Appendix 8.1: Underwater Noise Assessment

URS-EIA-REP-203876

South Stream Pipeline – Turkish Sector – Underwater Sound Analysis

Submitted to:
South Stream Transport B.V.

Authors:
Mikhail Zykov
Loren Bailey
Terry Deveau
Roberto Racca

25 November 2013

P001226-003
Document 00699
Version 1.0

JASCO Applied Sciences Ltd.
Suite 202, 32 Troop Ave.
Dartmouth, NS B3B 1Z1 Canada
Phone: +1-902-405-3336
Fax: +1-902-405-3337
www.jasco.com

Suggested citation:

Zykov, Mikhail, et al. 2013. *South Stream Pipeline – Turkish Sector – Underwater Sound Analysis*. JASCO Document 00699, Version 1.0. Technical report by JASCO Applied Sciences for South Stream Transport B.V.

Contents

Figures

Tables

1. Introduction

1.1. Scope of the Study

JASCO Applied Sciences has performed an acoustic propagation modelling study to estimate the extent of potential noise effects on marine mammals and fish during the construction of the South Stream natural gas pipeline at the bottom of the Black Sea. The study provides estimates of effect ranges from different acoustic aspects of the operations:

- Instantaneous sound exposure from individual vessels
- Aggregate instantaneous sound exposure from a group of vessels operating in the vicinity of each other
- Cumulative sound exposure for 24 hours of typical operations

The acoustic propagation model accounted for the variation of the bathymetry, geoacoustic properties of the sea bottom, and seasonal variation of the sound speed profile in the water column. Two sound speed profiles were considered, notionally bracketing the upper and lower bounds in terms of the acoustic propagation footprint.

A total of 6 scenarios for individual vessels, 4 scenarios for vessel groups, and 1 cumulative scenario were modelled, as well as a side-scan-sonar. The acoustic source levels for the vessels were estimated based on available measurements of the actual vessels or realistic proxies, suitably scaled where appropriate. The type, size, and the total propulsion power of the vessels were considered in the estimation.

1.2. Project Overview

The Turkey segment of the South Stream pipe-line is about 470 km long and goes through the abyssal part of the Black Sea at water depths 2000–2200 m.

The construction of the offshore section of the pipeline in deep water will be limited to the following main activities:

- Surveys of the pipeline route prior to, during and after the pipe-laying process and
- Offshore pipe-laying.

The vessel *GSP Prince* (7,600 kW) will be involved in the surveying operations using a remotely operated vessel (ROV) with side-scan sonar and/or multibeam sonar installed. The pipe-laying process will involve the large pipe-laying vessel Castorone (67,000 kW) or Saipem 7000 (70,000 kW). The tug *Normand Flipper* (7,160 kW) or similar will be used as a support vessel. The fast-supply vessel *GSP Lyra* (2,520 kW) will be used for crew changes.

1.3. Background–Underwater Acoustics

This section describes some basic principles and terms used in underwater acoustics, which will be relevant to the understanding of the model based estimation of sound exposure.

1.3.1. Types of Sound Sources

Underwater sounds can be classified in two major categories: continuous or impulsive. Continuous sounds, which include sound from stationary sources such as dredging operations at a marine terminal or moving sources such as transiting ships, gradually vary in intensity with time. Impulsive sounds, such as sounds from survey equipment or pile driving, are characterized by brief, intermittent acoustic events with rapid (usually less than a second) onset and decay back to ambient levels. All sources considered in this study except side-scan sonar produce continuous sounds.

1.3.2. Sound Level Metrics

Underwater sound amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the loudness of impulsive noise, from seismic airguns for example, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate the loudness of impulsive noise and its effects on marine life.

The zero-to-peak SPL, or peak SPL (L_{pk}, dB re 1 μPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic event, $p(t)$:

$$L_{\mathrm{pk}} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] \tag{1}$$

The peak SPL metric is commonly quoted for impulsive sounds, but it does not account for the duration or bandwidth of the noise. At high intensities, the peak SPL can be a valid criterion for assessing whether a sound is potentially injurious; however, because the peak SPL does not account for the duration, it is a poor indicator of perceived loudness.

The root-mean square (rms) SPL (L_p, dB re 1 μPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the acoustic event:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{2}$$

Think of the rms SPL as a measure of the average pressure or as the effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse or sweep. Because the window length, T, is the divisor, events more spread out in time have a lower rms SPL for the same total acoustic energy.

The sound exposure level (SEL, L_E, dB re 1 μPa^2·s) is a measure of the total acoustic energy contained in one or more acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

$$L_E = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_0 p_0^2\right) \tag{3}$$

where T_0 is a reference time interval of 1 s. The SEL represents the total acoustic energy received at some location during an acoustic event; it measures the sound energy to which an organism at that location would be exposed.

Cumulative SEL

SEL can be a cumulative metric if calculated over periods containing multiple acoustic events. The cumulative SEL (L_{EC}) can be computed by summing (in linear units) the SELs of the N individual events (L_{Ei}).

$$L_{EC} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{Ei}}{10}}\right) \tag{4}$$

Obtaining rms SPL from SEL

Because the rms SPL and SEL are both computed from the integral of square pressure, these metrics are related by a simple expression, which depends only on the duration of the energy time window T:

$$L_p = L_E - 10\log_{10}(T) \tag{5}$$

$$L_{p90} = L_E - 10\log_{10}(T_{90}) - 0.458 \tag{6}$$

where the 0.458 dB factor accounts for the rms SPL containing 90% of the total energy from the per-pulse SEL.

1.1.1. Transmission Loss

Transmission Loss (TL) is a measure of how sound levels change between a source and receiver over some distance. TL depends on the frequency and acoustic environment, including water sound speed profile, bathymetry, and subbottom geoacoustic properties. TL is calculated from source and received levels according to the equation:

$$TL = SL - RL \tag{7}$$

where SL is the source level (dB re 1 µPa at 1 m) and RL is the received sound pressure level (dB re 1 µPa) , and TL is the transmission loss (dB re 1 m).

1.1.2. Source Levels

Source level is a measure of the intensity of sound that a source emits, measured at a reference distance of 1 m. For point sources, such as a small transducer, source levels can be measured directly with a hydrophone at 1 m distance. For larger sources, source levels must be determined indirectly by measuring received levels at larger distances and back-propagating the levels to a reference distance of 1 m. For example, because ships radiate sound from their hull and propeller, their source levels must be measured at a distance such that the TL from the different points on the ship emitting sound is roughly the same. Source levels are calculated by re-arranging Equation 7 to the following:

$$SL = RL + TL \tag{8}$$

1.3.3. One-third-octave-band Analysis

Sounds that are composed of single frequencies are called “tones”; however, most sounds are generally composed of a broad range of frequencies (“broadband” sound) rather than pure tones. The distribution of sound power over frequency is described by the spectrum (or power spectral density, *S(f)*). The spectrum describes the fine scale features of the frequency distribution of a sound source. A coarser representation of the sound power distribution is often better suited to quantitative analysis. Frequency-band analysis divides the power spectrum into discrete passbands. The most common frequency band analysis scheme used in underwater acoustics is 1/3-octave-band analysis, which divides the power spectrum into adjacent passbands one-third of an octave wide (where an octave corresponds to a doubling of frequency). The advantage of modelling using 1/3-octave-bands is that it can resolve the frequency dependent propagation characteristics of a particular environment and efficiently compute the broadband sound pressure level.

The band pressure levels in the i[th] 1/3-octave-band ($L_b^{(i)}$) is computed from the power spectrum:

$$
\begin{aligned}
L_b^{(i)} &= 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \\
f_{hi} &= 10^{1/20} f_c(i) \\
f_{lo} &= 10^{-1/20} f_c(i) \\
f_c(i) &= 10^i/10
\end{aligned}
\tag{9}
$$

where f is the frequency, and $f_c(i)$ is the center frequency of the i[th] band. The sum of all band pressure levels is equal to the levels of the broadband signal:

$$
L_p = 10\log_{10}\sum_n 10^{L_b^{(i)}/10} \tag{10}
$$

where n is the number of bands. Figure 1 shows an example of a noise power spectrum and the corresponding 1/3-octave-band levels.

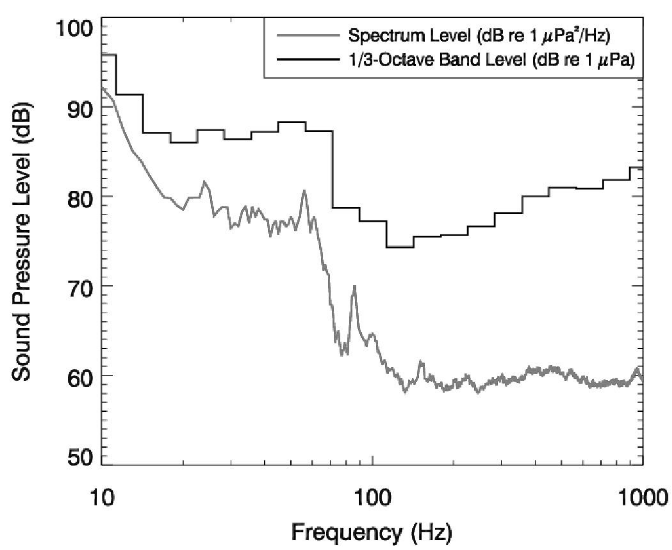


Figure 1. Ambient noise power spectrum (grey line) and the corresponding 1/3-octave-band levels (black line), plotted on a logarithmic frequency scale.

1.4. Frequency Weighting

The potential for anthropogenic noise to affect marine animals depends on how well the animal can hear the noise. Noises are less likely to disturb or injure animals if they are at frequencies that the animal cannot hear well except when the sound pressure is so high that it can cause physical injury. For sound levels that are too low to cause physical injury, frequency weighting based on audiograms may be applied to weight the importance of sound levels at particular frequencies in a manner reflective of an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

1.4.1. Type I (M-weighting) Marine Mammal Frequency Weighting

Based on a literature review of marine mammal hearing and on physiological and behavioural responses to anthropogenic sound, Southall et al. (2007) proposed standard frequency weighting functions—referred to as M-weighting functions—for five functional hearing groups of marine mammals:

- Low-frequency cetaceans (LFCs)—mysticetes (baleen whales)
- Mid-frequency cetaceans (MFCs)—some odontocetes (toothed whales)
- High-frequency cetaceans (HFCs)—odontocetes specialized for using high-frequencies
- Pinnipeds in water—seals, sea lions and walrus
- Pinnipeds in air (not addressed here)

The discount applied by the M-weighting functions for less-audible frequencies is less than that indicated by the corresponding audiograms (where available) for member species of these hearing groups. The rationale for applying a smaller discount than suggested by audiograms is due in part to an observed characteristic of mammalian hearing that perceived equal loudness curves increasingly have less rapid roll-off outside the most sensitive hearing frequency range as sound levels increase. This is why, for example, C-weighting curves for humans, used for assessing loud sounds such as blasts, are flatter than A-weighting curves, used for quiet to mid-level sounds. Additionally, out-of-band frequencies, though less audible, can still cause physical injury if pressure levels are sufficiently high. The M-weighting functions therefore are primarily intended to be applied at high sound levels where effects such as temporary or permanent hearing threshold shifts may occur. The use of M-weighting is considered precautionary (in the sense of overestimating the potential for exposure) when applied to lesser effects such as onset of behavioural response. Figure 2 shows the decibel frequency weighting of the four underwater M-weighting functions.

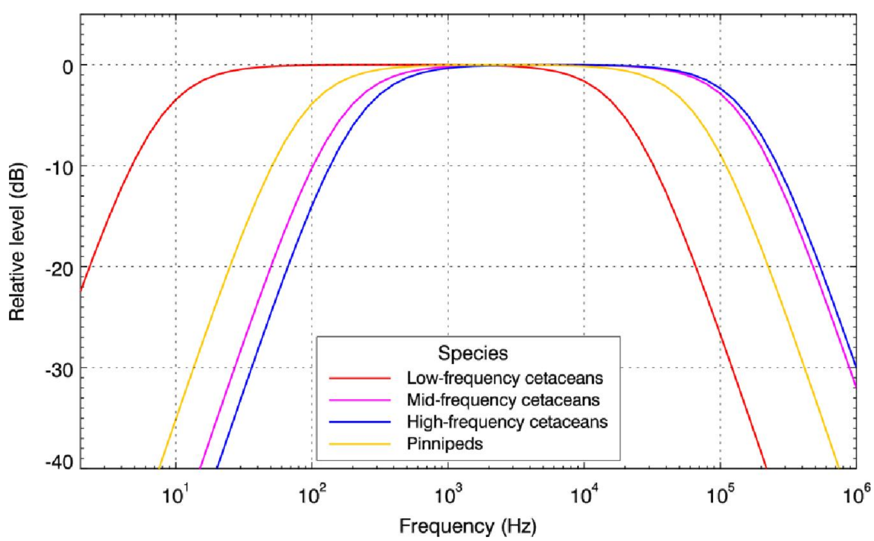


Figure 2. The standard M-weighting functions for the four underwater functional marine mammal hearing groups (Southall et al. 2007).

The M-weighting functions have unity gain (0 dB) through the passband and their high and low frequency roll-offs are approximately –12 dB per octave. The amplitude response in the frequency domain of the M-weighting functions is defined by:

$$G(f) = -20\log_{10}\left[\left(1+\frac{f_{\mathrm{lo}}^2}{f^2}\right)\left(1+\frac{f^2}{f_{\mathrm{hi}}^2}\right)\right] \tag{11}$$

The roll-off and passband of these functions are controlled by the parameters f_{lo} and f_{hi}, the estimated lower and upper hearing limits specific to each functional hearing group (Table 1).

Table 1. The low (f_{lo}) and high (f_{hi}) frequency cut-off parameters of the standard M-weighting functions for the four underwater functional marine mammal hearing groups (Southall et al. 2007).

Functional hearing group	f_{lo} (Hz)	f_{hi} (Hz)
Low-frequency cetaceans (LFC)	7	22 000
Mid-frequency cetaceans (MFC)	150	160 000
High-frequency cetaceans (HFC)	200	180 000
Pinnipeds in water (Pw)	75	75 000

1.4.2. Type II Marine Mammal Frequency Weighting

Subjective loudness measurements have recently been obtained for a bottlenose dolphin, which has allowed for the development of equal-loudness contours for this animal (Finneran and Schlundt 2011). Equal loudness contours (also called Fletcher-Munson curves) are the sound levels over the frequency spectrum for which a listener perceives constant loudness. These curves are the basis of the Occupational Safety and Health Administration (OSHA) noise regulation 1910.95. The equal-loudness contours determined by Finneran and Schlundt (2011) better match the frequency dependence of TTS onset data (Schlundt et al. 2000) than audiograms or the M-weighting curves. For this reason, and as an analogous use of equal-loudness contours in humans, the dolphin equal-loudness contours were used to develop marine mammal frequency weighting functions for the U.S. Navy (Finneran and Jenkins 2012). The (inverse) equal-loudness contours were fit with equations of the same form as the M-weighting function (Equation 11).

