings, sources as listed in Table 6.4.

6.3.2. 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 6.10) is generally used.

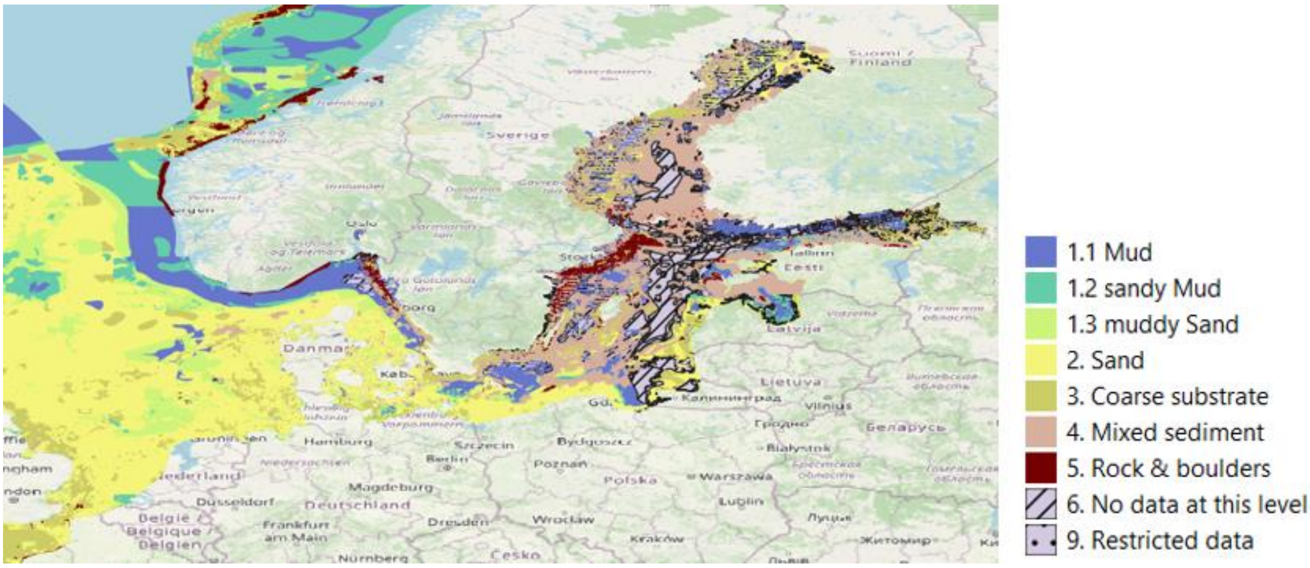

Figure 6.10: A section of the seabed substrate map, (Folk 7) (EMODnet, 2021).

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 6.5, utilizing information from (Jensen, et al., 2011; Hamilton, 1980).

Table 6.5: 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/m^3]	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 6.6, and resulted in a 484 point sediment model, with topsoil types shown in Figure 6.11. Primary seabed surface layers in the project area are mixed sediment and muddy sand with occurrences of sand and coarse substrate. Layer thickness of the upper sediment is not well defined in the available sources and a conservative thickness of 60 m is used throughout. Acoustic parameters for each layer are shown in Table 6.5. 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.

Table 6.6: Sediment model data sources.

Data source	Reference
Seabed substrate map	(EMODnet, 2021)
Acoustic parameter model for sediment types	Table 6.5

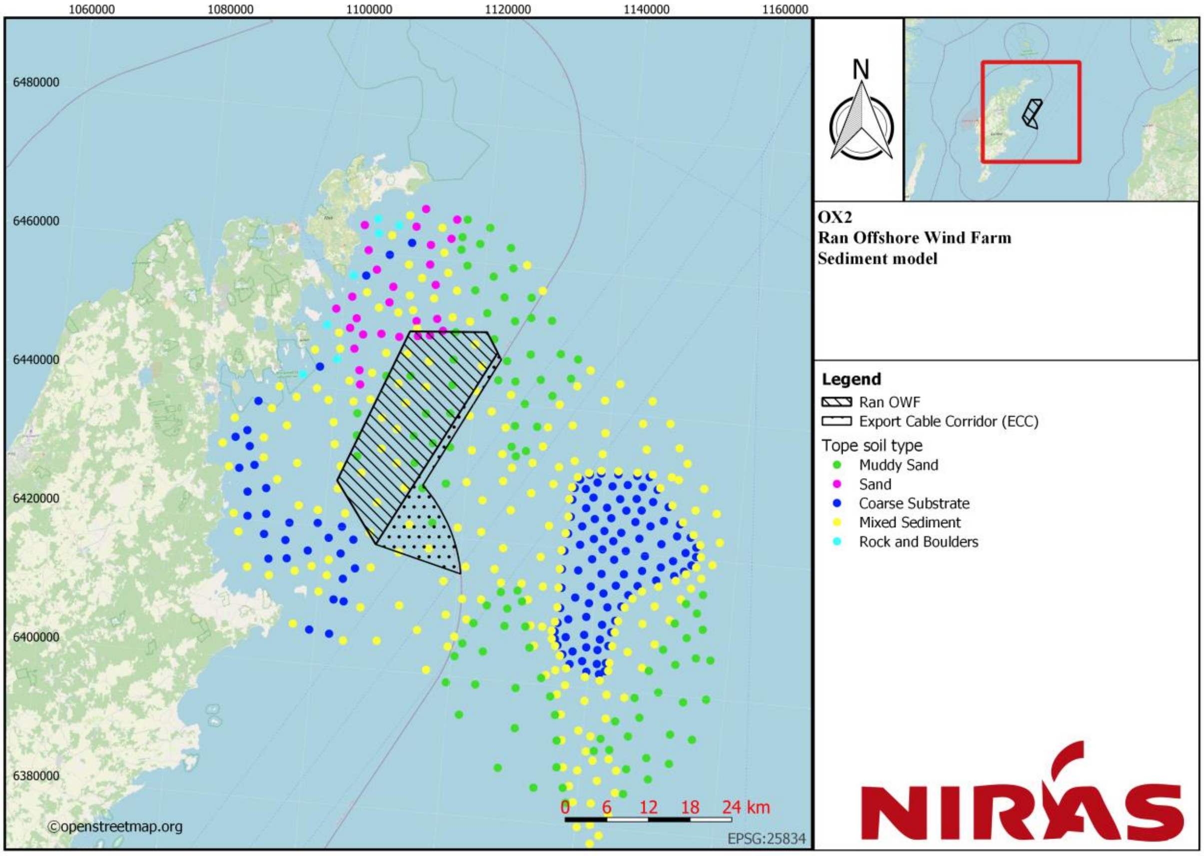

Figure 6.11: Sediment model points and topsoil layer type.

