8 UNDERWATER NOISE MODELLING – BACKGROUND & METHODS

8.1 INTRODUCTION

Activities associated with the construction, operations and decommissioning of the proposed Project will generate underwater noise that has the potential to disturb Valued Ecosystem Components (VECs) in Hecate Strait. Construction noise from vessels and equipment involved in the installation of turbines, platforms and cable infrastructure has the greatest potential for acoustic impacts on VECs. In particular, pile driving associated with installation of the wind turbine generator (WTG) substructures can generate potentially injurious underwater noise levels. In order to better assess the potential for noise impacts, JASCO Applied Sciences has carried out a modelling study, as part of the overall Noise and Vibration Study Program, in order to estimate underwater noise levels from these activities. This underwater noise study has applied numerical modelling techniques to predict noise footprints of the various noise sources associated with the Project. In addition, this study involved background literature reviews to obtain information on wind farm related noise sources, to research underwater noise mitigation options, and to investigate documented assessments from other wind farm projects.

This volume section is divided into a number of subsections that present findings and results from the underwater noise modelling component of the Noise and Vibration Study. Subsection 8.2reviews acoustics terminology, describes the noise modelling methodology, and presents the noise modelling results, as well as reviewing decommissioning noise and mitigation options for the Project. Subsection 8.3 provides summaries of acoustic metrics relevant to impacts of noise (pulsed and non-pulsed) on marine mammals, birds, fish and invertebrates. Subsection 8.4 includes a description of JASCO's Marine Operations Noise Model (MONM) as well as details of the bathymetry, sound speed profile and geoacoustic environmental inputs to the model. This subsection also provides a detailed description of all the wind farm construction and operation model scenarios that were considered for the desktop study. Details of the various model scenarios were based on the engineering Project Description document provided by NaiKun Wind Development Inc. (the Proponent) (Baird 2008), as well as on the Detailed Study Design document developed by JASCO as part of the initial environmental assessment noise scoping process (Austin 2008). Section 9 presents results in the form of noise contour maps (subsection 9.1), as well as tables of noise level threshold radii (subsection 9.2) for each of the Project model scenarios. At the end of Section 9 literature review summaries are presented for noise sources associated with wind farm decommissioning (subsection 9.3) as well as noise mitigation options for pile driving and vessel based wind farm construction activities (subsections 9.4). Sections 9.5 and 9.6 provide the discussion and conclusions respectively.

8.2 ACOUSTICS TERMINOLOGY

Sound is the result of mechanical vibration waves travelling through a fluid medium (*e.g.*, air or water) that generate a time-varying pressure disturbance. At a fixed receiver location, the pressure alternates positively and negatively above and below the ambient pressure. Sound waves may be perceived by the auditory system of an animal or human or measured using an acoustic sensor. Water is a very efficient conductor of sound; the speed of sound travelling in water is approximately 1.5 km/s, which is over 4 times the speed of sound in air. Sound is used extensively by marine organisms for communicating and learning about their environment. Humans also use sound to probe the marine environment and many human activities, like shipping, generate noise in the ocean.

Sources of noise in the ocean may be mechanical (*e.g.*, a ship), biological (*e.g.*, a whale) or environmental (*e.g.*, a storm). The term “noise” generally refers to unwanted ambient background sound that interferes with the detection of other sounds. Common sources of naturally occurring underwater environmental noise include wind, waves and seismic disturbances. Anthropogenic (*i.e.*, man-made) sources of underwater noise include marine transportation, construction, geophysical surveys and sonar. Noise in the ocean naturally varies from place-to-place and from time-to-time. Levels of background noise in the ocean depend primarily on wind and weather conditions as well as on the intensity and proximity of human activity.

8.2.1 Acoustic Metrics

Sound waves are typically described in terms of two characteristics: intensity and frequency. Intensity is measured in units of power-per-unit-area and frequency is measured in units of cycles-per-unit-time. The SI units of intensity and frequency are W/m^2 and Hz, respectively. Sound waves that are composed of single frequencies are called tones. Most sounds are generally composed of a broad range of frequencies (“broadband” sound) rather than pure tones. The loudness of a sound is related to its intensity; however, loudness is a subjective term that refers to the perception of sound intensity, rather than the actual intensity itself. For humans and other animals, loudness also depends on the frequency (or pitch) and duration of sound. Pulsed sounds and sounds with very short durations (less than a few seconds) are sometimes called transient sounds. Sounds with longer durations are called continuous sounds.

Sound pressure and intensity are most commonly measured on the decibel (dB) scale. The dB scale is a logarithmic scale that expresses a quantity relative to a predefined reference level. Sound pressure, in dB, is expressed in terms of the sound pressure level (SPL), symbolized L_P,

$$L_P = 20\log_{10}(P / P_{ref}) \qquad \textbf{Eq. 1}$$

where P is the pressure amplitude and P_{ref} is the reference sound pressure. For underwater sound, the reference pressure is generally taken to be 1 µPa (equal to 10^{-6} Pa or 10^{-11} bar).

It is important to note that decibels used for measuring underwater sound are not equivalent to decibels used for measuring airborne sound. Airborne decibels are based on a different standard reference pressure of 20 µPa. Furthermore, due to the differences in sound speed and density between the two media (one a liquid, the other a gas) an airborne pressure wave has greater intensity than an underwater sound wave with equivalent amplitude. Taking into account both the difference in reference pressures and the difference in medium properties, underwater decibels are approximately 63 dB greater than standard airborne decibels for a sound wave with the same intensity in both media.

8.2.1.1 Continuous Noise

Continuous noise, unlike pulsed noise, is characterized by gradual intensity variations over time. Noise from a transiting ship is an example of continuous noise. The intensity of continuous noise is generally given in terms of the measured *rms* SPL. Given a measurement of the time varying sound pressure *p(t)* from a given noise source at some location, the *rms* SPL (symbol L_P) is computed according to the following formula:

$$L_P = 10\log_{10} \frac{1}{T}\int_T p(t)^2 \, dt / P_{ref}{}^2$$ **Eq. 2**

where *T* is the measurement period. The *rms* SPL is effectively the mean sound intensity over the measurement period.

8.2.1.2 Pulsed Noise

Transient or pulsed noise is characterized by brief, intermittent acoustic events with rapid onset and decay back to pre-existing levels (*i.e.*, within a few seconds). Noise from pile hammering is an example of pulsed noise. Sound levels of transient noise are commonly characterized according to three different acoustic metrics: peak pressure, *rms* pressure and sound exposure level. The peak SPL (symbol L_{Pk}) is the maximum instantaneous sound pressure level measured over the pulse duration:

$$L_{Pk} = 20\log_{10}\left(\max\left|p(t)\right| / P_{ref}\right)$$ **Eq. 3**

where *p(t)* is the instantaneous pulse pressure as a function of time, measured over the pulse duration $0 \le t \le T$. This metric is very commonly quoted for impulsive sounds but does not take into account the pulse duration or bandwidth of a signal.

For pulsed noise, the *rms* sound pressure level may be measured over the pulse duration according to the following equation:

$$L_P = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)\, dt / P_{ref}{}^2\right)$$ **Eq. 4**

However, some ambiguity remains in how the pulse duration is defined. In studies of impulsive noise, the pulse duration is often taken to be the interval over which the cumulative energy curve rises from 5% to 95% of the total pulse energy. This interval contains 90% of the total pulse energy (T_{90}), and the SPL computed over this interval is commonly referred to as the 90% *rms* SPL (L_{P90}).

The sound exposure level or SEL (symbol L_E) is a measure of the total sound energy contained in one or more pulses. The SEL for a single pulse is computed from the time-integral of the squared pressure over the pulse duration:

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt / P_{ref}{}^2\right)$$

Eq. 5

Unlike the sound pressure level, the sound exposure level may also be applied as a dosage metric, meaning that its value increases with the number of exposure events. Unless otherwise stated, sound exposure levels for pulsed noise sources (*i.e.*, impact hammer pile driving) presented in this volume section refer to single pulse SELs.