To distinguish the new weighting functions from the ones described above, they are called *Type II*, and the standard weight functions of the previous section, *Type I*. The Type II fits suggest steeper roll-off at lower frequencies than the mid-frequency M-weighting curve. Because data for the equal-loudness contours did not cover the entire spectral range of the Type I M-weighting functions, the Type II M-weighting curves were modified rather than simply replaced. The lowest frequency for which subjective loudness data were obtained was 3 kHz, therefore Finneran and Jenkins (2012) took a conservative approach and set the mid-frequency M-weighting curve and the inverted equal loudness contour equal at 3 kHz. The result is that below 3 kHz the overall function is identical to the Type I M-weighting curves and above 3 kHz the overall function is equal to the fitted (inverse) equal-loudness contour. For LF and HF animals a similar procedure was used but the fitting parameters for the inverted equal-loudness contours were adjusted appropriately for LF and MF species, respectively. Because the subjective loudness data was from a cetacean those data were not extended to develop new frequency weighting functions for pinniped species.

Type II frequency weighting functions for cetaceans are calculated as:

$$G_1(f) = K_1 - 20\log_{10}\left[\left(1+\frac{f_{low1}^2}{f^2}\right)\left(1+\frac{f^2}{f_{hi1}^2}\right)\right] \quad (12)$$

$$G_2(f) = K_2 - 20\log_{10}\left[\left(1+\frac{f_{low2}^2}{f^2}\right)\left(1+\frac{f^2}{f_{hi2}^2}\right)\right] \quad (13)$$

where f_{low1} and f_{hi1} are the same parameter values for Type I M-weighting, and f_{low2} and f_{hi2} are the fitted parameters for the inverted equal-loudness contour adjusted for hearing group. K_2 is used to normalize the G_2 equation to zero at 10 kHz (the reference frequency for the subjective loudness studies) and K_1 is used to set the G_1 equation equal to the G_2 equation at 3 kHz for mid-frequency and high-frequency species. For low-frequency species, K_1 was adjusted so that the flat portion of the G_2 was 16.5 dB below the peak level of G_2 (as it was for the mid-frequency cetaceans). G_1 and G_2 are equal at 267 Hz for low-frequency species. Parameters for each of the cetacean groups are shown in Table 2 and the resulting Type II frequency weight curves are shown in Figure 3.

Table 2. Type II frequency weighting parameters for the cetacean functional hearing groups. Modified from Finneran and Jenkins (2012).

Cetacean functional hearing group	K_1 (dB)	f_{low1} (Hz)	f_{hi1} (Hz)	K_2 (dB)	f_{low2} (Hz)	f_{hi2} (Hz)	Inflection point (Hz)
Low-frequency	−16.5	7	22,000	0.9	674	12,130	267
Mid-frequency	−16.5	150	160,000	1.4	7,829	95 520	3 000
High-frequency	−19.4	200	180,000	1.4	9,480	108 820	3,000

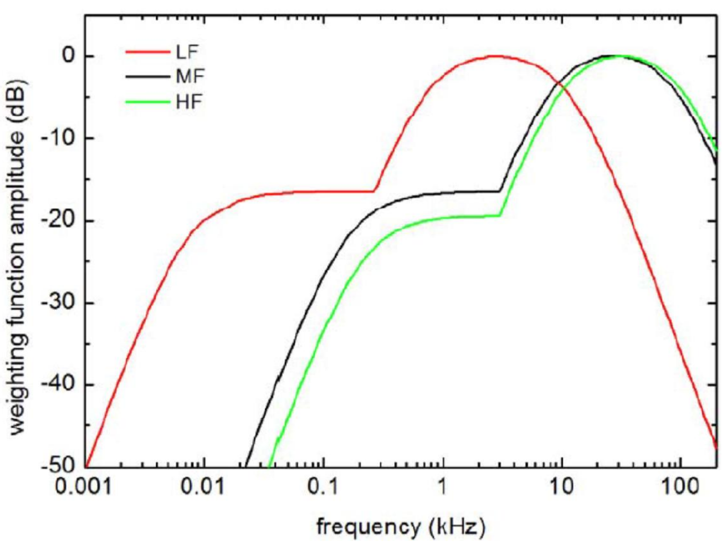


Figure 3. Type II frequency weighting functions for the cetacean functional hearing groups, low-frequency (LF), mid-frequency (MF), and high-frequency (HF). Modified from Finneran and Jenkins (2012).

1.4.3. Audiogram Weighting

Audiograms represent the hearing threshold for pure tones as a function of frequency. These species-specific sensitivity curves are generally U-shaped, with higher hearing thresholds at opposite ends of the audible frequency range.

Noise levels above hearing threshold are calculated by subtracting species-specific audiograms from the received 1/3-octave-band sound levels. The audiogram-weighted 1/3-octave-band levels are summed to yield broadband sound levels relative to each species' hearing threshold. Audiogram-weighted levels are expressed in units of dB above hearing threshold (dB re HT). Sound levels less than 0 dB re HT are below the typical hearing threshold for a species and therefore it is likely the animal does not hear them.

Table 3 provides the marine mammal and fish species that may be found in the vicinity of the pipeline route, along with the species-specific audiograms that were used to represent the hearing thresholds of each.

Table 3. List of species and their representative audiograms.

Species	Representative audiogram
Marine mammals	
Bottlenose dolphin (*Tursiops truncatus ponticus*)	Bottlenose dolphin (*Tursiops truncatus ponticus*)
Harbor porpoise (*Phocoena phocoena relicta*)	Harbor porpoise (*Phocoena phocoena relicta*)
Short beaked common dolphin (*Delphinus delphis ponticus*)	Bottlenose dolphin (*Tursiops truncatus ponticus*)
Fish	
Sprat (*Sprattus sprats)*	Atlantic herring (*Clupea harengus)*
Anchovy (*Engraulis enchrasicolus*)	Anchovy *(Anchoa mitchili*)
Kilka (*Cluponella cultriventris*)	Atlantic herring (*Clupea harengus)*
Shad (*Alosa maeotica* and *A.caspia*)	American shad (*Alosa sapidissima*)
Sturgeon (*Huso huso* and *Acipenser gueldenstaedtii*)	Lake sturgeon *(Acipenser fluvescens)*

Six audiograms were used to represent the above species (Figure 4), with some substitutions being made based on availability of audiograms and similarity within groups of species. The bottlenose dolphin (*Tursiops truncatus ponticus*) audiogram (Johnson, 1967) was used for both species of dolphin. Harbor seal audiogram data were based on Kastelein et al. (2002).

Four fish audiograms were used. The herring audiogram data (Enger, 1967) were used to represent species of sprat and kilka. Audiogram data for anchovy, shad, and sturgeon were provided by Ladich and Fay (2013).

To fit the modelled range of frequencies, audiograms were extended from the lowest measured frequency down to 10 Hz and from the highest measured frequency to 20 kHz. Although the extended portion of the audiogram data is not physiologically accurate, these animals likely have a higher hearing threshold at frequencies outside their hearing range, making the extensions a conservative approximation of hearing thresholds.

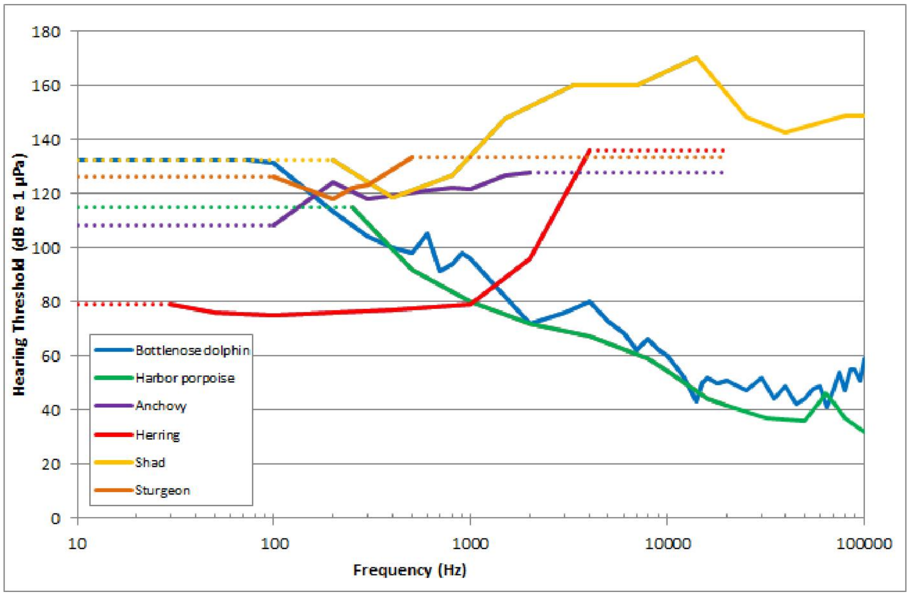


Figure 4. One-third-octave-band audiograms for bottlenose dolphin, harbor porpoise, anchovy, herring, shad, and sturgeon . Dotted lines represent extended hearing thresholds for modelling purposes.

1.5. Sound Level Thresholds Criteria

1.5.1. Injury Assessment

In keeping with the latest scientific approaches, injury effects assessment has been based on the cumulative sound exposure level (SEL) over a period of 24 hours. The pipe-laying operation (loudest among any possible activities at the three representative sites) has been modelled including realistic motion of pipe-lay vessel and support vessels such as pipe carrier ships shuttling to resupply (see sample maps listed in spreadsheet).

Two sets of criteria are available and currently considered valid for the assessment of ranges to injury (onset of PTS) from continuous noise: the Southall et al. (2007) criteria and the Finneran and Jenkins (2012) criteria also referenced as the US Navy criteria. The former uses a single threshold of 215 dB re µPa2-s SEL weighted according to the hearing class of the subjects using Type I weighting curves (M-weighting). The latter uses variable thresholds and newer Type II weighting functions that take into account subjective loudness and some additional data collected since the Southall et al. study. For Mid Frequency cetaceans (MFC; in the project area, primarily dolphins) the threshold is 198 dB re µPa2-s SEL with Type 2 MFC weighting. For High Frequency cetaceans (HFC; in the project area, primarily harbour porpoises) the threshold is 187 dB re µPa2-s SEL with Type 2 HFC weighting.

The results of the SEL based assessment can be presented in terms of the modelled area exposed to cumulative levels above the threshold over a 24 hour period (area of effect), as well as a range of effect that provides a linear "width" of the footprint relative to the main pipe-lay vessel. Because of the irregular and elongated shape of the cumulative footprint along the pipe-lay route, the effect range cannot be computed as a radius for equivalent area and is instead measured from the swath width of the footprint with suitable consideration of its shape.

The assessment of fish injury range is by far the most uncertain scientifically. The approach used in this study is derived from the work of Stadler and Woodbury (2009) whose criteria are based on hearing studies of fish exposed to airgun sounds. The Stadler and Woodbury criteria are commonly used for pile driving injury range estimation but can be reasonably applied to continuous sound, with some important considerations:

- In terms of the SEL metric, exposure to a few loud sounds is more damaging to fish than exposure to a larger number or longer duration of quieter sounds (Halvorsen et al. 2012). Therefore, use of Stadler and Woodbury (2009) criteria are precautionary when applied to exposure to continuous sound – and may possibly yield very conservative estimates of effect range and area.
- There are no data to indicate that shipping and shipping-like sounds can damage the hearing of fish with swim bladders but lacking specializations for enhanced acoustic pressure reception.
- Fish are typically sensitive only to low frequency sounds, with the best hearing range of most fish from about 100 Hz to 400 Hz. A low-pass filter with a corner frequency of 2 kHz is a conservative weighting function that rejects sounds at frequencies that fish do not hear, and is used in this study.

1.5.2. Behavioural Assessment

The “traditional” unweighted rms SPL criterion for behavioural effects onset at 120 dB re µPa cannot be outright dismissed despite its inability to account for species specific hearing differences, and it is included in this study at least for completeness and reference to common practice. It is also a criterion still invoked as the only acceptable approach for the harbour porpoise by studies as recent as Finneran and Jenkins (2012), who explicitly exclude that species from weighted metrics criteria because of its unique susceptibility and reaction to sound stimuli.

Behavioural criteria based on weighted metrics, such as those proposed by Finneran and Jenkins (2012) for marine mammal species other than harbour porpoises, are questionable in the case of continuous sounds such as those from vessels. The relatively high reaction thresholds that arise from their use would be difficult to defend by comparison with empirical evidence.

We consider audiogram based behavioural effect criteria to be the most justified for this assessment, given the well-defined identity of the relevant species in the region and the availability of reliable audiograms for those very species or reasonable surrogates. The most uncertain element in the use of audiogram-referenced levels (dB relative to hearing threshold or dBht) is the threshold to adopt for onset of behavioural disturbance. Nedwell et al (2005) proposed fixed thresholds of 75 and 90 dBht for all species as onset of mild and pronounced behavioural reactions respectively. The precautionary validity especially of the higher threshold has been called into question, and evidence can be found for reaction at significantly lower levels above hearing threshold: analysis based on measurements by Williams et al (2002) suggests that behavioural effects in resident killer whales may arise at levels of 65 dBht. Taking all factors into account we consider the 75 dBht threshold to be a reasonably conservative estimator of behavioural onset, and we have used it in the audiogram based assessment for this work.

2. Methods

2.1. Source Levels

2.1.1. Vessel Source Levels

There were no available measurement data for any of the vessels that were proposed for the pipe-laying operations for the South Stream project; JASCO, however, has an extensive collection of vessel source levels obtained either from field measurements performed by the company or from third party reports. This collection allows us to estimate the source levels of the vessels of interest by substituting for them the source level from a proxy vessel with similar specifications, for which measurements are available. When a proxy vessel is used, its specifications—type of vessel, propulsion power, deadweight, and length—are considered. In case the proxy vessel had different propulsion power specifications, the broadband source level was adjusted using simple formula

$$\mathrm{SL} = \mathrm{SL}_{ref} + 10\log\left(\frac{P}{P_{ref}}\right). \quad (14)$$

Here, the broadband source level (SL) of the vessel of interest operating at a given propulsion power (P) is estimated from the source level of a similar reference vessel (SL_{ref}) with a different propulsion power installed (P_{ref}). The same equation was used to scale down the broadband source level for the same vessel operating at reduced propulsion power.

The list of the vessels proposed for the South Stream pipeline construction project, which were considered in this study, is provided in Table 4. Figure 5 provides the source level spectrums in 1/3-octave bands that were used to estimate the impact of the specific vessels.

Table 4. List of the vessels to be engaged in the construction activities of the nearshore and offshore sections of the South Stream pipeline project. The proxy vessel that was used to establish the broadband source level (indicated) is also provided for each proposed vessel.