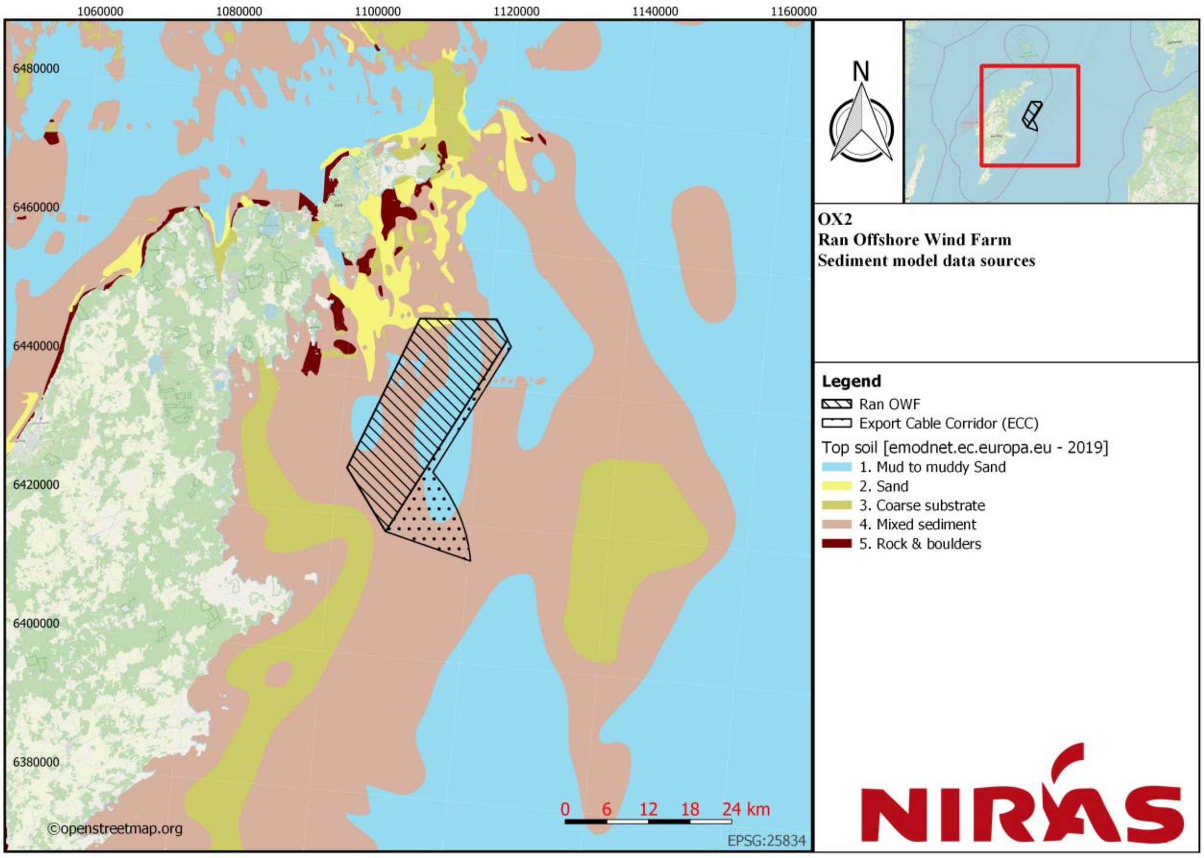

Figure 6.12: Sediment model data source, as listed in Table 6.6.

6.3.3. 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 8, 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.

$$\frac{\cos(\theta)}{c} = \text{constant} \qquad \text{Equation 8}$$

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 Baltic 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 6.3.2, 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 6.7, and through the NIRAS software tool "TRANSMIT", turned into sound speed profiles.

Table 6.7: 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.

A realistic worst case approach was agreed with Ran Vindpark AB. 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 6.2.4. 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 6.13 (temperature), Figure 6.14 (salinity), and in Figure 6.15 (sound speed). Profiles for the remaining positions are attached in Appendix 1. 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.