Impulse is another acoustic metric that is used for estimating mortality and injury from shock waves generated by high intensity impulse noise sources. Impulse (symbolized Φ) is defined to be the time integral of the instantaneous sound pressure during the initial shock pulse:

$$\Phi = \int_{T_0} p(t)dt$$

Eq. 6

where T_0 is the time duration of the initial shock pulse. Impulse is typically given in S.I. units of Pa·s.

8.2.2 Source Level and Transmission Loss

Sources of underwater noise, such as ship propellers and marine mammals, generate radiating sound waves whose intensity generally decays with distance from the source. The dB reduction in sound level that results from propagation of sound away from an acoustic source is called transmission loss (TL). The loudness or intensity of a noise source is quantified in terms of the source level (SL), which is the sound pressure level referenced to some fixed distance from a noise source. The standard reference distance for underwater noise sources is 1 m. By convention, underwater acoustic source levels are specified in units of dB re 1 µPa at 1 m. In the source-path-receiver model of sound propagation, the received SPL at some receiver position is equal to the source level minus the transmission loss along the propagation path between the source and the receiver (Richardson *et al*. 2005, p. 16). SPLs from a given noise source can be computed by combining acoustic source level measurements with transmission loss estimates. This is the method of modelling underwater sound propagation that has been applied in the present study.

8.2.3 1/3-Octave Band Analysis

The discussion of noise measurement presented thus far has not addressed the issue of frequency dependence. The distribution of noise power with frequency is described by the power spectrum (or power spectral density *S*(*f*)). The spectrum describes the fine scale features of the frequency distribution of a noise source. However, a coarser representation of the noise power distribution is often better suited to quantitative analysis. Frequency-band analysis divides the power spectrum into discrete pass-bands. The most common frequency band analysis scheme used in the field of acoustics is 1/3-octave (*i.e.*, "third"-octave) band analysis. This method is so called because it divides the power spectrum into adjacent pass-bands which are each one-third of an octave wide (where an octave corresponds to a doubling of frequency). Figure 8-1 shows an example of a noise power spectrum and the corresponding 1/3-octave band levels.

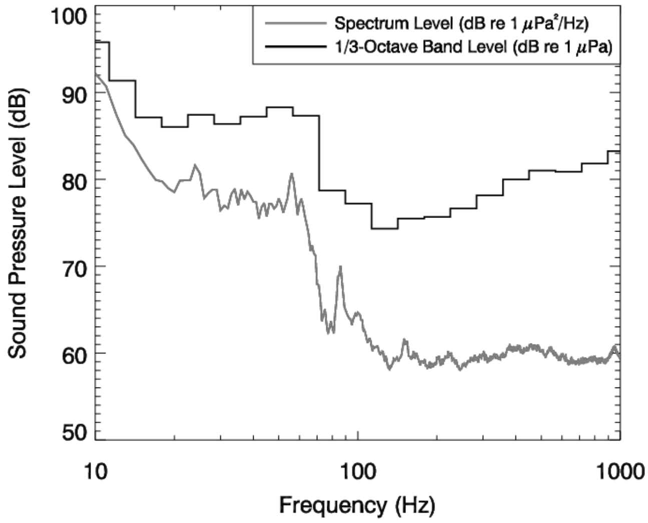


Figure 8-1 Plot of a Typical Ambient Noise Power Spectrum (grey line) and the Corresponding 1/3-octave Band Levels (black line). Note that Frequency is Plotted on a Log Scale and so the 1/3-octave Bands are Wider at Higher Frequencies.

The process of band-pass filtering sums all of the sound power outside of a narrowly defined frequency range (*i.e.*, inside the pass-band). These pass-bands do not overlap.

Table 8-1 lists the standard 1/3-octave band center frequencies. Note that the width of each 1/3-octave band is approximately 23% of the band center frequency. Standard center frequencies for 1/3-octave pass bands (in units of Hz) are given by the following formula:

$$f_c = 10^i / 10 \qquad i = 1, 2, 3... \qquad \textbf{Eq. 7}$$

where *i* is the band number (ISO 266-1975E). The low and high band limits, f_{lo} and f_{hi}, are equal to 89.1% (=$2^{-1/6}$) and 112.2% (=$2^{1/6}$) of the band center frequency, respectively.

Table 8-1 List of standard 1/3-octave band centre frequencies from 1 Hz to 8 kHz.

Band Centre Frequency f_c (Hz)			
1.0	10	100	1000
1.3	12.5	125	1250
1.6	16	160	1600
2.0	20	200	2000
2.5	25	250	2500
3.2	31.5	315	3150
4.0	40	400	4000
5.0	50	500	5000
6.3	63	630	6300
8.0	80	800	8000

The integral of the spectral power density inside a 1/3-octave band gives the fraction of the total sound pressure level contained within that 1/3-octave band. This is called the band pressure level (BPL). The BPL in the i^{th} 1/3-octave band (symbol $L_b^{(i)}$) may be computed from the power spectrum according to the following formula:

$$L_b^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right)$$ **Eq. 8**

where $S(f)$ is the spectral power density (units of $\mu Pa^2/Hz$) and f is frequency. Noise is customarily analyzed using several parallel 1/3-octave bands covering the frequency range of interest. The spectral power density is normally computed via a Discrete Fourier Transform (DFT) of a recorded pressure time series.

Propagation of sound is often modelled in 1/3-octave bands as well. Band pressure levels possess the convenient property that, when the power in all n 1/3-octave bands is summed together, it equals the total SPL of the broadband signal:

$$L_P = 10\log_{10}\sum_n 10^{L_b^{(i)}/10}$$ **Eq. 9**

The summing is performed in power units rather than decibel units, therefore, $10^{L/10}$ is used to convert decibels to power. The advantage of 1/3-octave band modelling is that it can resolve the frequency dependent propagation characteristics of a particular environment and still be used to efficiently compute the overall sound pressure level for any receiver position.

8.3 EFFECTS THRESHOLDS

The potential impact of anthropogenic (man-made) noise on a marine animal depends on the level of noise exposure. At moderate exposure levels, underwater noise may cause an overt change in the behaviour of a marine animal. At high exposure levels, underwater noise can induce a reduction in hearing sensitivity or even physical injury. The impact of noise exposure generally depends on a number of factors relating to the physical and spectral characteristics of the sound (*e.g.*, the intensity, peak pressure, frequency, duration, duty cycle), and relating to the animal under consideration (*e.g.*, hearing sensitivity, age, gender, behavioural status, prior exposures). The type and level of the impact also depends on whether the noise consists of single-pulse, multiple-pulse or non-pulsed sounds (Southall *et al.*, 2007). Common behavioural responses to anthropogenic noise exposure include startle or avoidance. At higher exposure levels, noise can induce temporary or permanent changes in an animal's hearing sensitivity. This reduction in hearing sensitivity is referred to as temporary threshold shift (TTS) or permanent threshold shift (PTS), depending on whether hearing sensitivity recovers after the exposure. At extreme intensity levels, exposure to certain kinds of noise (*e.g.*, pile driving or explosives) can cause physical trauma or death. For assessment purposes, effect threshold criteria may be used to establish zones of impact around marine noise sources. This study has taken each of the impact criteria described in the following text into consideration.