Vessel type	Representative vessel			Proxy vessel	
	Name	Propulsion power (kW)	Broadband SL (dB re 1 µPa at 1 m)	Name	Propulsion power (kW)
Anchor handling tug/support tug	*Normand Neptune*	14,000	189	*Katun*[1]	9,000
Fast supply vessel	*GSP Lyra*	2,520	188	*Rebound*[2]	250
Pipe-laying vessel (deep water, DP)	*Castorone*	67,000	192	*Solitaire*[3]	48,000

[1]Hannay et al. (2004)
[2]Kipple and Gabriele (2003)
[3]Nedwell and Edwards (2004)

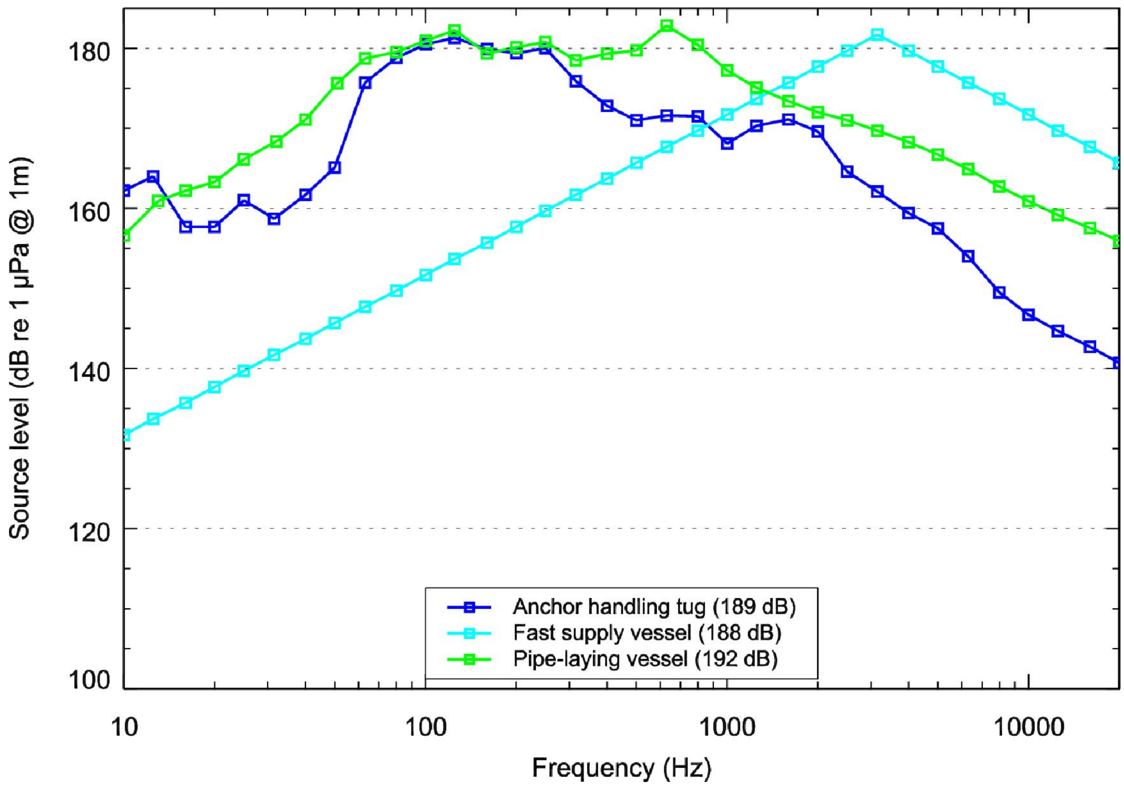


Figure 5. Source levels for the modelled vessels in 1/3-octave-bands. The numbers in the brackets indicate the broadband level in dB re 1 µPa at 1 m (rms SPL).

2.1.2. Side-scan Sonar

According to the project description documents, GSP Prince is the best vessel to provide survey support before, during, and after the pipe-laying operation. The survey equipment will be installed on a Remote Operated Vehicle (ROV) and will likely consist of side-scan sonar and/or multibeam echosounder. Both sonars emit high frequency acoustic energy (> 50 kHz) from two or more rectangular transducers.

2.1.2.1. Transducer Beam Theory

Mid- and high-frequency underwater acoustic sources for geophysical measurements create an oscillatory overpressure through rapid vibration of a surface, using either electromagnetic forces or the piezoelectric effect of materials. A vibratory source based on the piezoelectric effect is commonly referred to as a transducer, and may be capable of receiving, as well as emitting, signals. Transducers are usually designed to produce an acoustic wave of a specific frequency, often in a highly directive beam. The directional capability increases with increasing operating frequency. The main parameter characterizing directivity is the beamwidth, defined as the angle subtended by diametrically opposite “half power” (-3 dB) points of the main lobe (Massa 2003). For different transducers, the beamwidth varies from 180° (almost omnidirectional) to a few degrees.

Transducers are usually built with either circular or rectangular active surfaces. For circular transducers, the beam pattern in the horizontal plane (assuming a downward pointing main beam) is equal in all directions. The beam pattern of a rectangular transducer is variable with the azimuth in the horizontal plane.

The acoustic radiation pattern, or beam pattern, of a transducer is the relative measure of acoustic transmitting or receiving power as a function of spatial angle. Directionality is generally measured in decibels relative to the maximum radiation level along the central axis perpendicular to the transducer surface. The pattern is defined largely by the operating frequency of the device and the size and shape of the transducer. Beam patterns generally consist of a main lobe, extending along the central axis of the transducer, and multiple secondary lobes separated by nulls. The width of the main lobe depends on the size of the active surface relative to the sound wavelength in the medium. Larger transducers produce narrower beams. Figure 6 shows a 3-dimensional (3-D) visualization of a typical beam pattern for a circular transducer.

The true beam pattern of a transducer can be obtained only by in situ measurement of the emitted energy around the device. Such data, however, are not always available, and for propagation modelling it is often sufficient to estimate the beam pattern of the source based on transducer beam theory. An example of a measured beam pattern is shown in Figure 7.

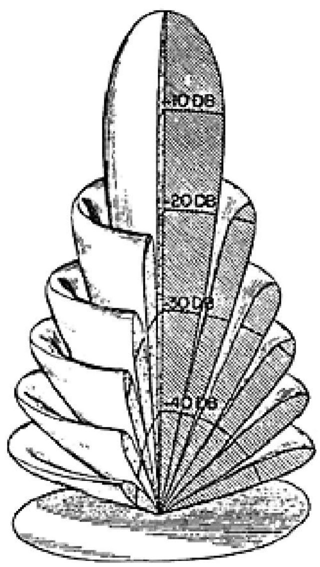


Figure 6. Typical 3-D beam pattern for a circular transducer (Massa 2003).

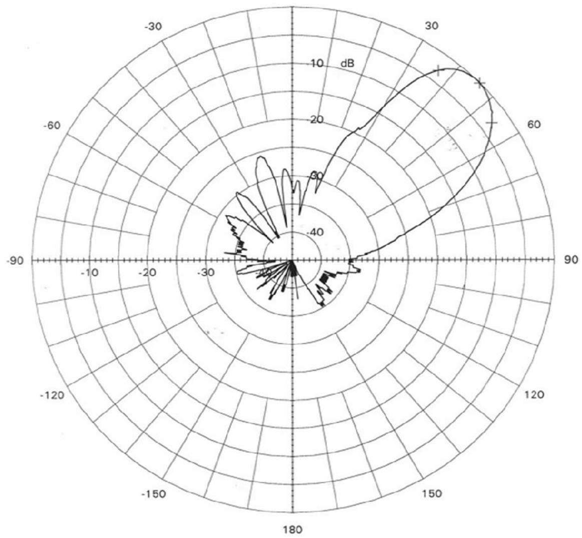


Figure 7. Vertical cross section of a beam pattern measured in situ from a transducer used by Kongsberg (source: pers. comm. with the manufacturer).

2.1.2.2. Rectangular Transducers

Rectangular transducer beam directivities were calculated from the standard formula for the beam pattern of a rectangular acoustic array (Kinsler et al. 1950; ITC 1993). This expression is the product of the toroidal beam patterns of two line arrays, where the directional characteristics in the along- and across-track directions are computed from the respective beamwidths. The directivity function of a toroidal beam relative to the on-axis pressure amplitude is:

$$R(\phi) = \frac{\sin\left(\pi L_{\lambda} \sin(\phi)\right)}{\pi L_{\lambda} \sin(\phi)} \quad \text{and} \quad L_{\lambda} = \frac{50}{\theta_{bw}}, \qquad (15)$$

where L_{λ} is the transducer dimension in wavelengths, θ_{bw} is the beamwidth in degrees, and ϕ is the angle from the transducer axis. Here again, the beam pattern of a transducer can be calculated using either the specified beamwidth in each plane or the dimensions of the active surface and the operating frequency of the transducer. The calculated beam pattern for a rectangular transducer with along- and across-track beamwidths of 4° and 10°, respectively, is shown in Figure 8.

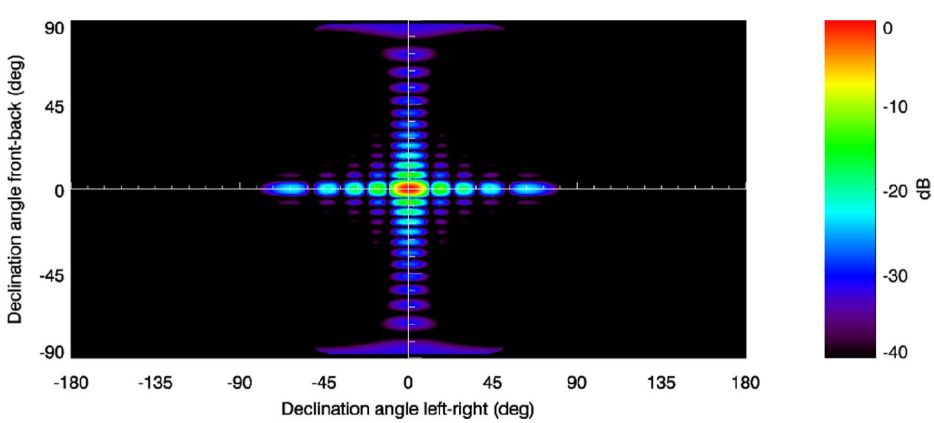


Figure 8. Calculated beam pattern for a rectangular transducer with a 4° × 10° beamwidth. The beam power function is shown relative to the on-axis level using the Robinson projection.

2.1.2.3. Multibeam Systems

High-frequency systems often have two or more transducers, e.g., side-scan and multibeam sonar. Typical side-scan sonar use two transducers, with the central axes directed perpendicular to the survey track and at some depression angle below the horizontal. In contrast, multibeam bathymetry systems can have upward of 100 transducers. Such systems generally consist of rectangular transducers and have a narrow beamwidth in the horizontal (along-track) plane (0.2°–3°) and a wide beamwidth in the vertical (across-track) plane.

For multibeam systems, the beam patterns of individual transducers are calculated separately and then combined into the overall pattern of the system based on the engagement type of the beams, which can be simultaneous or successive. If the beams are engaged successively, the source level of the system in a given direction is assumed to be the maximum source level realized from the individual transducers; if the beams are engaged simultaneously, the beam pattern of the system is simply the sum of all beam patterns. Figure 9 shows the predicted beam pattern for two rectangular transducers engaged simultaneously. These transducers have along- and across-track beamwidths of 1.5° and 50°, respectively.

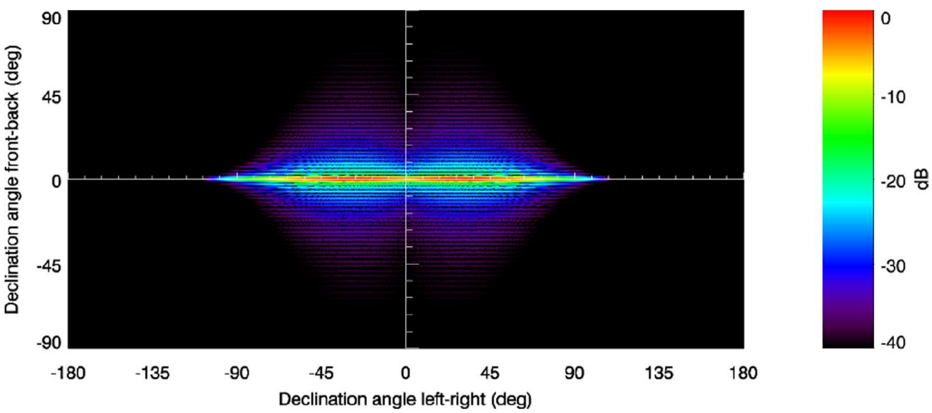


Figure 9. Calculated beam pattern for two rectangular transducers engaged simultaneously, with individual beamwidths of 1.5° × 50°, and a declination angle of 25°. The beam power function is shown relative to the on-axis level using the Robinson projection.

2.1.2.4. Side-scan Sonar

The exact model of the side-scan sonar to be used during survey for the South Stream pipe installation project is not known. Out of wide variety of side-scan sonars on the market, Edgetech Full Spectrum Chrip Side-scan Sonar was selected for modelling as this model specifically designed for installation on the ROVs.

Edgetech sonar consists of two transducers that feature 70°×0.8° beams directed at 10–20° angle below the horizontal plain (Figure 10). The peak level is estimated at 210 dB re 1 µPa at 1 m (Edgetech 2000), conversely, 207 dB re 1 µPa at 1 m rms SPL. The operational frequency is 75 kHz and the pulse length is 13 ms. The per-pulse SEL can be derived from the rms SPL and the pulse length using Equation 5. The per-pulse SEL is estimated at 188.1 dB re 1 µPa²·s.

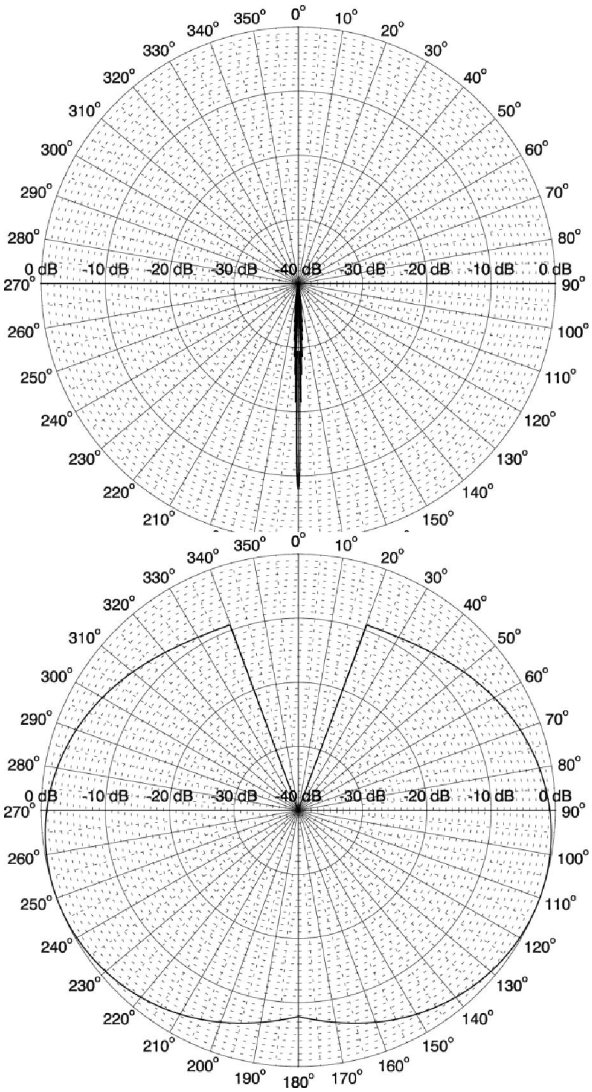


Figure 10. Vertical beam pattern calculated for the Edgetech Full Chirp Side-scan Sonar with two beams 70° × 0.8° width in the (left) along- and (right) across-track directions.