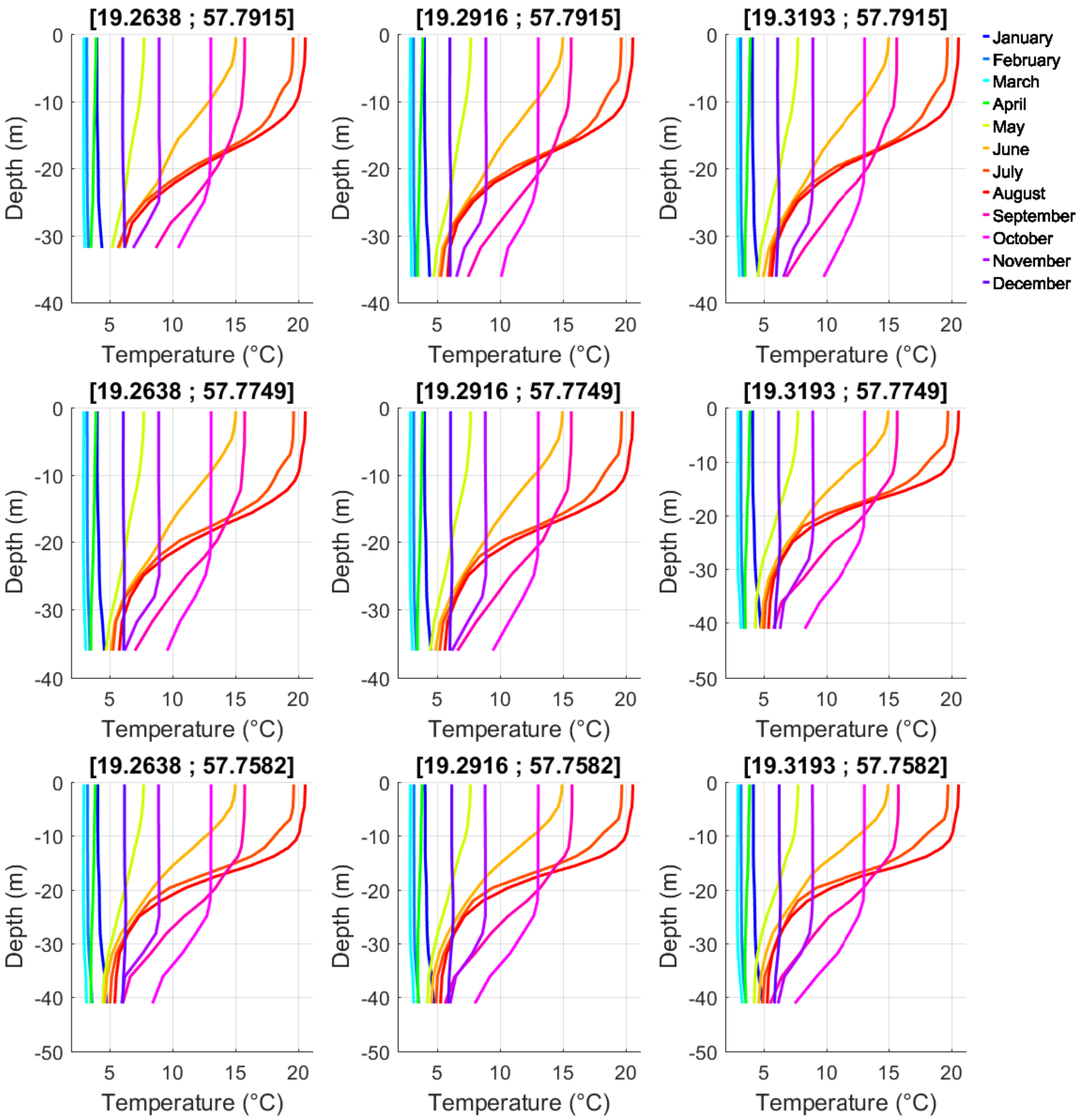

Figure 6.13: Temperature profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.

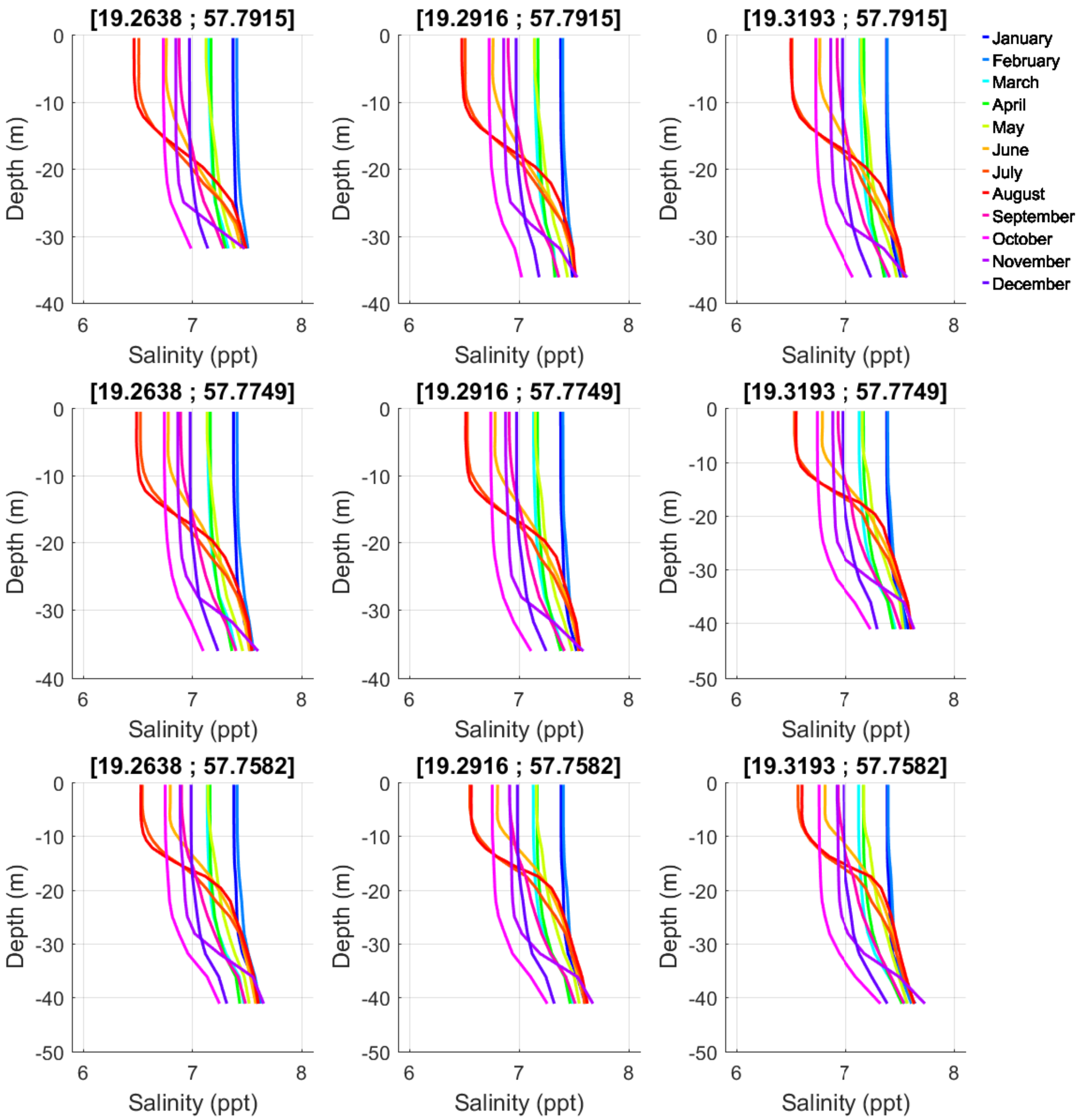

Figure 6.14: Salinity profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.