8.3.1 Marine Mammals and M-weighting

For pulsed noise, broadband received SPLs of 180 dB re 1 µPa (*rms*) and 190 dB re 1 µPa (*rms*) have previously been applied by the U.S. National Marine Fisheries Service as the "Level A Harassment" (potentially injurious) threshold levels, for cetaceans (*i.e.*, whales, dolphins and porpoises) and pinnipeds[1] (*i.e.*, walruses, seals and sea-lions) respectively (NMFS 2003). In addition, a 160 dB re 1 µPa (*rms*) level has commonly been accepted as the "Level B Harassment" (potential disturbance) behavioural threshold level for marine mammals based on observations of responses of baleen whales to seismic airgun sounds (Malme *et al*. 1983, 1984; Richardson *et al*. 1986). No specific underwater noise guidelines have been defined by the Department of Fisheries and Oceans Canada; however these U.S. standards have been applied to previous studies carried out in Canadian waters.

Recently, new science-based behavioural and injury criteria for pulsed noise have been proposed by a group of experts in bioacoustic research (Southall *et al*. 2007) based on a review of the most up-to-date published data on the effects of noise on marine mammals. The proposed new injury threshold criteria for pulsed noise are M-weighted received sound levels of 198 dB re 1 $\mu Pa^2 \cdot s$ (SEL) for cetaceans and 186 dB re 1 $\mu Pa^2 \cdot s$ (SEL) for pinnipeds. M-weighted levels are computed from frequency weighted noise levels, filtered in a manner reflective of the hearing bandwidth of specific species groups, namely low,

[1] Although the Level A *rms* SPL harassment threshold given here is higher for pinnipeds (190 dB) than for cetaceans (180 dB), current evidence indicates that pinnipeds would be injured at lower impulse noise thresholds than cetaceans (Southall *et al.* 2007). Therefore we recommend that the 190 dB *rms* SPL threshold not be used to estimate impulse noise impacts on pinnipeds.

mid, or high-frequency listening cetaceans and pinnipeds (see below). In addition, flat-weighted peak sound pressure levels of 230 dB re 1 µPa for cetaceans or 218 dB re 1 µPa for pinnipeds are also indicated as injury criteria thresholds for pulsed noise. A dual-criterion approach is suggested, where as soon as either the SPL (peak) or the SEL threshold is reached, injury is assumed possible. The proposed new behavioural threshold criteria for pulsed noise are received levels of 183 dB re 1 μPa^2 s (SEL, M-weighted) and 224 dB re 1 µPa (peak) for cetaceans and 171 dB re 1 μPa^2 s (SEL, M-weighted) and 212 dB re 1 µPa (peak) for pinnipeds.

The Southall *et al*. impact criteria for non-pulse (continuous) noise are different from those for pulsed noise events. Southall *et al*. (2007) recommend continuous noise injury threshold criteria of 230 dB re 1 µPa (peak) and 215 dB re 1 μPa^2 s (SEL) for cetaceans; for pinnipeds they recommend criteria of 218 dB re 1 µPa (peak) and 203 dB re 1 μPa^2 s (SEL). Observations of behavioural responses to non-pulsed noise have been documented for a range of received level conditions. Southall *et al.* (2007) conclude that low-frequency cetaceans (*i.e.*, mysticetes) may exhibit behavioural responses to *rms* received levels in the range of 120-160 dB re 1 µPa, while mid- and high-frequency listening cetaceans (*i.e.*, odontocetes) may exhibit behavioural responses at *rms* received levels as low as 90 dB re 1 µPa.

For non-injurious sound levels, frequency weighting curves may be applied to emphasize the importance of sound at particular frequencies where the receiver's hearing is most sensitive. This approach is almost always employed when assessing impact of noise on humans; two common weighting schemes used for humans are A-weighting (for continuous noise) and C-weighting (for impulsive noise). A similar approach has been devised by a NMFS-sponsored Noise Criteria Committee for use with marine mammal species (Gentry *et al*. 2004). This weighting scheme, referred to as M-weighting, proposes five weighting curves for different classes of marine mammals: low frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans, pinnipeds in water and pinnipeds in air. The five M-weighting curves are plotted in Figure 8-2. M-weighting de-emphasizes frequencies outside the functional bandwidth of marine mammals. M-weighting is only used for injury thresholds and not for acoustic detection or behavioural response thresholds. Injury thresholds do not (directly) relate to the absolute hearing sensitivity (audiogram) of the target species. Therefore, M-weighting does not scale SEL within the functional bandwidth. In the following figure, the weighting factors within the functional bandwidths are 0, independent of the target species, even though these animals would have quite different absolute hearing thresholds. The M-weighting curves are conservatively wide, in order to be precautionary.

For pulsed noise, M-weighting for low-frequency cetaceans, mid-frequency cetaceans and pinnipeds in water was applied to model results for the present study. M-weighting was applied to the 1/3-octave band sound level predictions from MONM prior to summing these band levels in order to compute M-weighted broadband levels.

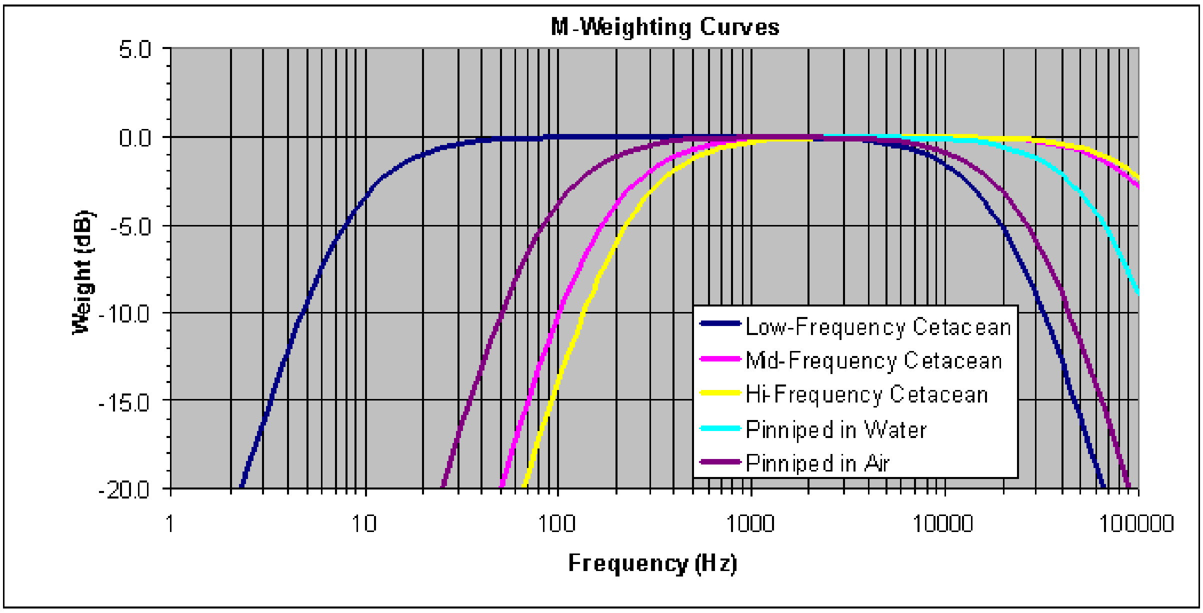


Figure 8-2 M-weighting curves for cetaceans and pinnipeds.

8.3.2 Fish and Invertebrates

Fisheries and Oceans Canada (DFO) and BC Marine and Pile Driving Contractors Association have established “best practices” guidelines for mitigating the effects of underwater noise emissions from pile driving on fish (BC Marine and Pile Driving Contractors Association, 2003). The guidelines state that any pile driving activity that generates peak SPLs in excess of 30 kPa (~210 dB re 1 µPa), or that causes a fish kill, must employ sound mitigation (such as a bubble curtain) in order to reduce sound levels to an acceptable level. The guidelines do not specify the measurement distance at which the 30 kPa threshold should be applied. During the 2007 pile driving for the NaiKun meteorological mast substructure, DFO recommended that the 30 kPa threshold criterion be applied at 10 m range from the piling (Racca *et al*., 2007). The available scientific evidence suggests that SEL should be used in addition to peak pressure in evaluating the cumulative effects of pulsed noise exposure on fish.