2.2. Sound Propagation Model

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 20 kHz was predicted with JASCO's Marine Operations Noise Model (MONM).

2.2.1. Two Frequency Regimes: *RAM* vs. *BELLHOP*

At frequencies ≤2 kHz and for omnidirectional sources, MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed. The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM-RAM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM-RAM's predictions have been validated against experimental data in several underwater acoustic measurement programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010). MONM-RAM incorporates the following site-specific environmental properties: a modelled area bathymetric grid, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

At frequencies >2 kHz, MONM employs the widely-used BELLHOP Gaussian beam ray-trace propagation model (Porter and Liu 1994) and accounts for increased sound attenuation due to volume absorption at these higher frequencies following Fisher and Simmons (1977). This type of attenuation is significant for frequencies higher than 5 kHz and cannot be neglected without noticeable effect on model results at long ranges from the source. MONM-BELLHOP accounts for the source directivity, specified as a function of both azimuthal angle and depression angle. MONM-BELLHOP incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area and underwater sound speed as a function of depth. In contrast to MONM-RAM, the geoacoustic input for MONM-BELLHOP consists of only one interface, namely the sea bottom. This is an acceptable limitation because the influence of the sub-bottom layers on the propagation of acoustic waves with frequencies above 1 kHz is negligible.

Both propagation models account for full exposure from a direct acoustic wave, as well as exposure from acoustic wave reflections.

2.2.2. N×2-D Volume Approximation

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (Figure 11).

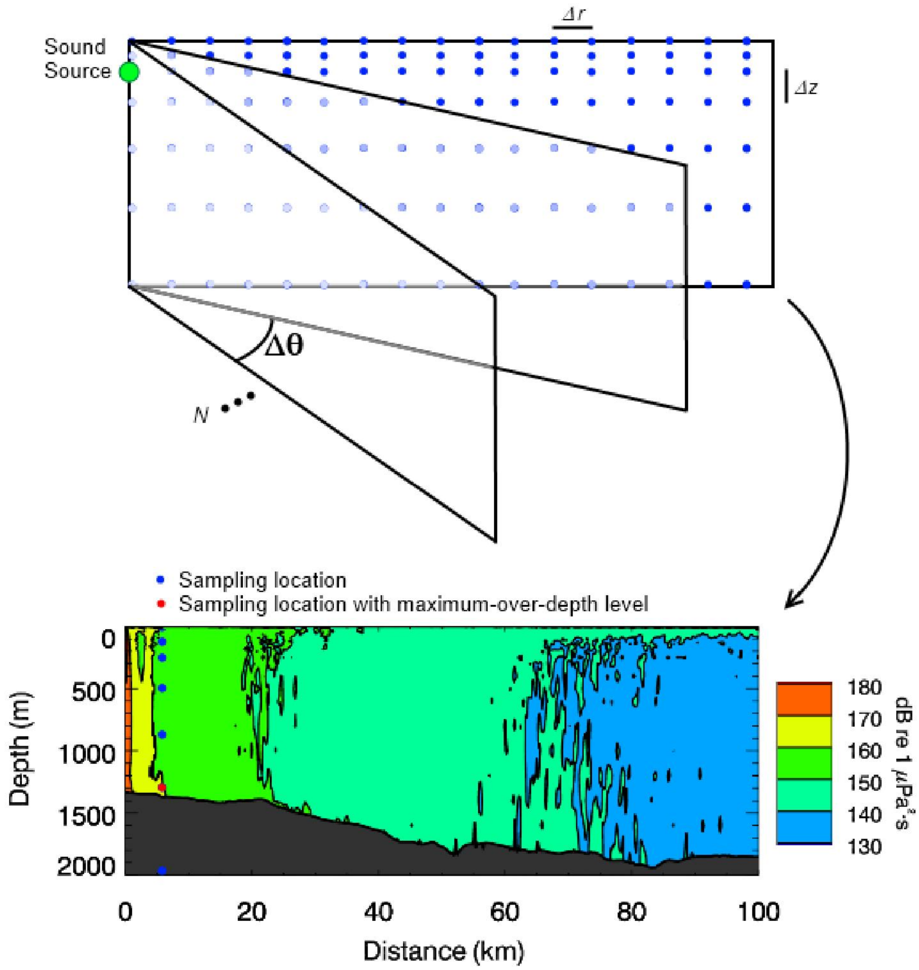


Figure 11. The *N*×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the center frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modelled to include the majority of acoustic energy emitted by the source. At each center frequency, the transmission loss is modelled within each of the *N* vertical planes as a function of depth and range from the source. The 1/3-octave-band received per-pulse SELs are computed by subtracting the band transmission loss values from the directional SL in that frequency band. Composite broadband received SELs are then computed by summing the received 1/3-octave-band levels.

The received per-pulse SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals in the area of interest. The received per-pulse SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column below, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per-pulse SELs are presented as colour contours around the source (e.g., Figure 12).

MONM's predictions have been validated against experimental data from several underwater acoustic measurement programs conducted by JASCO (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010).

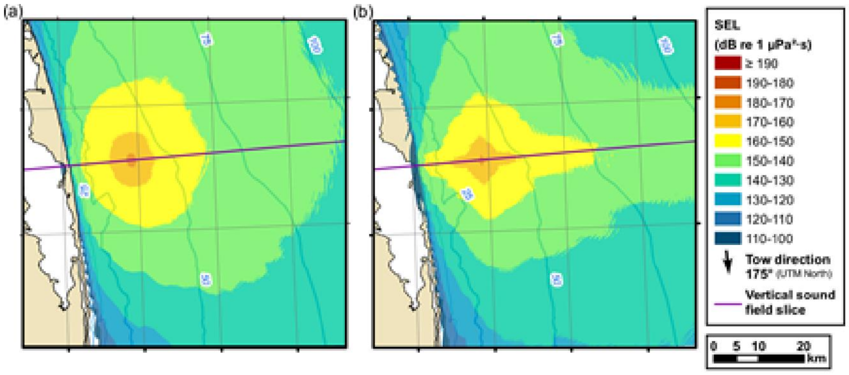


Figure 12. Maximum-over-depth sound exposure level (SEL) colour contour maps for two arbitrary sources.

2.2.3. Sampling of Model Results: Maximum-over-depth Rule

The received SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The received SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column below, i.e., the maximum-over-depth received SEL. This provides a conservative prediction of the received sound level around the source, independent of depth. These maximum-over-depth SELs are presented as colour contours around the source.

In principle, the sound field can be sampled at a vertical step size as fine as the acoustic field modelling grid, which varies from 2 m for low frequencies to 6 cm for high frequencies. Such a fine grid of samples, however, would be inefficient and provide a needlessly large quantity of data. The depth spacing between samples is therefore chosen based on the vertical variability of the acoustic field. Vertical variability depends on the variability of the sound speed profile, which is higher at the top of the water column and lower at greater depths. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals in the area of interest.

At each surface sampling location, the sound field was sampled at the following depths:

- 2 m
- every 5 m from 5 to 25 m
- every 25 m from 50 to 100 m
- every 50 m from 150 to 500 m
- every 100 m from 600 to 2200 m

2.3. Acoustic Impact Estimations

The acoustic impact estimations were performed in three ways:

- Instantaneous impact from single vessel
- Instantaneous impact from a group of vessels
- Cumulative impact over 24 hours of typical operations

2.3.1. Instantaneous Impact, Single Vessel

To calculate distances to specified sound level thresholds, the maximum level over all sampled depths was calculated at each horizontal sampling point within the modelled region. The radial grid of maximum-over-depth sound levels was then resampled (by linear triangulation) to produce a regular Cartesian grid (50 m cell size). The contours and threshold ranges were calculated from these flat Cartesian projections of the modelled acoustic fields of each vessel separately. To obtain the distances to the specified M-weighted sound level thresholds, the relative level value was applied to the acoustic field modelling frequency (Equations 11–13).

2.3.2. Instantaneous Impact, Vessel Group

The aggregate field for a group of vessels was calculated by summing up the acoustic fields of each individual vessel in the group using Equation 4. Prior to summation, the acoustic field representing the acoustic footprint of each vessel was shifted according to the position of that specific vessel in the group. The contours and threshold ranges for the aggregate field were calculated in the same manner as for the single vessel impact estimation (Section 2.3.1). The threshold affected areas were also calculated from the gridded field by multiplying the grid cell area by the number of grid cells that have the value above the threshold.

2.3.3. Cumulative Acoustic Impact, 24 Hour Operations

For 24 hour impact assessment separate track for each vessel was identified. First, the cumulative field for each individual vessel in the scenario was estimated. For that, multiple copies of the 1 second SEL field were created with 50 m shift along the track. All those fields were summed up and a correction factor to account for the vessel speed along the track was applied. Second, the cumulative fields for each vessel were summed up yielding the total cumulative field for 24 hour operation.

The contours and threshold ranges for the cumulative field were calculated in the same manner as for the single vessel impact estimation (Section 2.3.1). The threshold affected areas were also calculated from the gridded field by multiplying the grid cell area by the number of grid cells that have the value above the threshold.

2.4. Model Parameters

2.4.1. Bathymetry

The bathymetry is reproduced from the GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of the IOC and IHO, 2008. The Digital Atlas provides the gridded elevation coverage for the Earth with 30 arc minute resolution (~900 × 900 m for the studied region). The bathymetry data were re-gridded to cover a 400 × 400 km region, with a horizontal resolution of 500 × 500 m. The grid was created in the projected coordinates of the Universal Transverse Mercator (UTM) Zone 37.

2.4.2. Geoacoustic Properties

MONM requires specific values that describe the acoustic properties of the sediment in the propagation area:

- Sediment layer thickness
- Density
- Compressional sound speed
- Compressional attenuation
- Shear sound speed
- Shear attenuation

The geoacoustic profile for the deep part of the Black Sea was constructed based on the well log from Deep Sea Drilling Program (DSDP) Leg 42 Site 379 located approximately 220 km to the east from the chosen modelling location (The Shipboard Scientific Party 1978) and in a similar abyssal part of the Black Sea. The referenced report provides information on the compressional sound speed and density profile down to 670 m below the sea floor and indicates the estimated depth of the acoustic basement. The assumed geoacoustic profile for the modelled site is presented in Table 5.

Table 5. Estimated geoacoustic profile for the Black Sea Abyssal. Within each depth range, each parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm^3)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–10	Terrigenous mud	1.4–1.5	1500–1600	0.17–0.36	100	0.03
10–85		1.5–1.7	1600–1700	0.36–0.7		
85–150		1.7–1.8	1700–1800	0.7–0.8		
150–370		1.8–1.9	1800–1850	0.8–1.0		
370–1000		1.9	1850–2000	1.0–1.3		
1000–2000	Acoustic basement	2.5–2.6	3000–4000	0.4		
> 2000		2.6	4000	0.4		

2.4.3. Sound Speed Profiles

The sound speed profiles for the modelled sites were derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep), including 55 standard depths between 0 and 2000 m. The GDEM temperature-salinity profiles were converted to sound speed profiles according to the equations of Coppens (1981):

$$
\begin{aligned}
c(z,T,S,\phi) &= 1449.05 + 45.7t - 5.21t^2 - 0.23t^3 \\
&\quad + \left(1.333 - 0.126t + 0.009t^2\right)(S - 35) + \Delta \\
\Delta &= 16.3Z + 0.18Z^2 \\
Z &= \frac{z}{1000}\left[1 - 0.0026\cos(2\phi)\right] \\
t &= \frac{T}{10}
\end{aligned}
\qquad (16)
$$

where z is water depth (m), T is temperature (°C), S is salinity (psu), and ϕ is latitude (radians).

Mean monthly sound speed profiles were derived from the GDEM dataset at the modelled site for each of the twelve months of the year. Since the operational period was not finalized at the time the modelling was conducted , the months of February and August were selected as they provide the most and least favorable conditions for sound propagation (Figure 13).

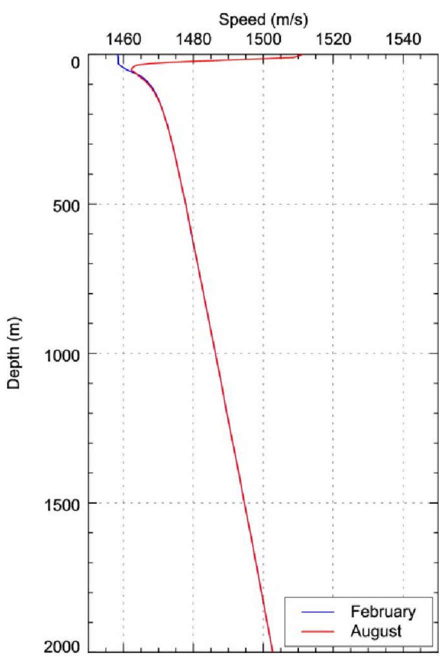


Figure 13. Comparison of sound speed profiles for February and August at the modelled site, derived from data obtained from *GDEM V 3.0* (Teague et al. 1990, Carnes 2009).

2.4.4. Geometry and Modelled Volumes

Sound fields were modelled along a series of radial profiles covering 360° with a horizontal angular resolution of $\Delta\theta = 5°$ for a total of $N = 72$ radial planes. The horizontal step size for virtual receivers along the profiles was 20 m. Each profile extended 100 km from the source or the shoreline, whichever was closer.

The transmission loss modelling results were obtained for at least two different source depths at each (see Table 7 in Section 3.2).

3. Modelled Scenarios

3.1. Modelling Site

The pipeline route proposed by South Stream passes through approximately 470 km of Turkish EEZ waters, to a maximum water depth of approximately 2200 m.

A modelling location was selected as representative of environmental parameters for the region such as bathymetry, geoacoustic properties of the sea bottom, and the prevailing water column sound speed profile. The site is in a deep offshore section where deep-water pipe-laying will take place. Support vessels will be present during operations.

The important attributes of the selected location (coordinates, water depth) are provided in Table 6.

Table 6. Proposed modelling location and its parameters.

Geographic coordinates	UTM coordinates (Zone)	Water depth at the source (m)
43° 03.6' N 33° 14.7' E	4767500 520000 (36)	2190

3.2. Single Vessel Scenarios

Single vessel scenarios were modelled at the target site. Each scenario was modelled in both summer (August) and winter (February) conditions, resulting in 6 single vessel scenarios. The important attributes and modelling parameters of each scenario are outlined in Table 7.

Table 7. Proposed single vessel scenarios and their modelling parameters.

	Vessel	Description	Source depth (m)	Broadband source level (dB)	Frequency range (Hz)
1	*Saipem 7000, Castorone*	Pipe-lay vessel	7	192	10–20000
2	*Normand Neptune*	Anchor handling tug	7	189	10–20000
3	*GSP Lyra*	Support vessel, crew changes	2	188	10–20000

3.3. Vessel Groups

This section discusses the modelled acoustic fields of sound generated during specific operations that require the use of multiple vessels acting in close proximity. Two scenarios were considered, each with the acoustic field modelled in both winter and summer conditions.