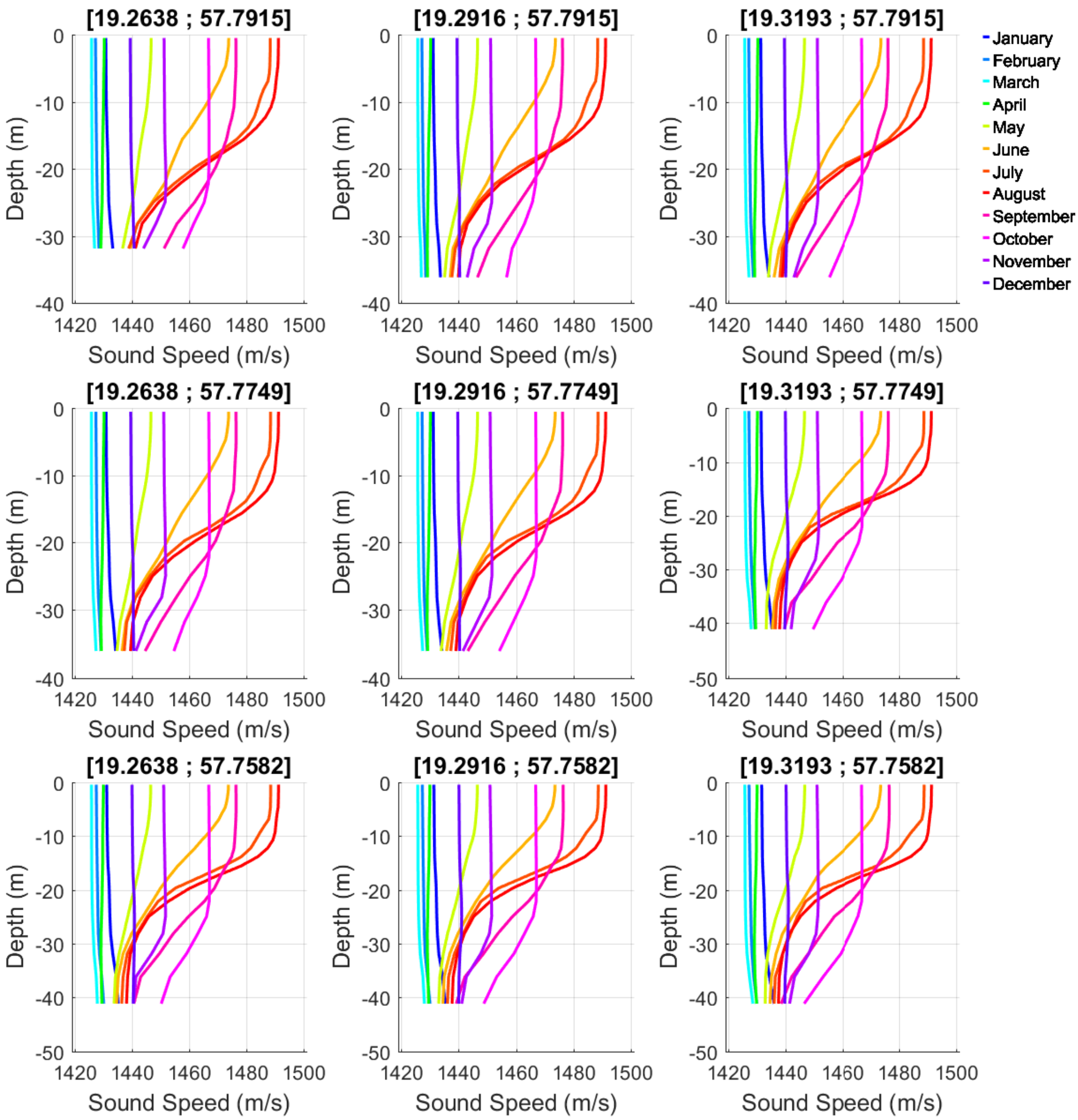

Figure 6.15: Sound speed profiles for the area around source position 1 for all months. Gridded layout reflects geographical location.

6.3.4. 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.

6.3.5. 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 9, from which is inferred that increasing frequency leads to increased absorption (Jensen, et al., 2011).

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11\mathrm{f}^2}{1+\mathrm{f}^2} + \frac{44\mathrm{f}^2}{4100+\mathrm{f}^2} + 3.0 \times 10^{-4}\mathrm{f}^2 \quad \left[\frac{\mathrm{dB}}{\mathrm{km}}\right] \qquad \text{Equation 9}$$

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.

6.4. Sound Propagation 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 dBSeaPE or 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]. For very high frequencies, dBSeaRay is typically preferred.

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 6.16, 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.

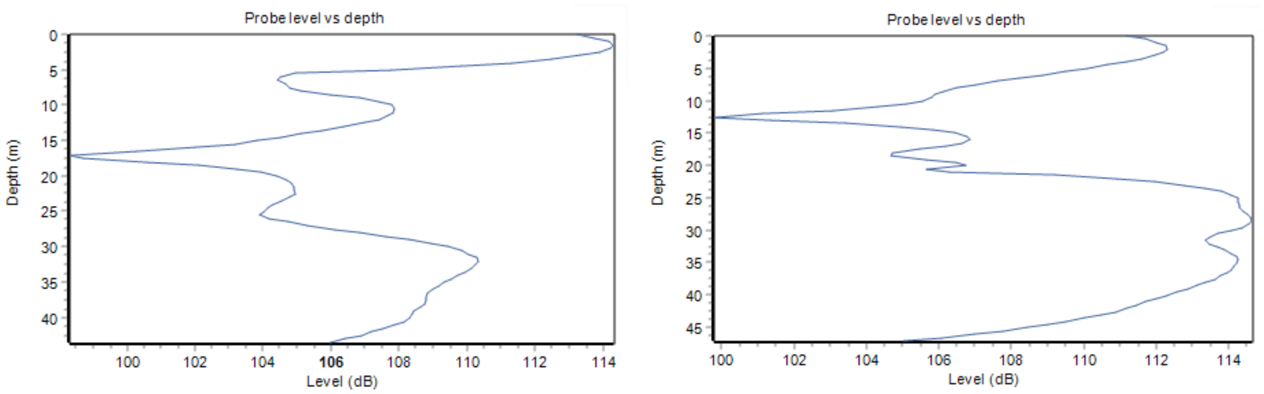

Figure 6.16: Concept of MOD, where the maximum sound level at any depth is extracted for each distance and radial interval. Example shows an MOD value of 114.2 dB (left side) at 1 m depth, and MOD value of 114.6 dB (right side) at 28 m depth.

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.

6.4.1. Settings

The software tool dBSea was used for sound propagation modelling, with the configuration listed in Table 6.8.

Table 6.8: Sound propagation modelling tool settings for dBSea.

Parameter	Value
Software version	2.3.6
Grid (range x depth) resolution	25 m x 0.5 m
Number of radials/transects	P1: 90 (4°) P2 and P3: 45 (8°)
Solver	dBSeaRay
Frequency range	Innomar: 1 kHz – 128 kHz Sparker: 12.5 Hz – 128 kHz Airgun: 12.5 Hz – 10 kHz

Post-processing of the raw sound propagation results into impact ranges was done in NIRAS software tool "SILENCE", which implements Equation 6, page 10 for batch processing of different installation scenarios and threshold criteria.

6.5. Results

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 4. 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.

Distance to PTS, TTS and injury threshold criteria describe the minimum distance from the source, a marine mammal, must at least be deterred to, prior to onset of survey activities, in order to avoid the respective impact.

Distance to behavioural threshold criteria describe the range at which behavioural reactions are likely to occur when the survey operates at full intensity. During soft start, the impact ranges will be shorter.

6.5.1. 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 μPa^{2}s], where "xx" refers to the species specific weighting function. Species specific fleeing behaviour as outlined in section 4.1 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 6.9 for harbour porpoise and Table 6.10 for seals.

Table 6.9: Impact ranges for harbour porpoise.