An interim set of science-based fish injury criteria for pile driving have recently been proposed by a group of bioacoustics experts in the U.S. (Popper *et al*. 2006, Carlson *et al*. 2007). These criteria were based on a review of the available scientific data regarding the effects of impulse noise on fish. The authors considered data for both auditory and non-auditory injuries to fish. Based on the experts' recommendations, a working group representing several U.S. state and federal agencies (NOAA, U.S. Fish and Wildlife Service, California/Washington/Oregon Departments of Transportation, California

Department of Fish and Game, and U.S. Federal Highway Administration) adopted the following threshold criteria for injuries to fish species of concern (*i.e.*, “listed” species):

> “*The agreed upon criteria identify sound pressure levels of 206 dB [re 1 µPa] peak and 187 dB [re 1 µPa^{2}s] accumulated sound exposure level (SEL) for all listed fish except those that are less than 2 grams. In that case, the criteria for the accumulated SEL will be 183 dB [re 1 µPa^{2}s].*” (Fisheries Hydroacoustic Working Group 2008)

At present, these criteria are believed to be the only science-based piling noise injury criteria for fish. No equivalent behavioural criteria exist for fish exposed to piling noise. Species at risk in the United States are listed by the Endangered Species Act (ESA) while species at risk in Canada are listed by the Species At Risk Act (SARA). There are no SARA listed species that will be encountered in the project area.

There is insufficient knowledge at this time to establish any equivalent pile driving injury thresholds for invertebrates. However, it is believed that invertebrates are less susceptible to injury from impulse noise than fish, primarily due to their lack of a swim bladder. Therefore, any mitigation which is undertaken to limit the effects of piling noise on fish is expected to be more than sufficient for mitigating injuries to invertebrates as well. No accepted threshold criteria are available to evaluate the effects of non-pulsed (continuous) noise on fish or invertebrates at this time. It is believed that noise levels generated by vessel-based activities and wind turbine operations are insufficient to induce injury in fish or invertebrates. Behavioural reactions to noise, if they exist, are expected to be species dependent. However, there are insufficient data available at this time to determine behavioural reactions of fish or invertebrates to continuous or impulsive noise.

8.3.3 Marine Birds

The only available data related to the effects of impulsive underwater noise on marine birds was published by Yelverton *et al.* (1973). The authors reported results from experiments designed to test the effects of high explosive shock-waves on submerged birds. From the experiments they determined that injury and mortality were most strongly correlated with impulse. From their data, the authors also developed the following mortality and injury criteria for birds:

- 50% mortality at Φ = 310 Pa·s
- Slight injuries only at Φ = 138 Pa·s
- No injuries at Φ = 41 Pa·s

When applied to pile driving, these criteria are expected to be highly precautionary since these mortality and injury criteria were derived for high explosives. This is because the onset of the shock pulse generated by high explosives is much more rapid than the shock pulse generated by impact hammer pile driving.

8.4 UNDERWATER MODELLING METHODS

8.4.1 MONM Model Description

Sound propagation modelling for wind farm construction and operation activities was performed to evaluate the extent of the area of potential impact using JASCO Applied Sciences' proprietary Marine Operations Noise Model (MONM). MONM computes acoustic propagation for arbitrary three-dimensional (3-D), range-varying acoustic environments via a wide-angled parabolic equation solution to the acoustic wave equation. The parabolic equation code in MONM is based on the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been extensively benchmarked for accuracy and is widely employed in the underwater acoustics community (Collins, 1993). MONM computes acoustic fields in 3-D by modelling transmission loss along evenly spaced radial traverses covering a 360 º swath from the source (so-called N×2-D modelling). MONM makes use of several types of environmental data including bathymetry, sound speed profiles, and geoacoustic profiles. The spatial sampling of the acoustic environment along model traverses used a 50 m range step. Frequency dependence of the sound propagation characteristics was treated by computing acoustic transmission loss at the center frequencies of all 1/3-octave bands between 10 Hz and 5 kHz. Received sound pressure levels in each band were computed by applying frequency-dependent transmission losses to the corresponding 1/3-octave band source levels. This approach has been validated against experimental data and has proven to be highly accurate for predicting noise levels in the vicinity of industrial operations (Hannay and Racca, 2005).

Sound level predictions from MONM were converted to noise contour maps, showing the estimated acoustic footprint for each operation. In order to be precautionary, the contours were based on the maximum sound level computed by MONM over all depths. Noise contours were converted to GIS layers for rendering on thematic maps. The contours were also analyzed to determine the 95 percentile radius for each noise threshold level. Given a regularly gridded spatial distribution of modeled received levels, the 95 percentile radius is defined as the radius of a circle that encompasses 95% of the grid points whose value is equal to or greater than the threshold value. This definition is meaningful in terms of impact because, regardless of the geometrical shape of the noise footprint for a given threshold level, it always provides a range beyond which no more than 5% of a uniformly distributed population would be exposed to sound at or above that level. Note that for scenarios involving spreads of vessels the center of this circle was taken to be the geometric centroid of the vessel positions. Tables of 95th percentile threshold ranges were computed for all wind farm construction and operation model scenarios (see Section 8.4.3).

8.4.2 Acoustic Environment

8.4.2.1 Sound Speed Profiles

MONM samples the vertical sound speed profile of the water column along each radial traverse extending from the sound source. Sound speed data used for this modelling study were obtained from the

Generalized Digital Environmental Model Variable Resolution (GDEM - V) database published by the U.S. Naval Oceanographic Office, which contains globally gridded ocean temperature and salinity data for each month of the year. The database has specialized extraction routines that use this information to compute sound speeds to various depths for the user-specified month and geographic location (Naval Oceanographic Office 2003). For this study, sound speeds were computed using GDEM - V for the month of July at a location within the wind farm grid (Lat = 53.9°, Lon = -131.6°). The profile chose for July is representative of summer conditions in Hecate Strait, which is the time period during which the construction activities will occur. Figure 8-3 shows the speed of sound as a function of depth. The solid line in this plot represents sound speed data obtained from GDEM - V directly, while the dashed line represents sound speeds extrapolated to greater depths using GDEM – V data from an adjacent database location (Lat = 52.4°, Lon = -130.3°). Th is extrapolation procedure was necessary to obtain sound speeds over the full range of depths for the area of interest as GDEM – V data at the wind farm grid did not extend beyond 120 m depth. The profile shown in Figure 8-3 is typical for summer months in Hecate Strait: sound speed decreases rapidly in shallow water (*i.e.*, for depths < 100 m) and becomes approximately constant in deeper water.

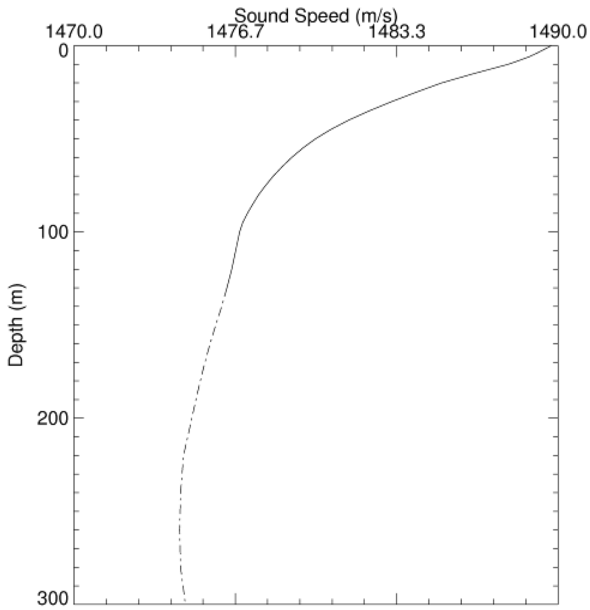


Figure 8-3 Average Monthly Sound Speed in Water Plotted as a Function of Fepth at the WFG for July.