For each scenario, only the vessels that make significant contributions to the acoustic field were included in the model. All proposed vessels for each operation have been considered, but those that have source levels too small to impact modelling results, as well as vessels that are not scheduled to be present consistently throughout the extent of the operation, are not included in the modelled acoustic field.

Vessels without known source levels have been modelled using a reference vessel of a similar type, with a correction factor to account for differences in size and power output. Correction factors are also used to account for a vessel operating below 100% load.

3.3.1. Scenario 1: Pipe-laying

Pipe-laying in water depths of 600 m and greater will be completed using the deep-water pipe-lay vessel Saipem 7000 or Castorone, likely utilizing the J-Lay method. The pipe-lay vessel will maneuver using DP thrusters, as anchors are not used in depths greater than 600 m. Other vessels which will be present throughout the operation and will contribute significantly to the acoustic field include a general support tug, at least one pipeline supply vessel, and a survey vessel for pre-lay and post-lay surveying.

Vessels which may be present, but will not contribute significantly to the acoustic field, include a multiservice vessel for ROV support diving and supply, a maintenance vessel for the delivery of spare parts, a collection vessel for fuel and wastewater, and a rescue vessel for emergencies.

A summary of the primary vessels and modelling parameters can be found in Table 8.

Table 8. Vessel spread for pipe-laying.

Vessel	Activity	Load (%)	Reference vessel	Correction factor (dB)	Coordinates	
					X	Y
Saipem 7000, Castorone (70,000 kW)	Pipe-laying	100	Saipem 7000, Castorone (70,000 kW)	0	0	0
Normand Neptune (13,880 kW)	Support, idle	20	Normand Neptune (13,880 kW)	-7	0	-500
Normand Flipper (7,160 kW)	Pipeline supply, transfer	100	Normand Neptune (13,880 kW)	-3	100	-300
GSP Prince (7,604 kW)	Survey, Transit	30	Normand Neptune (13,880 kW)	-8.2	200	-200

3.3.2. Scenario 2: Crew Change (Pipe-laying)

Since the deep-water pipe-lay vessel will maneuver using DP, most support vessels will not be affected by a crew change. It is assumed that the pipe supply vessel is on standby, and for maximum source levels, the crew change vessel is in transit at 100% load approximately 250-300 m from the pipe-lay vessel.

With the presence of the crew change vessel, the survey vessel GSP Prince, although present, is no longer a primary contributor to the acoustic field. Other vessels which may be present, but will not contribute significantly to the acoustic field, include a multiservice vessel for ROV support diving and supply, a maintenance vessel for the delivery of spare parts, a collection vessel for fuel and wastewater, and a rescue vessel for emergencies

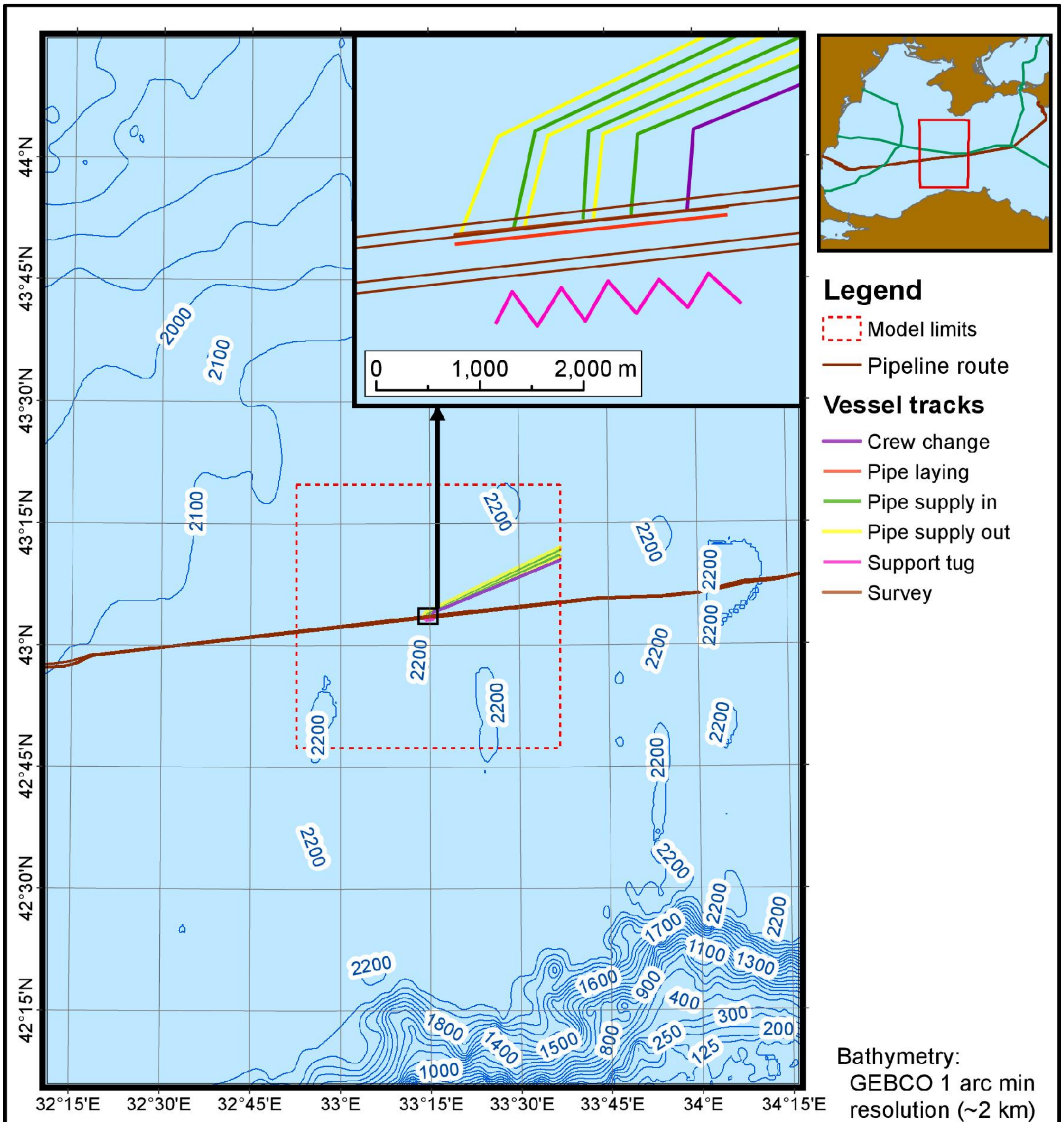
A summary of the primary vessels and modelling parameters can be found in Table 9.

Table 9. Vessel spread for pipe-laying crew change.

Vessel	Activity	Load (%)	Reference vessel	Correction factor (dB)	Coordinates	
					X	Y
Saipem 7000, Castorone (70,000 kW)	Pipe-laying	100	*Saipem 7000*, *Castorone* (70,000 kW)	0	0	0
Normand Neptune (13,880 kW)	Support, idle	20	*Normand Neptune* (13,880 kW)	−7	500	0
Normand Flipper (7,160 kW)	Pipeline supply, idle	20	*Normand Neptune* (13,880 kW)	−3	0	400
GSP Lyra (2,520 kW)	Crew change, transit	100	*GSP Lyra* (2,520 kW)	−8.2	200	200

3.4. Cumulative

One cumulative exposure scenario was modeled at the target site. The cumulative scenario estimates the cumulative acoustic exposure field around the pipe-laying operation over 24 hours. Only activities that happen during a typical day of operations were assessed. Johansson and Andersson (2012) reported vessel tracks in the proximity of the pipe-laying operation during Nord Stream construction project in the Baltic Sea. The pattern of these tracks was taken into account when designing the tracks for the three cumulative scenarios in this study (Figure 14). The supply operations were assumed to occur from a port on the Russian shore of the Black Sea.



Description: Cumulative scenario tracks	0 15 30 60 km
Project: South Stream Offshore Pipeline (Turkey Sector)	JASCO APPLIED SCIENCES
Datum: WGS 1984 — **Projection:** UTM zone 36	
Date: 25 November 2013 — **Created By:** Mikhail M. Zykov	

Figure 14. Tracks geometry for cumulative exposure modelling scenario.

The pipe-laying operation will be performed by large size pipe-laying vessel utilizing dynamic positioning system. The assumed productivity is about 3 km of pipeline per 24 hr period. The length of the pipe-laying vessel track was chosen accordingly (Table 10). The post-laying survey vessel follows parallel track with 50 m offset and 5 knots speed. Support tug is present in the area for the whole period and follows a zigzag track 500–1000 m from the pipe-laying vessel track. The supply tug vessel approaches the pipe-laying vessel three times and crew change occurs once.

Table 10. Generic activities considered for cumulative exposure modeling scenario.

Track #	Activity	Track length (km)	Speed along the track (kn)	Time on the track	Vessel	Duty cycle (%)
1	Pipe-laying	3	0.06	24 hr	*Castoro Sei*	60
2	Supply 1 in	37	10	2 hr	*Normand Flipper*	100
3	Supply 1 out	37	10	2 hr	*Normand Flipper*	100
2	Supply 2 in	37	10	2 hr	*Normand Flipper*	100
3	Supply 2 out	37	10	2 hr	*Normand Flipper*	100
2	Supply 3 in	37	10	2 hr	*Normand Flipper*	100
3	Supply 3 out	37	10	2 hr	*Normand Flipper*	100
4	Crew change	37	30	40 min	*GSP Lyra*	100
5	Survey	3	4	25 min	*GSP Prince*	30
6	Anchor handling	4	0.08	24 hr	*Normand Neptune*	20

4. Results

4.1. Single-Vessel Instantaneous Sound Fields

The summary of behavioural effect ranges and areas according to unweighted and audiogram weighted criteria for the three vessels operating at the target site for the February and August time frames are presented in Table 11 and Table 12. The 95% range radii (km) and equivalent area (km^2) are shown for bottlenose dolphin, harbour porpoise, anchovy, herring, shad, and sturgeon. Quantities marked "n/a" are too small to estimate. A map of maximum-over-depth unweighted sound pressure levels around one of the representative vessel sources for the February time frame at this site is provided in Figure 15.

Table 11. Behavioural effect 95% ranges (km) and areas (km^2) are tabulated based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, without and with audiogram weighting applied for bottlenose dolphin and harbour porpoise.

		Unweighted to 120 dB re 1 µPa		BDolphin to 75 dBht		HPorpoise to 75 dBht	
		Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)
Pipe-laying Vessel: *Saipem 7000, Castorone*	Feb	34.6	3170.0	0.11	0.05	0.22	0.17
	Aug	9.9	325.0	0.11	0.05	0.22	0.17
Support tug Vessel: *Norman Neptune*	Feb	9.5	194.0	n/a	n/a	< 0.05	0.01
	Aug	8.0	170.0	n/a	n/a	< 0.05	0.01
Support vessel Vessel: *GSP Lyra*	Feb	15.1	684.0	0.36	0.44	0.68	1.52
	Aug	5.7	107.0	0.38	0.48	0.78	1.98

Table 12. Behavioural effect 95% ranges (km) and areas (km^2) are tabulated based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, with audiogram weighting applied for anchovy, herring, shad, and sturgeon.

		Herring to 75 dBht		Anchovy to 75 dBht		Shad to 75 dBht		Sturgeon to 75 dBht	
		Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)
Pipe-laying Vessel: *Saipem 7000, Castorone*	Feb	0.14	0.06	n/a	n/a	n/a	n/a	n/a	n/a
	Aug	0.14	0.06	n/a	n/a	n/a	n/a	n/a	n/a
Support tug Vessel: *Norman Neptune*	Feb	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a
	Aug	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a
Support vessel Vessel: *GSP Lyra*	Feb	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Aug	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

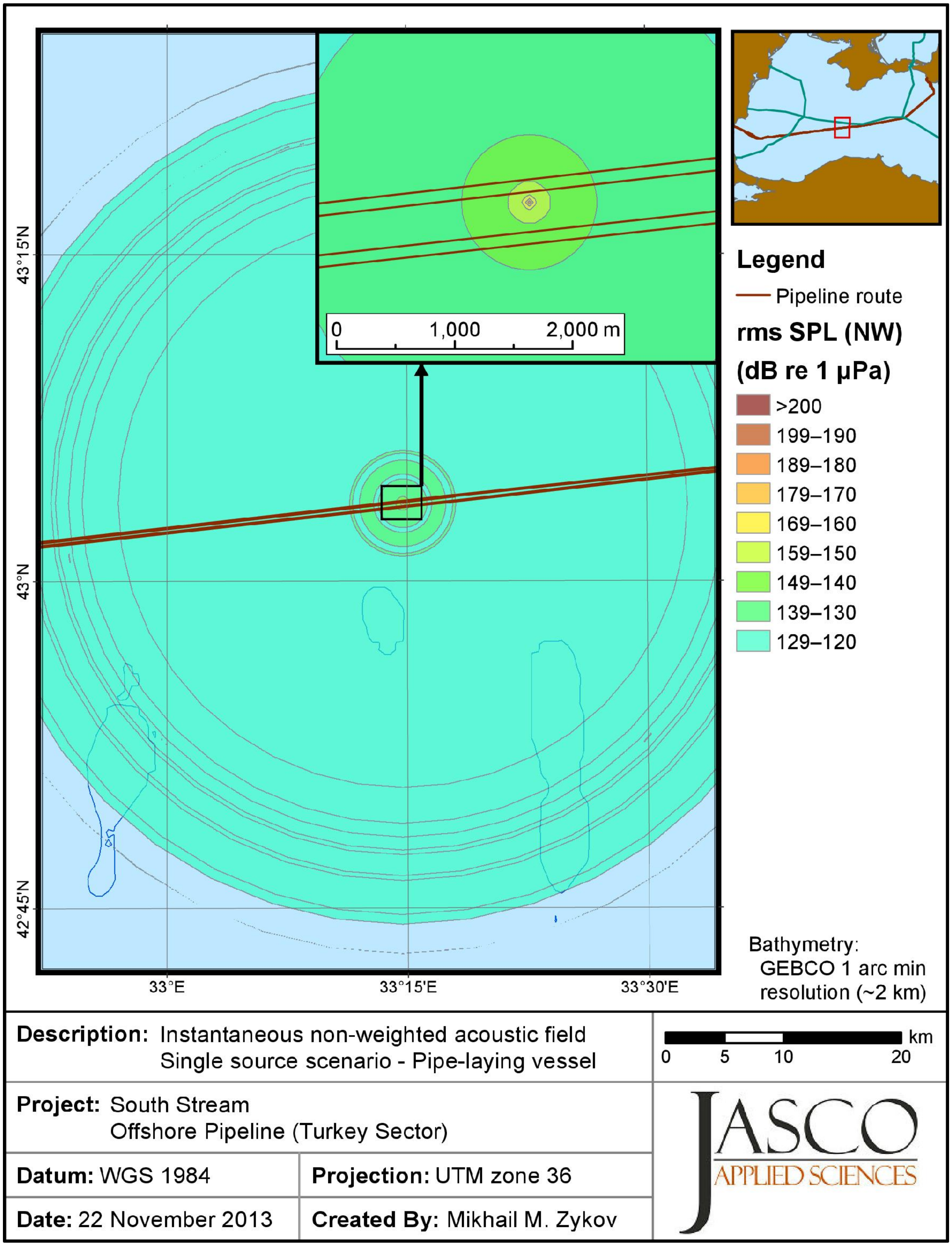


Figure 15. Broadband (10 Hz–20 kHz) maximum-over-depth sound pressure levels for the pipe-laying vessel at the target site. Blue contours indicate water depth in metres.