Position	Harbour porpoise (VHF): Threshold criteria impact ranges				
	PTS		TTS		Behaviour
	Impulsive	Non-impulsive	Impulsive	Non-impulsive	Impulsive
Innomar Medium 100 (SBP) – distances relative to vessel					
1	-	< 100 m	-	< 100 m	1450 m
2	-	< 100 m	-	< 100 m	1600 m
3	-	< 100 m	-	< 100 m	1500 m
GeoSource 200-400 – distances relative to vessel					
1	< 100 m	-	190-700	-	1750 m
2	< 100 m	-	225-875	-	2200 m
3	< 100 m	-	250-775	-	1850 m
Sercel mini GI 60 in3 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	550 m
2	< 100 m	-	< 100 m	-	550 m
3	< 100 m	-	< 100 m	-	575 m
All sources active (combined)					
1	< 100 m	< 100 m	250-725 m	< 100 m	1800 m
2	< 100 m	< 100 m	225-875 m	< 100 m	2200 m
3	< 100 m	< 100 m	275-850 m	< 100 m	1850 m

Table 6.10: Impact ranges for seals.

Position	Seals (PCW): Threshold criteria impact ranges				
	PTS		TTS		Behaviour
	Impulsive	Non-impulsive	Impulsive	Non-impulsive	-
Innomar Medium 100 (SBP) – distances relative to vessel					
1	-	< 100 m	-	< 100 m	-
2	-	< 100 m	-	< 100 m	-
3	-	< 100 m	-	< 100 m	-
GeoSource 200-400 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	-
2	< 100 m	-	< 100 m	-	-
3	< 100 m	-	< 100 m	-	-
Sercel mini GI 60 in3 – distances relative to vessel					
1	< 100 m	-	< 100 m	-	-
2	< 100 m	-	< 100 m	-	-
3	< 100 m	-	< 100 m	-	-
All sources active (combined)					
1	< 100 m	< 100 m	< 100 m	< 100 m	-
2	< 100 m	< 100 m	< 100 m	< 100 m	-
3	< 100 m	< 100 m	< 100 m	< 100 m	-

7. Conclusion

For harbour porpoise, it is concluded that the equipment type causing the highest levels of Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) is the Innomar system and the Sparker system, while the Sparker system alone results in the strongest behavioural effects.

For the geophysical survey activities PTS is thus likely to occur in harbour porpoise present at distances of up to 100 m from the survey vessel, and also up to 100 m from any of the towed equipment. For TTS in harbour porpoise, impact ranges were found to be up to 875 m from the towed Sparker system. For seals, where PCW weighting is applied, PTS and TTS are both unlikely to occur beyond 100 m from source vessel and from any towed equipment.

It should be noted, that the maximum impact range represents marine mammals located directly in the path of the survey vessel, whereas those marine mammals located perpendicular to, or behind the survey vessel path, have significantly reduced impact ranges.

For harbour porpoise behaviour response, through the $L_{p,rms,125ms,VHF} = 103\ dB$ threshold value, the impact distance was found to be up to 2.2 km from the towed sparker system.

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Appendix 1

Temperature, Salinity and Sound Speed Profiles
Position 2 – 3

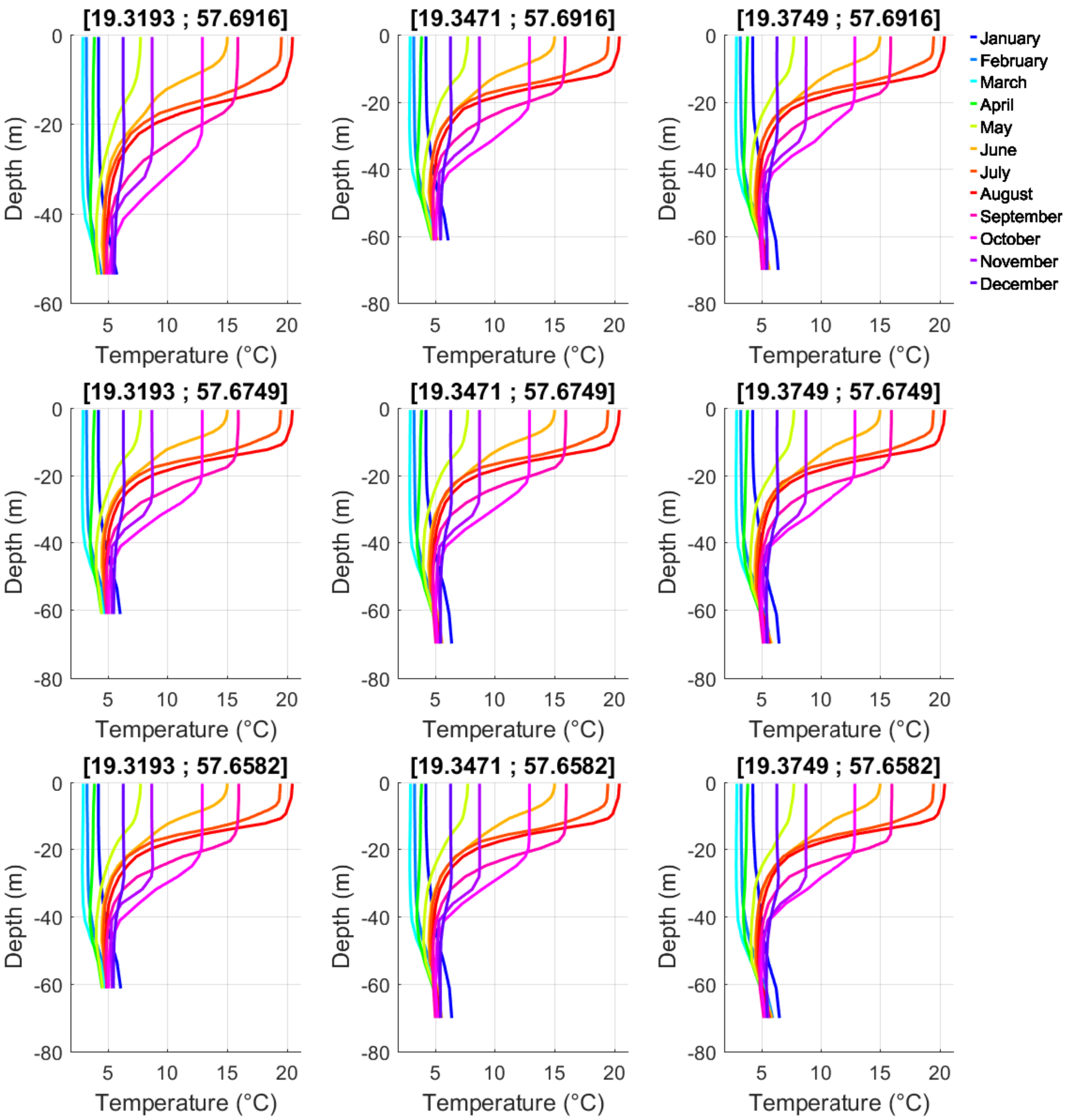

Figure 0.1: Temperature profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.