8.4.2.2 **Geoacoustics**

Underwater sound propagation is strongly influenced by the geoacoustic parameters of the seabed, which include the density, seismic P-wave and S-wave speeds, and the seismic wave-attenuation of seabed materials. MONM takes each of these parameters into account when calculating propagation loss. For this study, ocean-bottom geology varies over the project site (MacGillivray 2006a), and therefore, geoacoustic profile parameters were determined for three locations: within the wind farm grid, along the transmission cable corridor in Hecate Strait and along the transmission cable corridor in Chatham Sound.

At the wind farm grid, the seabed is characterized by a layer of sandy sediment overlying consolidated tertiary sediments (Barrie *et al*. 1990). Based on MacGillivray's (2006a) modelling work in this area, the geology was parameterized for this study as a layer of sand overlying a bedrock of consolidated tertiary sediments. The thickness of the surface sand layer was increased from MacGillivray's (2006a) 5 m to 20 m, based on local information provided by NaiKun Wind Development Inc. (Zykov *et al*. 2007). The geoacoustic properties of these materials, *i.e.*, compressional speed (c_p), density (ρ), P-attenuation (α_p), shear speed (c_s) and S-attenuation (α_s), vary with depth (z) and are summarized in Table 8-2.

Table 8-3 and Table 8-4 summarize the modelled geoacoustic profile parameters for the seabed along the transmission cable corridor running through Hecate Strait and Chatham Sound respectively. Along the corridor in Hecate Strait, the seabed consists of a layer of glacial till deposited on top of consolidated tertiary sediments, so bottom parameters for till and bedrock were used for modelling in this region. Similarly, the ocean-bottom in Chatham Sound is characterized by a layer of glacial till overlying granite rock (MacGillivray 2006a) and was parameterized as till and granite for sound level calculations.

Table 8-2 Geoacoustic Profile Parameters used for Modelling the Seabed within the WFG

Material	z (m)	c_P (m/s)	ρ (g/cm3)	α_P (dB/λ)	c_S (m/s)	α_S (dB/λ)
Sand	0	1700	1.90	0.40	150	4.0
	3	1740	1.90	0.40		
	5	1760	1.95	0.45		
	20	1800	1.95	0.45		
Bedrock	20	2200	2.30	0.10		
	100	2300	2.40	0.10		
	200	2450	2.50	0.10		
	>200	2450	2.50	0.10		

Table 8-3 Geoacoustic Profile Parameters used for Modelling the Seabed along the Transmission Cable Corridor in Hecate Strait.

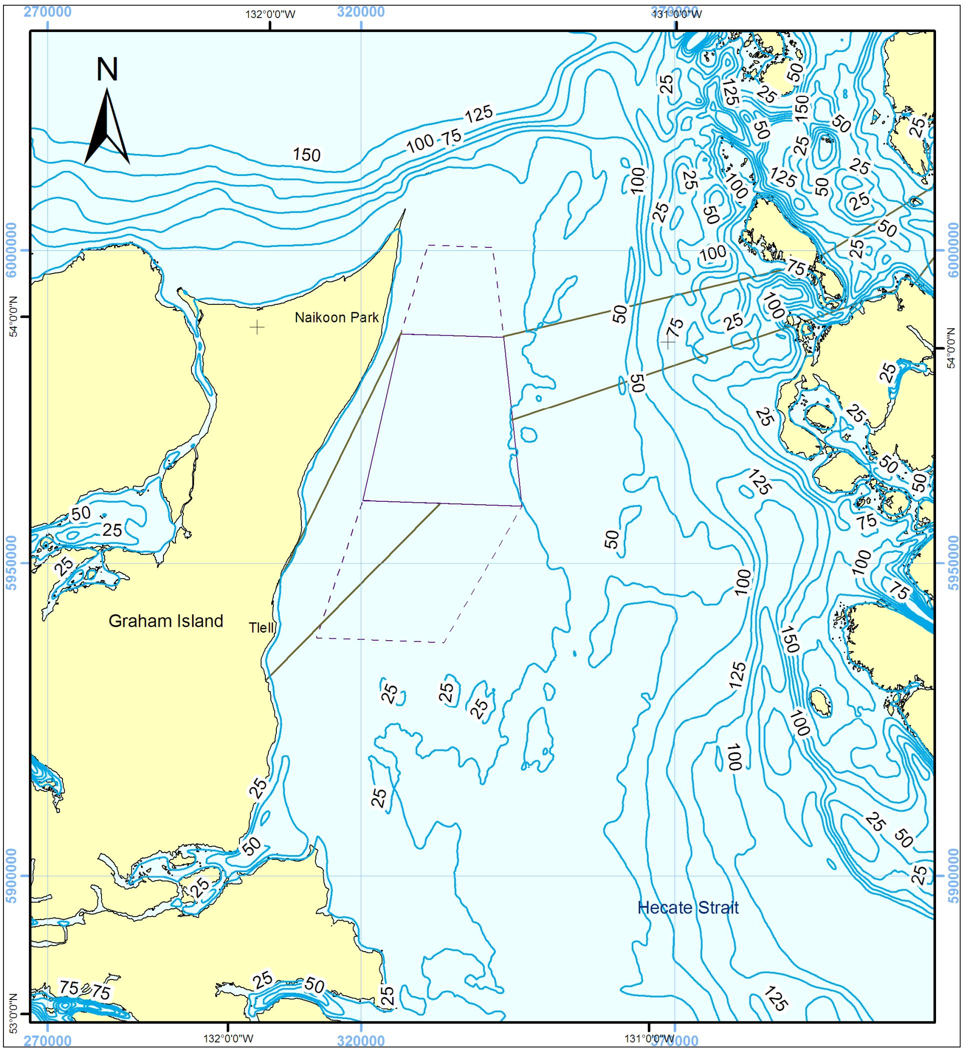
Material	z (m)	c_p (m/s)	ρ (g/cm^3)	α_P (dB/λ)	c_S (m/s)	α_S (dB/λ)
Till	0	1604	1.77	0.16	378	1.81
	5	1610	1.77	0.16		
	10	1616	1.77	0.16		
	12	1619	1.77	0.16		
	15	1622	1.77	0.16		
Bedrock	15	2200	2.20	0.10		
	500	2797	2.20	0.10		

Table 8-4 Geoacoustic profile parameters used for modelling the seabed along the transmission cable corridor in Chatham Sound.

Material	z (m)	c_p (m/s)	ρ (g/cm^3)	α_P (dB/λ)	c_S (m/s)	α_S (dB/λ)
Till	0	1604	1.77	0.16	378	1.81
	3	1608	1.77	0.16		
	5	1610	1.77	0.16		
Granite	5	5500	2.60	0.05		
	500	6109	2.60	0.05		

8.4.2.3 **Bathymetry**

At each grid step in the modelling process, MONM samples the depth of the ocean bottom from gridded bathymetry files for the model area. For this study, high-resolution digital point bathymetry data were obtained from digital charts provided by the Canadian Hydrographic Service for Dixon Entrance, Hecate Strait and Queen Charlotte Sound. The original data, which cover the entire Queen Charlotte Basin, were converted from latitude/longitude coordinates into UTM coordinates and resampled onto a constant 100 m × 100 m grid using bilinear interpolation. This grid was then used to determine depth points along each modelling radial. Figure 8-4 shows a contour map of the digital bathymetry data that was used for Hecate Strait.