4.2. Side-Scan Sonar

As a representative sonar source, modelling is included for an Edgetech Full Spectrum Chirp side-scan sonar, a type likely to be used in a ROV mounted application (as would be used for pipeline route inspection). This source is modelled for an instantaneous, i.e., not cumulative, scenario.

There are well-accepted impact criteria for sonar sources that are based on the instantaneous root-mean-square sound pressure level metric (rms SPL). For injury we use the generic (NMFS) standard threshold of 180 dB re 1 µPa unweighted. For behaviour effects we follow Finneran and Jenkins (2012), which provides criteria specifically for sonar type sources. Their criteria for mid-frequency and high-frequency cetaceans are based on Type I weighting of the SPL and do not provide a single threshold value but rather refer to a Behavioural Response Function (BRF)—see Figure 16.

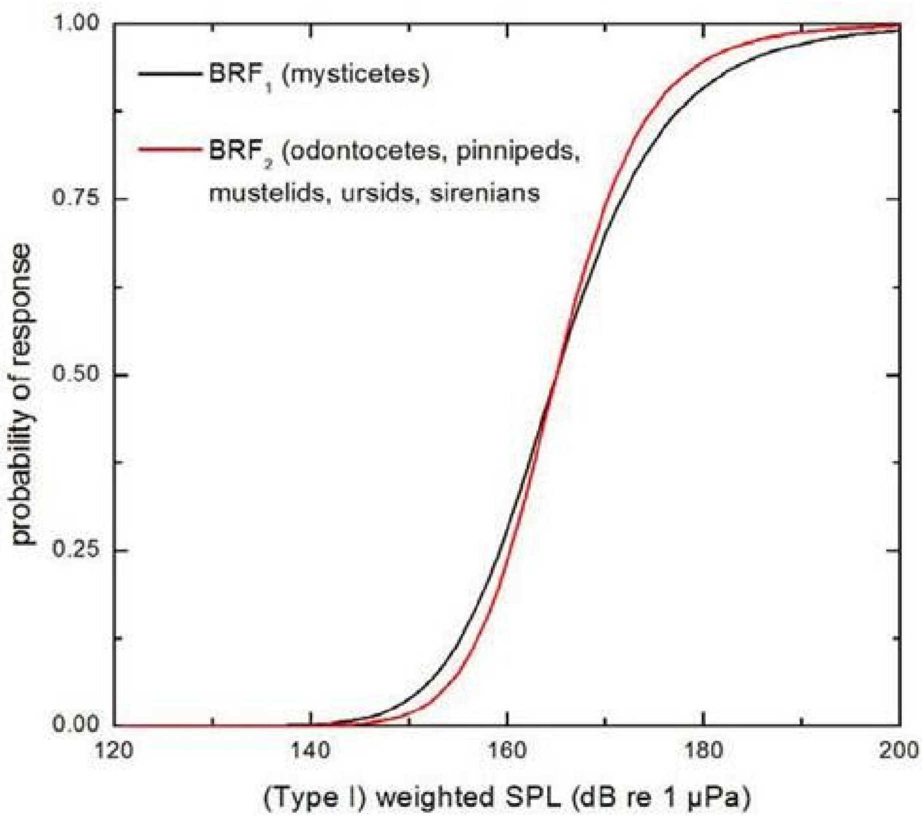


Figure 16. Behavioural Response Function (BRF) per Finneran and Jenkins (2012).

For a reasonably precautionary result we choose a 25% probability of response that maps to a weighted SPL of 160 dB re dB re 1 µPa. Using this threshold we compute the effect range and area for mid and high frequency cetaceans. Finneran and Jenkins (2012), however, exclude harbour porpoises from this criterion due to the high susceptibility to disturbance of this species, and they recommend adopting the generic (NMFS) standard threshold of 120 dB re 1 µPa unweighted. We therefore provide effect range and area also based on that criterion, which is significantly more precautionary.

Table 13 shows the estimated injury and behavioural effect ranges and areas. A representative exposure map is shown in Figure 17.

Table 13. Injury and behavioural effect 95% ranges (km) and areas (km^2) are tabulated for the deep-water site based on the horizontal distances from the source to modelled narrowband (1 Hz at 75 kHz) maximum-over-depth sound level thresholds.

		Range (km)	Area (km^2)
Generic (NMFS) injury threshold (180 dB re 1 μPa rms SPL, unweighted)	Feb	< 0.01	< 0.0001
	Aug	< 0.01	< 0.0001
Generic (NMFS) behaviour threshold (120 dB re 1 μPa rms SPL, unweighted)	Feb	0.90	0.18
	Aug	0.90	0.18
Mid-Frequency Cetaceans behaviour (160 dB re 1 uPa SPL MFC Type I)	Feb	0.12	0.0005
	Aug	0.12	0.0005
High-Frequency Cetaceans behaviour (160 dB re 1 uPa SPL HFC Type I)	Feb	0.12	0.0005
	Aug	0.12	0.0005

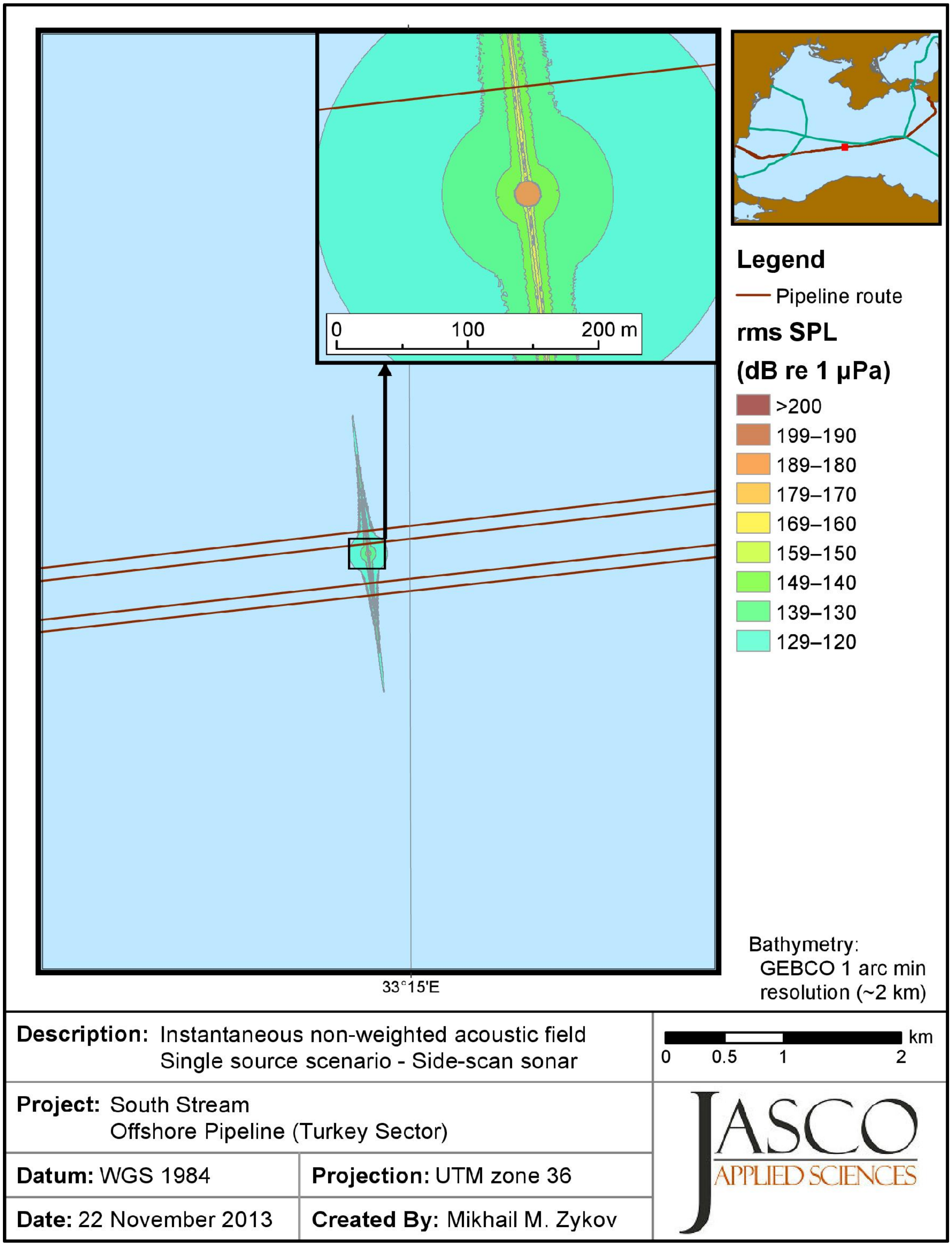


Figure 17. Narrowband (1 Hz at 75 kHz) maximum-over-depth sound pressure levels for the Edgetech Full Spectrum Chirp side-scan sonar at the target site. Blue contours indicate water depth in metres.

4.3. Vessel Group Instantaneous Sound Field

The summary of behavioural effect ranges and areas according to unweighted and audiogram weighted criteria for 2 groupings, for the February and August time frames, are presented in the following sections. In Table 14 through Table 17, the behavioural effect 95% range (km) and area (km²) are shown for bottlenose dolphin, harbour porpoise, anchovy, herring, shad, and sturgeon. Quantities marked "n/a" are too small to estimate. A map of maximum-over-depth unweighted sound pressure levels around one of the representative vessel groupings for the February time frame is also provided in Figure 18.

4.3.1. Scenario 1: Pipe-laying (J-Lay)

Table 14. Behavioural effect 95% ranges (km) and areas (km²) are tabulated for the deep water pipe-laying vessel grouping (VG1), based on the horizontal distances from the loudest source at the center of the group to the modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, without and with audiogram weighting applied for bottlenose dolphin and harbour porpoise.

		Unweighted to 120 dB re 1 µPa		BDolphin to 75 dBht		HPorpoise to 75 dBht	
		Range (km)	Area (km²)	Range (km)	Area (km²)	Range (km)	Area (km²)
Pipe-Laying (J-Lay)	Feb	39.1	4410.0	0.50	0.06	0.40	0.20
	Aug	12.4	507.0	0.50	0.06	0.40	0.23

Table 15. Behavioural effect 95% ranges (km) and areas (km²) are tabulated for the deep water pipe-laying vessel grouping (VG1), based on the horizontal distances from the loudest source at the center of the group to the modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, with audiogram weighting applied for anchovy, herring, shad, and sturgeon.

		Herring to 75 dBht		Anchovy to 75 dBht		Shad to 75 dBht		Sturgeon to 75 dBht	
		Range (km)	Area (km²)	Range (km)	Area (km²)	Range (km)	Area (km²)	Range (km)	Area (km²)
Pipe-Laying (J-Lay)	Feb	0.50	0.10	n/a	n/a	n/a	n/a	n/a	n/a
	Aug	0.50	0.10	n/a	n/a	n/a	n/a	n/a	n/a

4.3.2. Scenario 2: Crew Change (Pipe-laying)

Table 16. Behavioural effect 95% ranges (km) and areas (km^2) are tabulated for the deep water pipe-laying crew change vessel grouping (VG2), based on the horizontal distances from the loudest source at the center of the group to the modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, without and with audiogram weighting applied for bottlenose dolphin and harbour porpoise.

		Unweighted to 120 dB re 1 μPa		BDolphin to 75 dBht		HPorpoise to 75 dBht	
		Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)
Crew Change: (for pipe-laying operation)	Feb	39.4	4810.0	0.60	0.53	0.92	1.74
	Aug	13.3	587.0	0.64	0.61	1.01	2.26

Table 17. Behavioural effect 95% ranges (km) and areas (km^2) are tabulated for the deep water pipe-laying crew change vessel grouping (VG2), based on the horizontal distances from the loudest source at the center of the group to the modelled broadband (10–20000 Hz) maximum-over-depth sound level thresholds, with audiogram weighting applied for anchovy, herring, shad, and sturgeon.

		Herring to 75 dBht		Anchovy to 75 dBht		Shad to 75 dBht		Sturgeon to 75 dBht	
		Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)
Crew Change: (for pipe-laying operation)	Feb	0.50	0.10	n/a	n/a	n/a	n/a	n/a	n/a
	Aug	0.50	0.10	n/a	n/a	n/a	n/a	n/a	n/a

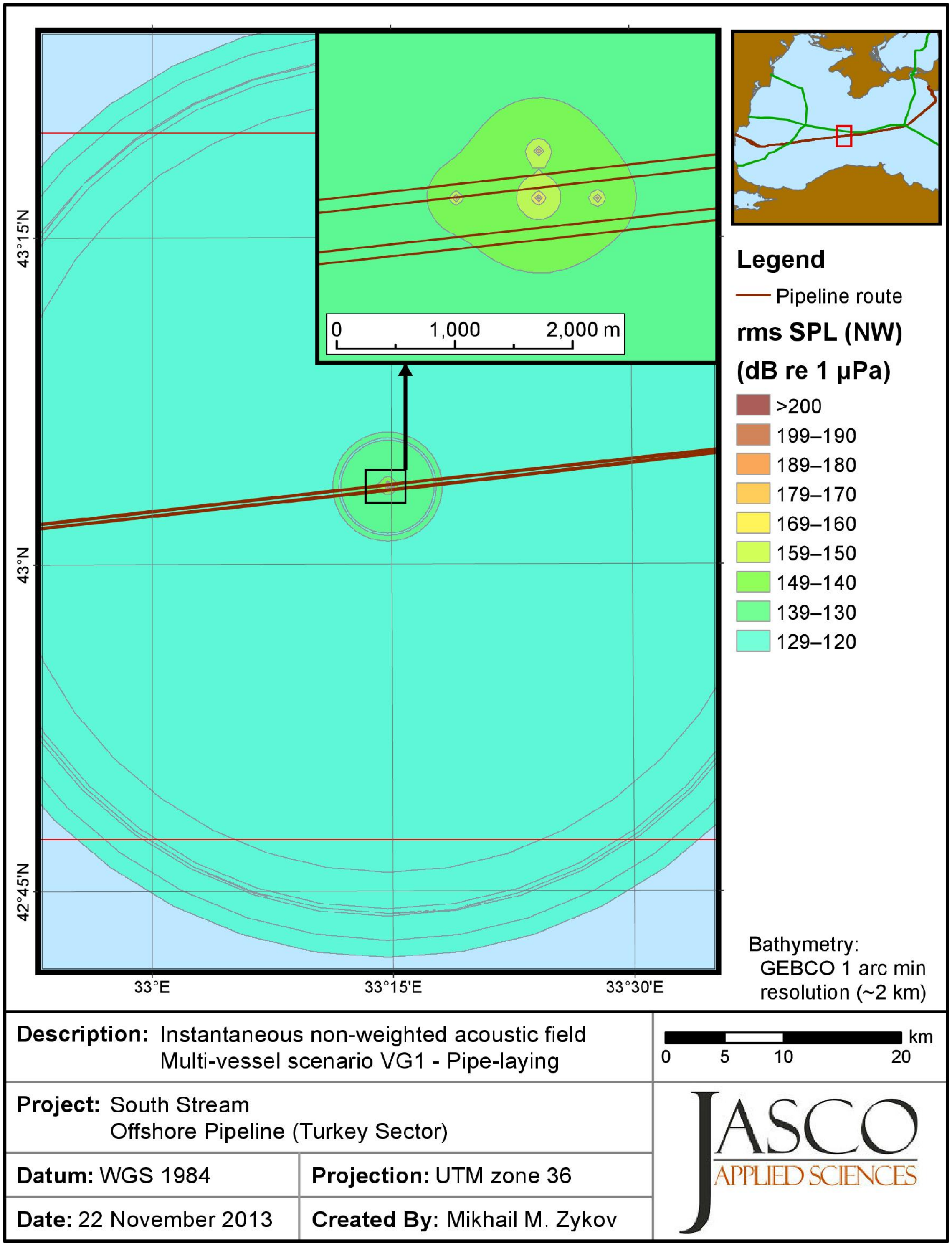


Figure 18. Broadband (10 Hz–20 kHz) maximum-over-depth sound pressure levels for the pipe-laying vessel group (VG1). Blue contours indicate water depth in metres.