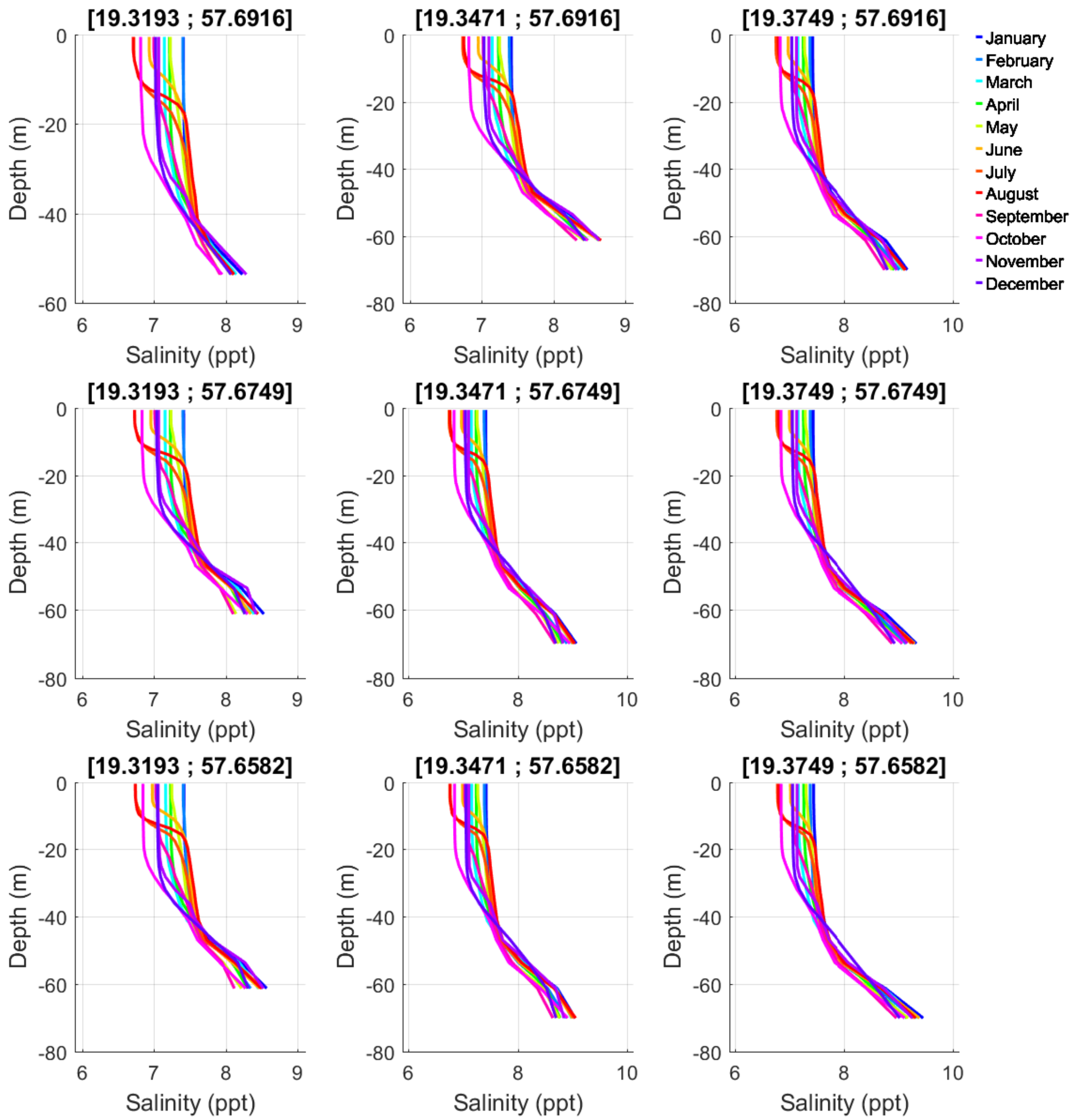

Figure 0.2: Salinity profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.