Projection: UTM ZONE 9 Datum: NAD83
1:800,000

0 10 20 40 km

December 16 2008

Cable IUP Boundary

Windfarm IUP Boundary

Control Area Boundary

Bathymetry contours indicate water depth in metres

HECATE STRAIT BATHYMETRY

JASCO RESEARCH LTD

NAIKUN WIND DEVELOPMENT

Figure 8-4 Bathymetry Map of Hecate Strait.

8.4.3 Model Scenarios

Table 8-5 provides a summary of the construction and operations scenarios that were modelled in order to provide a precautionary estimate of the noise footprint from the project activities of greatest concern. The scenarios considered were based on descriptions of the expected construction and operations activities outlined in the project description (Baird 2008). Table 8-5 summarizes the activities accounted for by each scenario, as well as each scenario's location. The subsections that follow provide more detailed information about the parameters used to model the noise sources associated with each activity. Source level measurements were unavailable for the vessels and equipment listed in the Project Description at the time of writing. Therefore, a literature review was conducted in order to identify source level measurements from similar equipment performing similar operations. Source levels for these proxy noise sources were used as model input parameters. Appendix 8-1 provides modelled 1/3-octave band source levels for the vessels employed in each of the model scenarios.

Table 8-5 Construction and Operations Activities Accounted for by each Model Scenario, as well as each Scenario Location.

No.	Name	Location
1	Positioning of WTG Installation Vessels	Wind Farm Grid
2A	Tripod/Lattice Impact Pile Driving Without Mitigation	Wind Farm Grid
2B	Monopile Impact Pile Driving Without Mitigation	
3A	Tripod/Lattice Impact Pile Driving With Mitigation	Wind Farm Grid
3B	Monopile Impact Pile Driving With Mitigation	
4A	Tripod/Lattice Vibro-hammer Pile Driving	Wind Farm Grid
4B	Monopile Vibro-hammer Pile Driving	
5	Transport of WTG and Substructure to Wind Farm Grid	Transmission Cable Corridor in Hecate Strait
6	Installation of WTG and Substructure	Wind Farm Grid
7	Subsea Cable-Lay in Chatham Sound	Transmission Cable Corridor in Chatham Sound
8	Subsea Cable-Lay in North Central Hecate Strait	Transmission Cable Corridor in Hecate Strait
9	Cable Pull into WTG Substructures	Wind Farm Grid
10	Transport of Converter Platform to Wind Farm Grid	Transmission Cable Corridor in Hecate Strait
11	Converter Platform Installation	Wind Farm Grid
12	Scour Protection Placement	Wind Farm Grid
13	Rock Dumping at Cable/Pipeline Crossing	Transmission Cable Corridor in Chatham Sound
14	Turbine Operations	Wind Farm Grid
15	Turbine Maintenance	Wind Farm Grid

8.4.3.1 Construction

Scenario 1 - Positioning of WTG Installation Vessels:

This scenario accounts for noise produced at the wind farm grid by positioning of the jack-up barge used for WTG installations, as well as positioning of installation crane vessels used for WTG substructure installations, piling, levelling and grouting. These activities involved two anchor handling tugs positioning a 100 m x 100 m square barge, and one support vessel and one supply vessel, both on standby. Table 8-6 summarizes the engine power, length, draft, source coordinates, activity, proxy source and broadband source level of each noise source included in scenario 1. Measured 1/3-octave band acoustic source levels for the Britoil 51 (Hannay *et al*. 2004), an anchor handling tug, were used to model the anchor handling tugs. Sound produced by the support and supply vessels on standby were modelled using 1/3-octave band source levels for a dynamic positioning dive support vessel, the Fu Lai (MacGillivray 2006b). The engine power of the Fu Lai is twice the engine power of the proposed support/supply vessels, so 3 dB was subtracted from the source levels to account for noise reduction due to engine power differences (a doubling in power or intensity corresponds to an increase in intensity level by 3 dB).

Table 8-6 Scenario 1 Noise Source Specifications, including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description[3]	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1 μPa·m)
Support Vessel	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	339406, 5981101	Stand-by	Fu Lai[1]	174.9 dB
Supply Vessel	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	338830, 5980939	Stand-by	Fu Lai[1]	174.9 dB
Anchor Handling Tug 1	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339210, 5981162	Anchor Handling	Britoil 51[2]	193.2 dB
Anchor Handling Tug 2	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339024, 5980876	Anchor Handling	Britoil 51[2]	193.2 dB

[1] MacGillivray 2006b
[2] Hannay *et al*. 2004
[3] Note that the abbreviation "bhp" indicates brake horsepower

Scenario 2A – Tripod/Lattice Impact Pile Driving Without Mitigation:

Scenario 2A accounts for noise produced by impact hammer pile driving of a single support pile for the tripod (three piles) and lattice (four piles) WTG foundation options with no noise mitigation. At each site, it is expected that the piles will be driven sequentially, not simultaneously. The pile diameters for the lattice and tripod foundations are anticipated to be 2 m and 3 m respectively. For the modelling we have considered the most conservative case: a single source corresponding to a 550 kJ hydraulic pile driving hammer, driving a 3 m diameter hollow steel pile into the substrate. Table 8-7 summarizes the pile driving energy, pile diameter and location of the noise source that was assumed for this model scenario.

Tripod/lattice impact hammer pile driving was modelled using adjusted 1/3-octave band pile driving source levels from measurements of the 2001 San-Francisco Oakland Bay Bridge pile installation demonstration project (PIDP) (Caltrans 2001). These levels were back-propagated to the standard reference distance of 1 m from the source and converted from SPL to SEL before modelling. In addition, source levels were lowered by 2.6 dB in order to account for the decreased expected hammer energy (550 kJ versus 1000 kJ) that would potentially be needed for driving 3 m diameter piles within the wind farm. This 2.6 dB adjustment was derived based on the reasonable assumption that pulse energy from pile driving is linearly proportional to the ram energy used to hammer the pile (*i.e.*, the decibel adjustment was 10 $\log_{10}$(550 kJ / 1000 kJ)). The repetition rate of the pile driving pulses is expected to be approximately 30 blows/minute and the total time for driving a single pile is approximately 2 hours.

Impact hammer pile driving generates pulsed noise, as opposed to non-pulsed noise and so noise from this source was modelled in terms of single-impulse SEL (total pulse energy) rather than *rms* SPL (*rms* pulse amplitude). SEL (symbolized L_E) can be related to 90% *rms* SPL (symbolized L_{P90}) by using the following equation:

$$L_E = L_{P90} + 10\log_{10}(T_{90}) + 0.458 \qquad \text{Eq. 10}$$

where the last term accounts for the fact that only 90% of the total SEL is delivered over the standard pulse period. Assuming a pulse duration of approximately 100 msec, the *rms* SPL is thus 10 dB greater than the modelled single-impulse SEL.

Peak pressure levels and impulse were also estimated for this scenario based on the PIDP measurements. Free-field time-domain source pressure waveforms for pile driving were not available and so peak pressures could not be modelled directly using MONM. Instead, decay of the peak levels and impulse with range were estimated assuming geometrical spreading of sound pressure from the pile. The geometrical decay was calibrated against peak sound pressure levels and impulse measured at 100 m range from the PIDP pile driving data (Caltrans 2001). As with the 1/3-octave band levels, these levels were reduced by 2.6 dB to account for the expected decrease in pile driving energy. Geometrical spreading is expected to be a good approximation to actual peak pressure decay at short ranges where high peak and impulse levels are encountered.