4.4. Cumulative Exposure

In the tabular results in this section, the effect range is not related to the effect area by a regular mathematical expression or geometric formula, which would lack meaning given the elongated shape of the cumulative exposure area along the pipeline track. The ranges were instead derived by considering the maximum off-track width to which the given level was estimated to reach, thus establishing the closest equivalent to a vessel-centric "safety range" concept for the cumulative exposure metric.

The results presented in Table 18 and displayed as a map of unweighted cumulative levels in Figure 19 are for the modelling scenario corresponding to winter (February) sound propagation conditions, which produces the most extended footprints. This yields precautionary estimates for the relatively small ranges of effect at an injury level.

Table 18. Injury effect ranges (km) and areas (km^2) are tabulated for the deep water pipe-lay scenario based on maximum-over-depth sound level thresholds. Conditions are for the month of February.

	Range (km)	Area (km^2)
Mid-Frequency Cetaceans injury (215 dB re 1 µPa2-s MFC Type I)	n/a	n/a
Mid-Frequency Cetaceans injury (198 dB re 1 µPa2-s MFC Type II)	n/a	n/a
High-Frequency Cetaceans injury (215 dB re 1 µPa2-s HFC Type I)	n/a	n/a
High-Frequency Cetaceans injury (172 dB re 1 µPa2-s HFC Type II)	0.02	1.2
Fish injury, body mass > 2g (187 dB re 1 µPa2-s LP filter 2kHz)	0.36	3.8

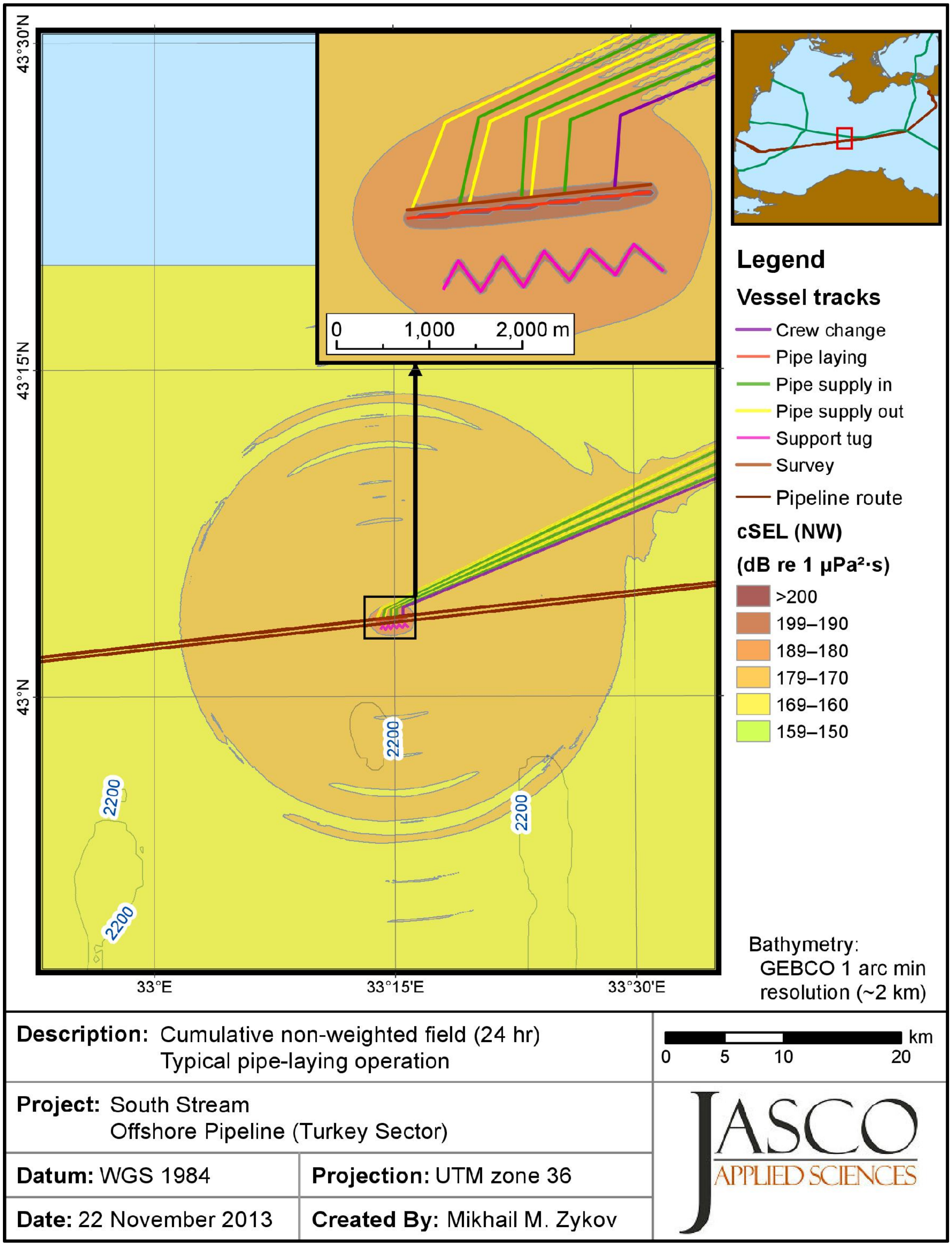


Figure 19. Colour-shaded zones depict broadband (10 Hz–20 kHz) unweighted cumulative SEL for the deep water pipe-laying scenario. The acoustic field is modelled for conditions prevalent in February. Blue contours indicate water depth in metres.

5. Remarks on Effect Range Estimates

With the exception of fish for which an injury effect range of about 0.4 km and effect area of 3.8 km^2 are predicted for a 24-hour operation, the injury footprint of the operations is estimated to be virtually insignificant. The injury result for fish must be considered with the caveats listed in section 1.5.1, primarily deriving from the fact that impact results derived from studies of exposure to pulse sound are likely to be overly precautionary (possibly by a wide margin) when applied to continuous sound exposure.

Based on audiogram weighted criteria, behavioural effect ranges for individual and group vessel operations are only estimated to be significant for dolphins, porpoises and to some degree herring, with effect ranges never exceeding 1 km for the loudest source at any modelled location.

The comparison of injury and behavioural effect ranges may in specific cases, particularly for fish species, appear counterintuitive to the expectation that behavioural effects should extend to markedly greater distances than injury. This inconsistency arises, aside from the large uncertainty in current estimation of the effects of continuous noise on fish, from the different exposure metrics on which the results are based: an instantaneous sound pressure level for behavioural effects, and an accumulation of acoustic energy over time for injury effects.

Literature Cited

[ITC] International Transducer Corporation. 1993. *Application Equations for Underwater Sound Transducers* (pamphlet). International Transducer Corporation, Santa Barbara, CA.

Aerts, L., M. Blees, S. Blackwell, C. Greene, K. Kim, D. Hannay, and M. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort Sea, July-August 2008: 90-day report*. LGL Report P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc. and JASCO Applied Sciences for BP Exploration Alaska. 199 p. http://www.nmfs.noaa.gov/pr/pdfs/permits/bp_liberty_monitoring.pdf.

ANSI S1.4-1983. R2006. *American National Standard Specification for Sound Level Meters*. American National Standards Institute, New York.

Buckingham, M.J. 2005. Compressional and shear wave properties of marine sediments: Comparisons between theory and data. *Journal of the Acoustical Society of America* 117(1): 137-152.

Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. NRL Memorandum Report 7330-09-9165. US Naval Research Laboratory, Stennis Space Center, MS. 21 p.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93: 1736-1742.

Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178-182.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862-863.

Dickerson, C., K.J. Reine, and D.G. Clarke. 2001. *Characterization of underwater sounds produced by bucket dredging operations* (webpage). U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://el.erdc.usace.army.mil/elpubs/pdf/doere14.pdf.

Edgetech. 2000. AUV/UUV Sonar Payload. Technical Data sheet.

Enger, P.S. 1967. Hearing in herring. *Comparative Biochemistry and Physiology* 22(2): 527-538.

Finneran, J. and A.K. Jenkins. 2012. Criteria and Thresholds for Navy Acoustic Effects Analysis Technical Report. *SPAWAR Marine Mammal Program*.

Finneran, J.J. and C.E. Schlundt. 2011. Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 130(5): 3124-3136.

Fisher, F.H. and V.P. Simmons. 1977. Sound absorption in sea water. *Journal of the Acoustical Society of America* 62(3): 558-564.

Funk, D., D. Hannay, D. Ireland, R. Rodrigues, and W. Koski (eds.). 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report*. LGL Report P969-1. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 218 p. http://www-static.shell.com/static/usa/downloads/alaska/shell2007_90-d_final.pdf.

Halvorsen, M.B., B.M. Casper, C.M. Woodley, T.J. Carlson, and A.N. Popper. 2012. Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. *PLoS ONE* 7(6): e38968.

Hannay, D., A. MacGillivray, M. Laurinolli, and R. Racca. 2004. *Sakhalin Energy: Source Level Measurements from 2004 Acoustics Program*. Version 1.5. Technical report prepared for Sakhalin Energy by JASCO Applied Sciences.

Hannay, D. and R. Racca. 2005. *Acoustic model validation*. Document 0000-S-90-04-T-7006-00-E, Revision 02. Technical report for Sakhalin Energy Investment Company Ltd. by JASCO Research Ltd. 34 p. http://www.sakhalinenergy.com/en/documents/doc_33_jasco.pdf.

Ireland, D.S., R. Rodrigues, D. Funk, W. Koski, and D. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. LGL Report P1049-1. 277 p.

Johansson, A.T. and M.H. Andersson. 2012. *Ambient underwater noise levels at Norra Midsjöbanken during construction of the Nord Stream pipeline*. FOI-R--3469--SE. FOI, Swedish Defence Research Agency for Nord Stream AG and Naturvårdsverket (Swedish Environment Protection Agency). 65 p. http://www.nord-stream.com/press-info/library/?pk=194.

Johnson, C.S. 1967. Sound detection thresholds in marine mammals. In Tavolga, W. (ed.). *Marine Bioacoustics*. Pergamon, New York. pp. 247-260.

Kastelein, R.A., P. Bunskoek, M. Hagedoorn, W.W.L. Au, and D. de Haan. 2002. Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. *Journal of the Acoustical Society of America* 112(1): 334-344.

Kinsler, L.E., A.R. Frey, A.B. Coppens, and J.V. Sanders. 1950. *Fundamentals of acoustics*. John Wiley & Sons Inc., New York.

Kipple, B. and C. Gabriele. 2003. *Glacier Bay watercraft noise: report to Glacier Bay National Park by the Naval Surface Warfare Cent-Detachment Bremerton*. Technical Report NSWCCD-71-TR-2003/522.

Ladich, F. and R. Fay. 2013. Auditory evoked potential audiometry in fish. *Reviews in Fish Biology and Fisheries* 23(3): 317-364.

MacGillivray, A.O. 2006. *Underwater acoustic source level measurements of Castoro Otto and Fu Lai*. JASCO Applied Sciences Ltd.

Massa, D.P. 1999. *Choosing and ultrasonic sensor for proximity or distance measurement; part 2: Optimizing sensor selection* (webpage). Sensors, March 1, 1999. http://www.sensorsmag.com/sensors/acoustic-ultrasound/choosing-ultrasonic-sensor-proximity-or-distance-measurement-838.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25th June, London, U.K.

Nedwell, J.R. and B. Edwards. 2004. *A review of measurements of underwater man-made noise carried out by Subacoustech Ltd, 1993 – 2003*. Report ref: 534R0109. Subacoustech. 131 p. http://www.subacoustech.com/information/downloads/reports/534R0109.pdf.

Nedwell, J.R., J. Lovell, and A.W.H. Turnpenny. 2005. Experimental validation of a species-specific behavioral impact metric for underwater noise. *Journal of the Acoustical Society of America* 118(3): 2019-2019.

Nedwell, J.R., A.W.H. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, and J.A.L. Spinks. 2007. *A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise*. Report No. 534R1231 prepared by Subacoustech Ltd. for the UK Department of Business, Enterprise and Regulatory Reform under Project No. RDCZ/011/0004. www.subacoustech.com/information/downloads/reports/534R1231.pdf.

O'Neill, C., D. Leary, and A. McCrodan. 2010. Sound source verification. (Chapter 3) In Blees, M.K., K.G. Hartin, D.S. Ireland, and D. Hannay (eds.). *Marine mammal monitoring and mitigation during open water seismic exploration by Statoil USA E&P Inc. in the Chukchi Sea, August-October 2010: 90-day report*. LGL Report P1119. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. for Statoil USA E&P Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. pp. 1-34.

Porter, M.B. and Y.-C. Liu. 1994. Finite-element ray tracing. *In*: Lee, D. and M.H. Schultz (eds.). *Proceedings of the International Conference on Theoretical and Computational Acoustics*. Volume 2. World Scientific Publishing Co. pp. 947-956.

Robinson, S.P., P.D. Theobald, G. Hayman, L.S. Wang, P.A. Lepper, V. Humphrey, and S. Mumford. 2011. *Measurement of Noise Arising from Marine Aggregate Dredging Operations*. MALSF (MEPF Ref no. 09/P108).

Schlundt, C.E., J.J. Finneran, D.A. Carder, and S.H. Ridgway. 2000. Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. *Journal of the Acoustical Society of America* 107(6): 3496-3508.

Shimkus, K.M., Ya. P. Malovitsky, and S.I. Shumenko. 1978. *In* Ross, D. A., Y. P. Neprochnov, et al. 1978. Initial Reports of the Deep Sea Drilling Project, Volume 42, Part 2: Washington (U.S. Government Printing Office), p. 469-482.

The Shipboard Scientific Party, 1978. Site 379. *In* Ross, D. A., Neprochnov, Y. P., et al. 1978. Initial Reports of the Deep Sea Drilling Project, Volume 42, Part 2: Washington (U.S. Government Printing Office), p. 29-118.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals* 33(4): 411-521.