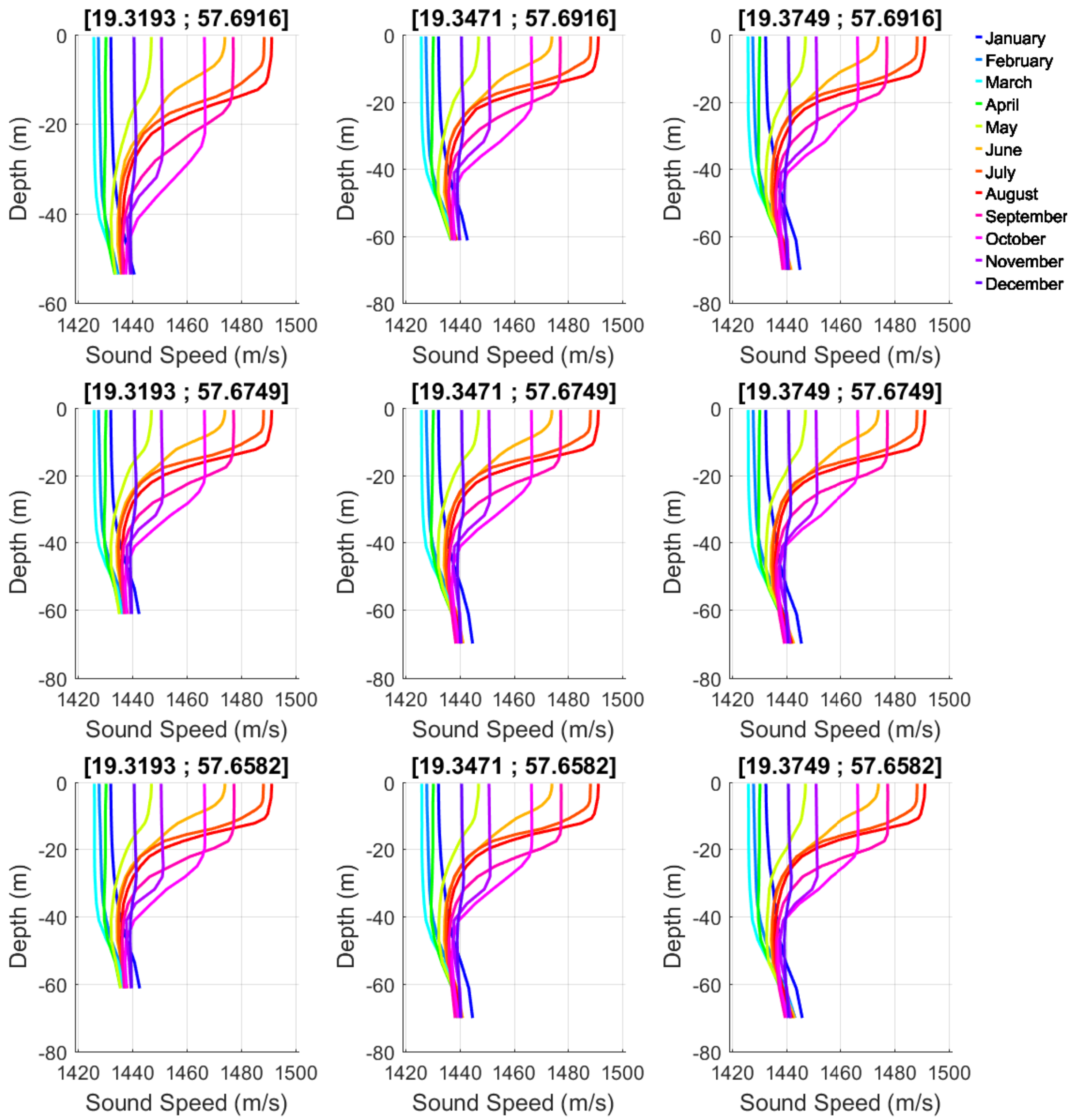

Figure 0.3: Sound speed profiles for the area around source position 2 for all months. Gridded layout reflects geographical location.

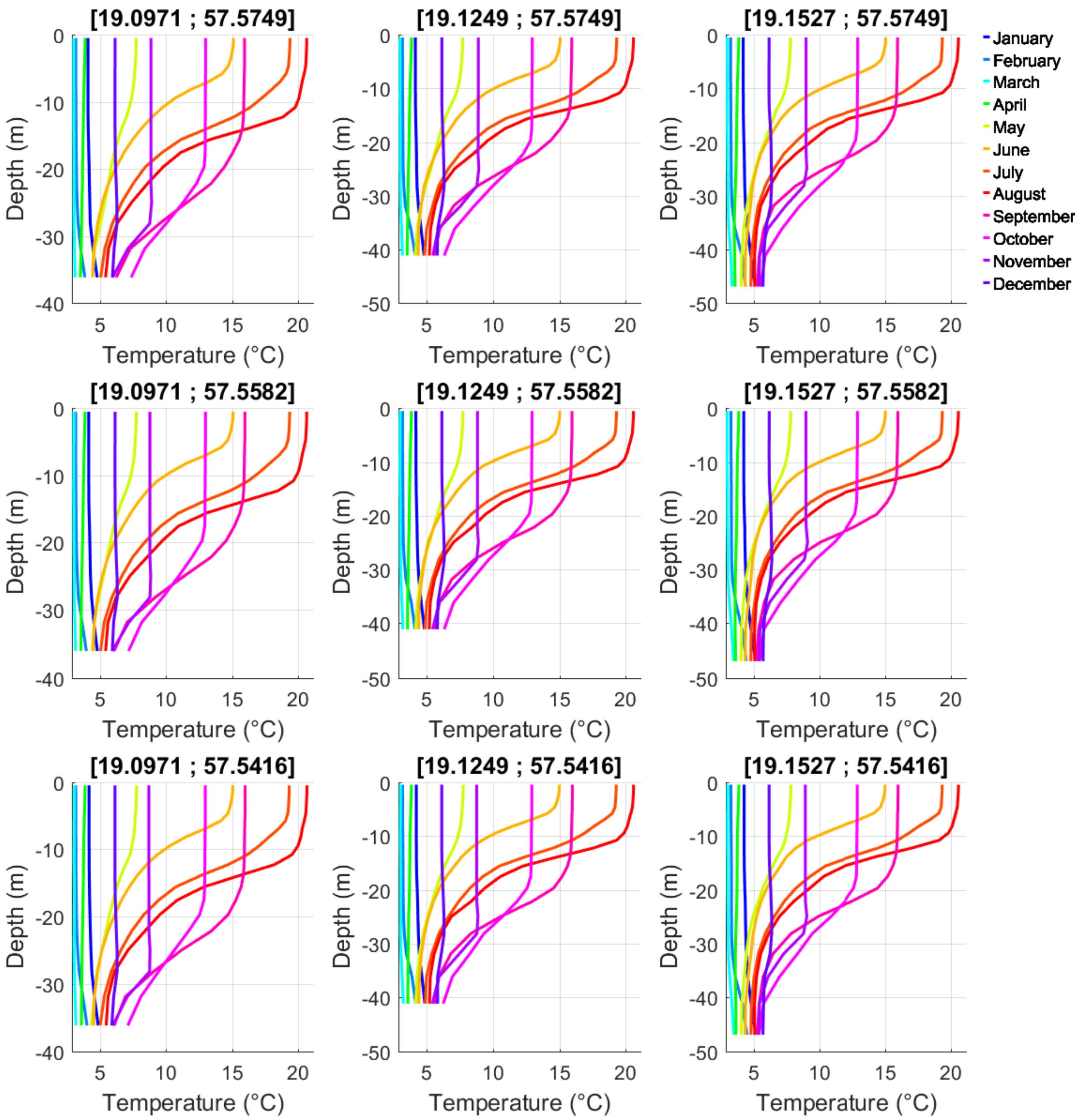

Figure 0.4: Temperature profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.