Table 8-7 Scenario 2A Noise Source Specifications, Including Pile Driving Ram Energy, Pile Diameter, Source Location and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL
Hydraulic Pile Driving Hammer	Energy = 550 kJ Pile Diameter = 2-3 m	339116, 5981018	Impact Hammering	1000 kJ Impact hammer[1] (-2.6 dB)	SEL=215.3 dB//1µPa^2 s@1m Peak SPL=244.7 dB//1µPa@1m Impulse=1891 Pa·s@1m

[1] Caltrans 2001

Scenario 2B – Monopile Impact Pile Driving Without Mitigation:

Scenario 2B accounts for noise produced by impact hammer pile driving of a monopile wind turbine foundation with no noise mitigation. The pile diameter for the monopile foundation is anticipated to be 4.5-5 m. For the modelling we have considered the most conservative case: a single source corresponding to a 1200 kJ hydraulic pile driving hammer, driving a 5 m diameter hollow steel pile into the substrate. The repetition rate of the pile driving pulses is expected to be approximately 30 blows/minute and the total time for driving a single pile is approximately 2 hours. The pile driving energy, pile diameter and location of the noise source that was assumed for this model scenario are summarized in Table 8-8.

Monopile impact hammer pile driving 1/3-octave band source levels, as well as peak and impulse levels, were estimated using the PIDP measurements (Caltrans 2001) as described above for the tripod/lattice foundations in Scenario 2A. However, for the monopile foundations considered here, the PIDP source levels were increased by 0.8 dB (instead of decreased by 2.6 dB) to account for the increased expected hammer energy (1200 kJ versus 1000 kJ) that would potentially be needed for driving 4.5-5.0 m monopiles within the wind farm.

Table 8-8 Noise Source Specifications, Including Pile Driving Ram Energy, Pile Diameter, Source Location and Broadband Source Level (SL), for Scenario 2B.

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL
Hydraulic Pile Driving Hammer	Energy = 1200 kJ Pile Diameter = 4.5-5 m	339116, 5981018	Impact Hammering	1000 kJ Impact hammer[1] (+0.8 dB)	SEL=218.7 dB//1µPa^2 s@1m Peak SPL=248.0 dB//1µPa@1m Impulse=2793 Pa·s@1m

[1] Caltrans 2001

Scenario 3A – Tripod/Lattice Impact Pile Driving With Mitigation:

Scenario 3A accounts for noise produced by impact hammering of a single support pile for the tripod (three piles) and lattice (four piles) WTG substructure options with additional noise mitigation. This scenario assumes a 10 dB reduction in the overall sound levels from scenario 2A due to acoustic attenuation from a bubble curtain, pile sheath or similar sound barrier mitigation method around the pile (see Section 9.4.1 for a discussion of pile driving noise mitigation options). The 10 dB reduction in sound levels was selected as a precautionary estimate of the sound barrier noise attenuation, based on measurements of bubble curtain effectiveness from the 2007 meteorological-mast pile driving study at the wind farm site (Racca *et al*. 2007). Table 8-9 summarizes the pile driving energy, pile diameter and location of the noise source that was assumed for this model scenario. As with scenario 2A, noise from this source was modelled in terms of SEL rather than SPL. SEL model results for this scenario were converted to *rms* SPL over the pulse duration by adding 10 dB, which corresponds to ~100 msec pulse length for the pile driving. The repetition rate (~30 blows/min) and total piling duration (~2 hours) are the same for the mitigated and unmitigated piling. Peak sound pressure levels and impulse were also estimated for this scenario based on the same geometrical spreading methodology as was used for scenario 2A.

Table 8-9 Scenario 3A Noise Source Specifications, Including Pile Driving Energy, Pile Diameter, Source Location and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL
Hydraulic Pile Driving Hammer with Noise Mitigation	Energy = 550 kJ Pile Diameter = 2-3 m	339116, 5981018	Impact Hammering	1000 kJ Impact hammer[1] (-2.6 dB)	SEL=205.3 dB//µPa^2 s@1m Peak SPL=234.7 dB//µPa@1m Impulse=598 Pa·s@1m

[1] Caltrans 2001

Scenario 3B – Monopile Impact Pile Driving With Mitigation:

Scenario 3B accounts for noise produced by impact hammering of a monopile WTG foundation with additional sound barrier noise mitigation. This scenario assumes a 10 dB reduction in the overall sound levels from scenario 2B due to acoustic attenuation from sound barrier mitigation around the pile. The pile driving energy, pile diameter, and location of the noise source that was assumed for this model scenario are summarized in Table 8-10. The repetition rate (~30 blows/min) and total piling duration (~2 hours) are the same for the mitigated and unmitigated piling. Peak sound pressure levels and impulse were also estimated for this scenario based on the same geometrical spreading methodology as was used for scenario 2B.

Table 8-10 Noise Source Specifications, Including Pile Driving Energy, Pile Diameter, Source Location and Broadband Source Level (SL) for Scenario 3B.

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL
Hydraulic Pile Driving Hammer with Noise Mitigation	Energy = 1200 kJ Pile Diameter = 4.5-5 m	339116, 5981018	Impact Hammering	1000 kJ Impact hammer[1] (+0.8 dB)	SEL=208.7 dB//1µPa^2 s@1m Peak SPL=238.0 dB//1µPa@1m Impulse=883 Pa·s@1m

[1] Caltrans 2001

<u>Scenario 4A – Tripod/Lattice Vibro-hammer Pile Driving</u>:

Scenario 4A accounts for noise produced by vibro-hammering of the support piles for the tripod (three piles) and lattice (four piles) WTG substructure options. No sound barrier mitigation was assumed for this scenario. The scenario consisted of a single source corresponding to vibratory driving of a 2-3 m diameter hollow steel pile into the substrate. Vibro-hammering was modelled using adjusted 1/3-octave band vibro-hammering source levels from measurements of the 2007 meteorological-mast pile driving at the WFG site (Racca *et al*. 2007). The proxy source levels were for an APE 300 vibro-hammer with 1842 kN centrifugal force driving a 0.9 m diameter pile. These source levels were increased by 5.2 dB in order to account for the increased force necessary for driving larger diameter piles. Table 8-11 summarizes the pile diameter and location of the noise source that was assumed for this model scenario. Note that vibro-hammering is a non-pulsed (*i.e.*, continuous) noise source.

Table 8-11 Scenario 4A noise source specifications, including pile diameter, source location and source level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Vibratory Hammer	Pile Diameter = 2-3 m	339116, 5981018	Vibro Hammering	APE 300 Vibro hammer[1]	192.1 dB

[1] Racca *et al*. 2007

<u>Scenario 4B – Monopile Vibro-hammer Pile Driving</u>:

Scenario 4B accounts for noise produced by vibro-hammering of a monopile WTG foundation with no noise mitigation. The scenario consisted of a single source corresponding to vibratory driving of a 4.5-5.0 m diameter hollow steel pile into the substrate. Vibro-hammering was modelled using adjusted 1/3-octave band vibro-hammering source levels from measurements of the 2007 meteorological-mast pile driving at the WFG site (Racca *et al*. 2007). The proxy source levels were for an APE 300 vibro-hammer with 1842 kN centrifugal force driving a 0.9 m diameter pile. These source levels were increased by 7.4 dB for scenario 4B in order to account for the increased force necessary for driving larger diameter piles. Table 8-12 summarizes the pile diameter and location of the noise source that was assumed for this model scenario. Note that vibro-hammering is a non-pulsed (*i.e.*, continuous) noise source.

Table 8-12 Noise Source Specifications, Including Pile Diameter, Source Location And Source Level (SL) for Scenario 4B.

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Vibratory Hammer	Pile Diameter = 4.5-5 m	339116, 5981018	Vibro Hammering	APE 300 Vibro hammer[1]	194.4 dB

[1] Racca *et al*. 2007

Scenario 5 - Transport of WTG and Substructure to Wind Farm Grid:

This scenario accounts for noise produced by a heavy lift transport vessel transiting across Hecate Strait during delivery of WTGs, towers, and substructures to the installation site. Measurements of the Overseas Harriet (Arveson *et al*. 2000), a cargo vessel, travelling at 12 kt provided a suitable proxy source for these activities. Therefore, 1/3-octave band acoustic source levels for this vessel were used as model input parameters. Table 8-13 summarizes the engine power, length, draft, UTM source location, activity, proxy source and broadband SL for this noise source.