Stadler, J.H. and D.P. Woodbury. 2009. *Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria*. *Inter-Noise 2009: Innovations in Practical Noise Control*, 2009 August 23-26, Ottawa, Canada.

Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167-7183.

Warner, G., C. Erbe, and D. Hannay. 2010. Underwater sound measurements. (Chapter 3) In Reiser, C.M., D.W. Funk, R. Rodrigues, and D. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. pp. 1-54. http://www-static.shell.com/static/usa/downloads/alaska/report_2009_shell_90-d_report_plus_appendices.pdf.

Williams, R., D.E. Bain, J.K.B. Ford, and A.W. Trites. 2002. Behavioral responses of male killer whales to a “leapfrogging” vessel. *Journal of Cetacean Research and Management* 4: 305-310.

Appendix A. Tables of Threshold Ranges and Areas

A.1. Single-Vessel Instantaneous Sound Fields

Table A-1. 95% ranges (km) and exposure areas (km^2) are tabulated for unweighted rms SPL thresholds for specific modelled broadband (10–20000 Hz) maximum-over-depth sound levels, for both February and August time frames, for three single-vessel activity sources.

	February						August					
rms SPL (dB re 1 µPa)	Pipe-laying		Support tug		Support vessels		Pipe-laying		Support tug		Support vessels	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
180	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
170	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
160	< 0.05	0.01	n/a	n/a	n/a	n/a	< 0.05	0.01	n/a	n/a	n/a	n/a
150	0.16	0.09	0.11	0.05	0.11	0.05	0.16	0.09	0.11	0.05	0.11	0.05
140	0.56	1.05	0.43	0.6	0.4	0.53	0.61	1.24	0.46	0.69	0.43	0.6
130	4.42	43.5	1.33	5.84	3.29	28.6	2.26	16.8	1.48	7.21	1.63	8.78
120	34.6	3170	9.46	194	15.1	684	9.93	325	7.98	170	5.7	107

Table A-2. 95% ranges (km) and exposure areas (km^2) are tabulated for pipe-laying activity, based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound levels, for both February and August time frames, with audiogram weighting applied for bottlenose dolphin, harbour porpoise, herring, anchovy, shad, and sturgeon.

	February											
dBht	Activity: Pipe-laying—Vessels: Saipem 7000, Castorone											
	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	< 0.05	0.01	0.11	0.05	0.07	0.02	n/a	n/a	n/a	n/a	n/a	n/a
75	0.11	0.05	0.22	0.17	0.14	0.06	n/a	n/a	n/a	n/a	n/a	n/a
70	0.22	0.17	0.4	0.52	0.27	0.24	n/a	n/a	n/a	n/a	n/a	n/a
60	0.62	1.27	1.33	5.85	0.81	2.21	n/a	n/a	n/a	n/a	n/a	n/a
50	3.61	41.4	6.46	138	6.35	107	n/a	n/a	n/a	n/a	n/a	n/a
40	11.1	377	21.3	1500	52.7	8090	0.11	0.05	n/a	n/a	n/a	n/a

	August											
dBht	Activity: Pipe-laying—Vessels: Saipem 7000, Castorone											
	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	< 0.05	0.01	0.11	0.05	0.07	0.02	n/a	n/a	n/a	n/a	n/a	n/a
75	0.11	0.05	0.22	0.17	0.14	0.06	n/a	n/a	n/a	n/a	n/a	n/a
70	0.22	0.17	0.43	0.6	0.27	0.25	n/a	n/a	n/a	n/a	n/a	n/a
60	0.72	1.71	1.46	7.05	0.9	2.71	n/a	n/a	n/a	n/a	n/a	n/a
50	2.51	20.9	4.69	55.9	2.96	29	n/a	n/a	n/a	n/a	n/a	n/a
40	8.07	137	12	272	13.9	634	0.11	0.05	n/a	n/a	n/a	n/a

Table A-3. 95% ranges (km) and exposure areas (km^2) are tabulated for support tug activity, based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound levels, for both February and August time frames, with audiogram weighting applied for bottlenose dolphin, harbour porpoise, herring, anchovy, shad, and sturgeon.

	February											
dBht	Activity: Support tug—Vessel: Norman Neptune											
	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	n/a	n/a	n/a	n/a	0.07	0.02	n/a	n/a	n/a	n/a	n/a	n/a
75	n/a	n/a	< 0.05	0.01	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a
70	< 0.05	0.01	0.1	0.03	0.22	0.17	n/a	n/a	n/a	n/a	n/a	n/a
60	0.18	0.11	0.32	0.34	0.68	1.53	n/a	n/a	n/a	n/a	n/a	n/a
50	0.57	1.09	1.01	3.42	2.12	14.9	n/a	n/a	n/a	n/a	n/a	n/a
40	4.9	67.3	9.44	221	22.9	1340	0.1	0.03	n/a	n/a	n/a	n/a

	August											
dBht	Activity: Support tug—Vessel: Norman Neptune											
	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	n/a	n/a	n/a	n/a	< 0.05	0.01	n/a	n/a	n/a	n/a	n/a	n/a
75	n/a	n/a	< 0.05	0.01	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a
70	< 0.05	0.01	0.07	0.02	0.22	0.17	n/a	n/a	n/a	n/a	n/a	n/a
60	0.16	0.09	0.34	0.36	0.74	1.79	n/a	n/a	n/a	n/a	n/a	n/a
50	0.67	1.48	1.21	4.85	2.35	18.3	n/a	n/a	n/a	n/a	n/a	n/a
40	3	24.1	5.27	64.8	10.7	377	0.1	0.03	n/a	n/a	n/a	n/a

Table A-4. 95% ranges (km) and exposure areas (km^2) are tabulated for support vessel activity, based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound levels, for both February and August time frames, with audiogram weighting applied for bottlenose dolphin, harbour porpoise, herring, anchovy, shad, and sturgeon.

	February											
	Activity: Support vessel—Vessel: GSP Lyra											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	< 0.05	0.01	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	0.22	0.17	0.4	0.53	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
75	0.36	0.44	0.68	1.52	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
70	0.63	1.29	2.66	9.53	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
60	3.58	38.6	6.42	136	0.14	0.06	n/a	n/a	n/a	n/a	n/a	n/a
50	10.1	334	18.1	1030	0.47	0.73	n/a	n/a	n/a	n/a	n/a	n/a
40	26.9	2230	42.5	5720	1.42	6.73	n/a	n/a	n/a	n/a	n/a	n/a

	August											
	Activity: Support vessel—Vessel: GSP Lyra											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	< 0.05	0.01	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
80	0.22	0.17	0.43	0.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
75	0.38	0.48	0.78	1.98	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
70	0.71	1.68	1.38	6.33	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
60	2.28	17.1	3.78	44.8	0.11	0.05	n/a	n/a	n/a	n/a	n/a	n/a
50	5.7	107	9.25	229	0.5	0.85	n/a	n/a	n/a	n/a	n/a	n/a
40	13.6	576	14.1	655	1.77	10.3	n/a	n/a	n/a	n/a	n/a	n/a

A.2. Side-Scan Sonar

Table A-5. 95% ranges (km) and exposure areas (km^2) are tabulated for unweighted rms SPL thresholds, and mid- and high-frequency Type I weighting, for modelled narrowband (1 Hz at 75 kHz) maximum-over-depth sound levels, for both February and August time frames, for the Edgetech Full Spectrum Chirp side-scan sonar source.

	February					
rms SPL (dB re 1 µPa)	Unweighted		Mid-frequency Type I		High-frequency Type I	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
180	0.004	0.0000785	0.004	0.0000785	0.004	0.0000785
170	0.037	0.000154	0.028	0.000113	0.028	0.000113
160	0.131	0.000616	0.115	0.000531	0.118	0.000531
150	0.290	0.00322	0.261	0.00229	0.266	0.00246
140	0.490	0.0129	0.451	0.0102	0.460	0.0106
130	0.713	0.0491	0.673	0.0394	0.683	0.0408
120	0.904	0.176	0.877	0.141	0.883	0.148

	August					
rms SPL (dB re 1 µPa)	Unweighted		Mid-frequency Type I		High-frequency Type I	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
180	0.004	0.0000785	0.004	0.0000785	0.004	0.0000785
170	0.037	0.000154	0.028	0.000113	0.028	0.000113
160	0.131	0.000616	0.115	0.000531	0.118	0.000531
150	0.290	0.00322	0.260	0.00229	0.266	0.00246
140	0.489	0.0129	0.450	0.00985	0.459	0.0106
130	0.712	0.0491	0.673	0.0387	0.682	0.0408
120	0.904	0.175	0.876	0.141	0.882	0.148

A.3. Vessel Group Instantaneous Sound Field

Table A-6. 95% ranges (km) and exposure areas (km^2) are tabulated for unweighted rms SPL thresholds for specific to modelled broadband (10–20000 Hz) maximum-over-depth sound levels, for both the February and August time frames, for the vessel group scenarios VG1: Pipe-laying (J-Lay) and VG2: Crew Change (Pipe-laying).

	February				August			
rms SPL (dB re 1 µPa)	VG1		VG2		VG1		VG2	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
180	0.4	n/a	0.28	n/a	0.4	n/a	0.28	n/a
170	0.7	0.01	0.5	0.01	0.7	0.01	0.5	0.01
160	0.7	0.02	0.5	0.02	0.7	0.02	0.5	0.02
150	0.65	0.18	0.45	0.24	0.65	0.19	0.45	0.24
140	0.81	1.86	0.84	1.91	0.86	2.21	0.93	2.43
130	4.52	62.5	6.41	136	2.67	23.3	2.95	28.6
120	39.1	4410	39.4	4810	12.4	507	13.3	587

Table A-7. 95% ranges (km) and exposure areas (km^2) are tabulated for pipe-laying (J-Lay) activity at the shallow water site (S03), based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound levels for vessel group scenario VG1: Pipe-laying (J-Lay), for both February and August time frames, with audiogram weighting applied for bottlenose dolphin, harbour porpoise, herring, anchovy, shad, and sturgeon.

	February											
	Activity: Pipe-laying (J-Lay)											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	0.7	0.01	0.7	0.01	0.7	0.01	n/a	n/a	n/a	n/a	n/a	n/a
80	0.7	0.02	0.5	0.06	0.5	0.04	n/a	n/a	n/a	n/a	n/a	n/a
75	0.5	0.06	0.4	0.2	0.7	0.13	n/a	n/a	n/a	n/a	n/a	n/a
70	0.4	0.15	0.46	0.62	0.56	0.51	n/a	n/a	n/a	n/a	n/a	n/a
60	0.68	1.5	1.54	7.88	1.11	3.84	0.7	0.01	n/a	n/a	n/a	n/a
50	3.72	45.9	6.58	143	6.58	143	0.7	0.01	0.4	n/a	0.7	0.01
40	12.4	511	24.6	1960	66.4	13400	0.5	0.09	0.7	0.01	0.7	0.01

	August											
	Activity: Pipe-laying (J-Lay)											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	0.7	0.01	0.7	0.01	0.7	0.01	n/a	n/a	n/a	n/a	n/a	n/a
80	0.7	0.02	0.5	0.06	0.5	0.04	n/a	n/a	n/a	n/a	n/a	n/a
75	0.5	0.06	0.4	0.23	0.7	0.13	n/a	n/a	n/a	n/a	n/a	n/a
70	0.4	0.15	0.5	0.72	0.6	0.55	n/a	n/a	n/a	n/a	n/a	n/a
60	0.78	1.99	1.52	7.71	1.2	4.55	0.7	0.01	n/a	n/a	n/a	n/a
50	2.55	21.5	4.65	62.9	3.75	46.6	0.7	0.01	0.4	n/a	0.7	0.01
40	8.06	153	11.9	341	15	748	0.5	0.09	0.7	0.01	0.7	0.01

Table A-8. 95% ranges (km) and equivalent areas (km^2) are tabulated for crew change (pipe-laying) activity at the shallow water site (S03), based on the horizontal distances from the source to modelled broadband (10–20000 Hz) maximum-over-depth sound levels for vessel group scenario VG2: Crew Change (Pipe-laying), for both February and August time frames, with audiogram weighting applied for bottlenose dolphin, harbour porpoise, herring, anchovy, shad, and sturgeon.

	February											
	Activity: Crew change (pipe-laying)											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	0.5	0.02	0.4	0.07	0.5	0.01	n/a	n/a	n/a	n/a	n/a	n/a
80	0.46	0.19	0.64	0.62	0.4	0.03	n/a	n/a	n/a	n/a	n/a	n/a
75	0.6	0.53	0.92	1.74	0.5	0.1	n/a	n/a	n/a	n/a	n/a	n/a
70	0.86	1.5	2.85	13.5	0.5	0.4	n/a	n/a	n/a	n/a	n/a	n/a
60	3.79	44.4	6.55	141	0.98	2.99	0.5	0.01	n/a	n/a	n/a	n/a
50	12.1	409	20.8	1160	6.44	137	0.5	0.01	0.28	n/a	0.5	0.01
40	29.8	2620	48	7350	62.2	10900	0.5	0.07	0.5	0.01	0.5	0.01

	August											
	Activity: Crew change (pipe-laying)											
dBht	Bottlenose Dolphin cetaceous		Harbour Porpoise cetaceous		Pacific Herring		Bay Anchovy		American Shad		Lake Sturgeon	
	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e	$R_{95\%}$	A_e
90	0.5	0.02	0.4	0.07	0.5	0.01	n/a	n/a	n/a	n/a	n/a	n/a
80	0.46	0.19	0.67	0.71	0.4	0.03	n/a	n/a	n/a	n/a	n/a	n/a
75	0.64	0.61	1.01	2.26	0.5	0.1	n/a	n/a	n/a	n/a	n/a	n/a
70	0.96	1.95	1.6	7.05	0.5	0.44	n/a	n/a	n/a	n/a	n/a	n/a
60	2.45	18.2	3.98	50	1.06	3.56	0.5	0.01	n/a	n/a	n/a	n/a
50	6.14	124	9.29	282	3.35	37	0.5	0.01	0.28	n/a	0.5	0.01
40	13.6	615	14.9	721	14.4	683	0.5	0.07	0.5	0.01	0.5	0.01

A.4. Cumulative Exposure

Table A-9. Exposure areas (km^2) are tabulated for the pipe-laying scenario for 24-hour cumulative SEL for unweighted, fish-weighted, and MFC and HFC Types I and II weightings, using the maximum-over-depth acoustic field calculated for the month of February.

	Scenario: Pipe Laying					
cSEL (dB re 1 µPa^2-s)	Un-weighted	Fish (0.01 – 2 kHz)	Type I MFC	Type I HFC	Type II MFC	Type II HFC
	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
215	0.0025	n/a	n/a	n/a	n/a	n/a
210	0.075	0.073	0.052	0.045	n/a	n/a
200	0.16	0.16	0.12	0.11	n/a	n/a
198	0.23	0.23	0.14	0.13	0.0075	n/a
190	1.38	1.09	0.84	0.79	0.093	0.08
187	4.46	3.81	1.72	1.51	0.1	0.093
180	13.9	13.4	9.91	8.62	0.43	0.16
172	443	412	293	216	1.68	1.17
170	1130	1060	663	562	2.42	1.48