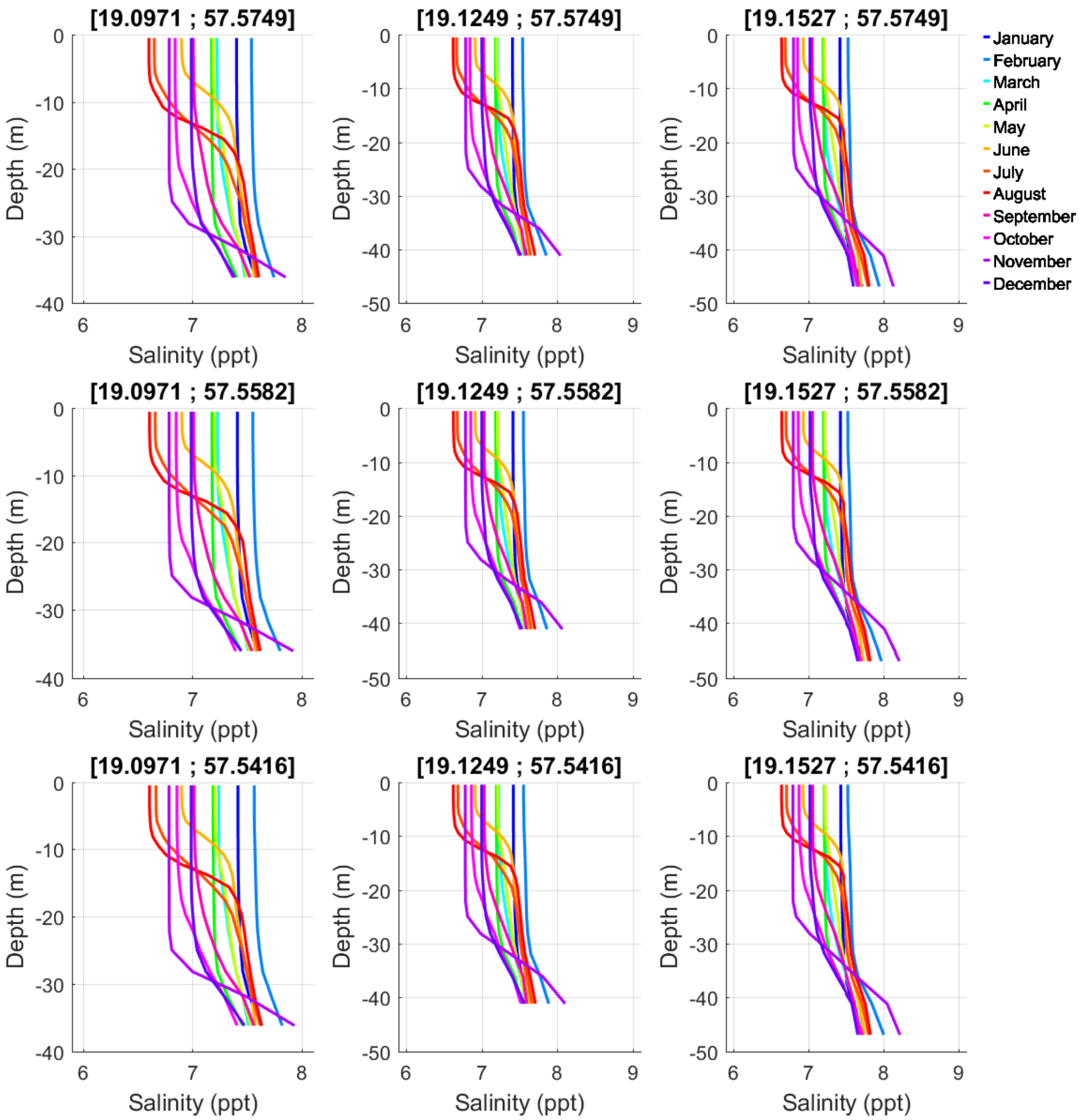

Figure 0.5: Salinity profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.

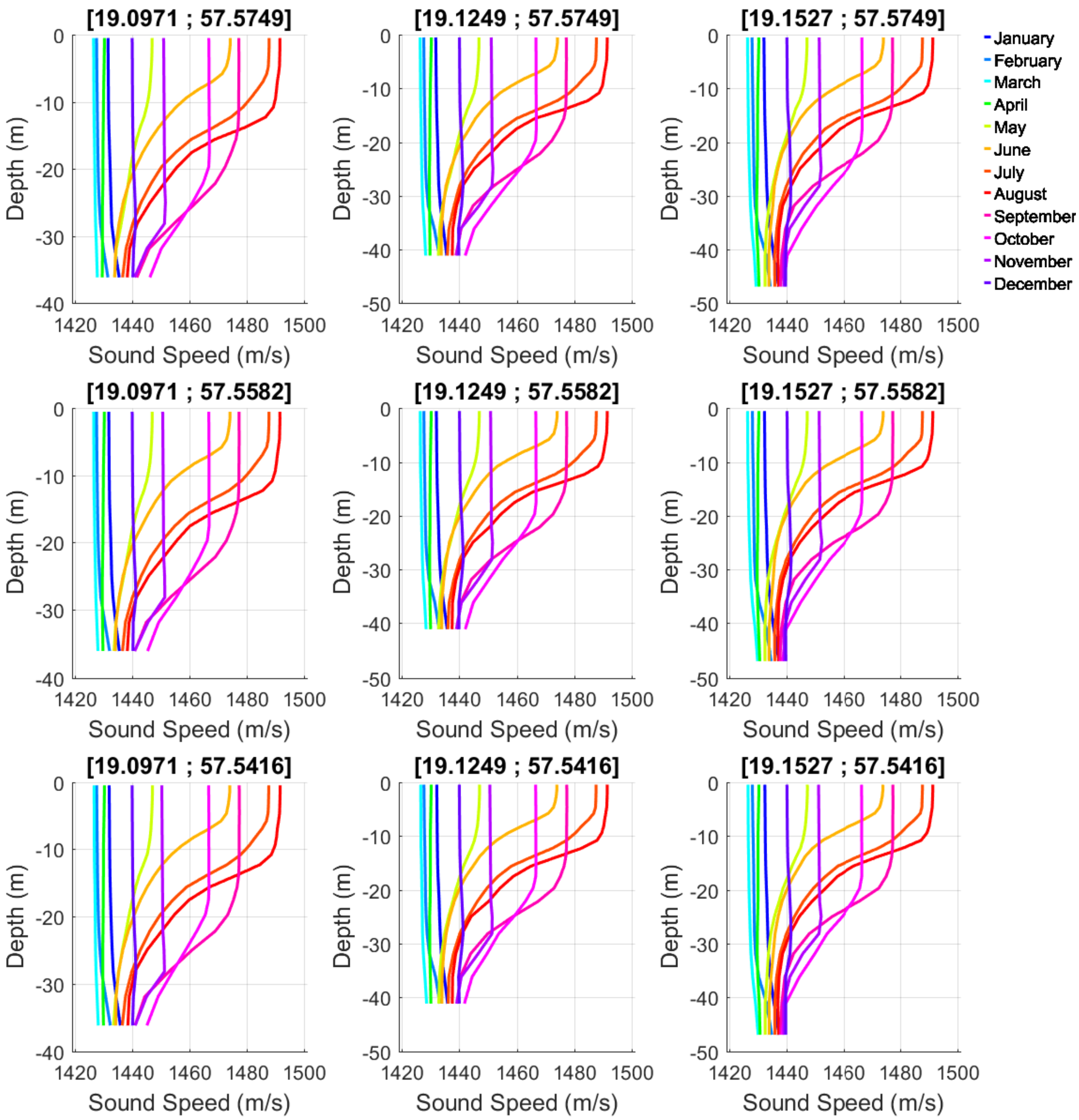

Figure 0.6: Sound speed profiles for the area around source position 3 for all months. Gridded layout reflects geographical location.