Table 8-13 Scenario 5 Noise Source Specification Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Heavy Lift Transport Vessel	Propulsion Power = 11586 hp, Thruster Power = 6169 hp, Length = 144.2 m, Draft = 7.5 m	366271, 5986776	Transiting	Overseas Harriette[1]	183.6 dB

[1] Arveson *et al*. 2000

Scenario 6 - Installation of WTG and Substructure:

This scenario accounts for the noise produced at the wind farm grid by a heavy lift transport vessel on dynamic positioning during installation of a WTG and its corresponding substructure. A review of the available literature found no published source levels for a heavy lift transport vessel maintaining position and the most representative among the available source measurements were 1/3-octave band source levels for a dynamic positioning dive support vessel, the Fu Lai (MacGillivray 2006b). The Fu Lai's dynamic positioning source levels were therefore used as model input parameters for the heavy lift transport vessel. The engine power, length, draft, UTM source coordinates, activity, proxy source and broadband SL of the proposed heavy lift transport vessel modelled in this scenario are summarized in Table 8-14.

Table 8-14 Scenario 6 noise source specifications including propulsion power, length, draft, source location, activity, proxy source and broadband source level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Heavy Lift Transport Vessel	Propulsion Power = 11586 hp, Thruster Power = 6169 hp, Length = 144.2 m, Draft = 7.5 m	336686, 5980735	Holding Position	Fu Lai[1]	177.9 dB

[1] MacGillivray 2006b

Scenario 7 - Subsea Cable-Lay in Chatham Sound:

Scenario 7 accounts for noise generated by subsea cable-laying along the transmission cable corridor in Chatham Sound. These activities involved a cable-lay vessel and a dive support vessel, both operating on dynamic positioning. They were modelled using 1/3-octave band acoustic source levels for a dynamic positioning dive support vessel, the Fu Lai (MacGillivray 2006). Source specifications for this scenario, including engine power, length, draft, UTM source location, activity, proxy source and broadband SL are summarized in Table 8-15.

Table 8-15 Scenario 7 noise source specifications, including source propulsion power, length, draft, source location, activity, proxy source broadband source level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Cable-lay Vessel	Propulsion Power = 7200 bhp, Thruster Power = 4000 bhp, Length = 82.5 m, Draft = 6.2 m	408533, 600114	Dynamic Positioning	Fu Lai[1]	177.9 dB
Dive Support Vessel	Propulsion Power = 7400 bhp, Thruster Power = 5032 bhp, Length = 107.2 m, Draft = 6.6 m	408783, 6001144	Dynamic Positioning	Fu Lai[1]	177.9 dB

[1] MacGillivray 2006b

Scenario 8 - Subsea Cable-Lay in North Central Hecate Strait:

Scenario 8 accounts for noise produced during subsea cable-lay activities within the transmission cable corridor in north central Hecate Strait. One cable-lay vessel and one dive support vessel, both operating on dynamic positioning, were used to represent cable-laying activities. The Fu Lai (MacGillivray 2006b), a dynamic positioning dive support vessel, provided a suitable proxy source for both noise sources therefore 1/3-octave band acoustic source levels for this vessel were used as model input parameters. Table 8-16 provides a summary of the engine power, length, draft, UTM source coordinates, activity, proxy source and broadband SL for the vessels modelled in this scenario.

Table 8-16 Scenario 8 Noise Source Specifications, Including Propulsion Power, Length, Draft, Source Coordinates, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Cable-lay Vessel	Propulsion Power = 7200 bhp, Thruster Power = 4000 bhp, Length = 82.5 m, Draft = 6.2 m	366065, 5986763	Dynamic Positioning	Fu Lai[1]	177.9 dB
Dive Support Vessel	Propulsion Power = 7400 bhp, Thruster Power = 5032 bhp, Length = 107.2 m, Draft = 6.6 m	366315 5986763	Dynamic Positioning	Fu Lai[1]	177.9 dB

[1] MacGillivray 2006b

Scenario 9 - Cable Pull into WTG Substructures:

This scenario account for the noise produced at the wind farm grid caused by cable pull into the WTG substructures. It is anticipated that the loudest noise source involved with these activities will be a cable-lay vessel operating on dynamic positioning. A review of the available literature found no published source levels for a dynamic positioning cable-lay vessel and the most representative among the available source measurements were 1/3-octave band source levels for a dynamic positioning dive support vessel, the Fu Lai (MacGillivray 2006b). The Fu Lai's dynamic positioning source levels were therefore used as model input parameters for the cable-lay vessel. Table 8-17 summarizes the engine power, length, draft, UTM source location, activity, proxy source, and broadband SL of the noise source modelled in this scenario.

Table 8-17 Scenario 9 Noise Source Specification Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Cable-lay Vessel	Propulsion Power = 7200 bhp, Thruster Power = 4000 bhp, Length = 82.5 m, Draft = 6.2 m	336686, 5980735	Dynamic Positioning	Fu Lai[1]	177.9 dB

[1] MacGillivray 2006b

Scenario 10 - Transport of Converter Platform to Wind Farm Grid:

Scenario 10 accounts for noise produced during transport of the converter platform across Hecate Strait from the mainland to the wind farm grid. Transport was represented by four ocean-going tugs moving a 100 m x 100 m square barge, two pulling from the bow and two pushing at the stern. Two additional ocean-going tugs were included, a stand-by tug, positioned behind the barge to be used as back-up for the barge moving tugs, and a marshalling tug, leading the group. Each noise source was modelled using 1/3-octave band acoustic source levels for an ocean-going tug, the Britoil 51 (Hannay *et al.* 2004), transiting at half-speed, with the exception of the Marshalling tug. The engine power of the marshalling tug is anticipated to be half that of the Britoil 51, and as such, 3 dB was subtracted from each 1/3 octave band level for this source to account for engine power differences. The engine power, length, draft, UTM source coordinates, activity, proxy source and broadband SL for each noise source are summarized in Table 8-18.

Table 8-18 Noise Source Specifications for the Vessels Modelled in Scenario 10, Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1µPa·m)
Marshalling Tug	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	365177, 5986524	Transiting	Britoil 51[1]	181.9 dB
Pulling Tug 1	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	365966, 5986665	Transiting	Britoil 51[1]	184.9 dB
Pulling Tug 2	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	365948, 5986743	Transiting	Britoil 51[1]	184.9 dB
Pushing Tug 1	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	366297, 5986741	Transiting	Britoil 51[1]	184.9 dB
Pushing Tug 2	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	366279, 5986819	Transiting	Britoil 51[1]	184.9 dB
Stand-by Tug	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	366610, 5986855	Transiting	Britoil 51[1]	184.9 dB

[1] Hannay *et al.* 2004

Scenario 11 - Converter Platform Installation:

This scenario accounts for the noise produced at the wind farm grid during installation of the Converter platform. Installation activities were represented by six anchor handling tugs positioning a 100 m x 100 m square barge: two anchor handling and four holding position. In addition, a support vessel positioned behind the barge and supply vessel leading the group were included. For the tugs performing anchor handling, the Britoil 51 (Hannay *et al*. 2004), an anchor handling tug, provided a suitable proxy source, and therefore, 1/3-octave band acoustic source levels for this vessel were used as model input parameters. 1/3-octave band acoustic source levels for the Maersk Rover (Austin *et al*. 2005), another anchor handling tug holding position, were used as model input parameters for the other four tugs. Noise levels produced by the support and supply vessels were modelled using 1/3-octave band source levels for the Fu Lai (MacGillivray 2006b). However, the engine power of the Fu Lai is twice the engine power of the proposed support/supply vessels, and as such, 3 dB was subtracted from each band level to account for noise reduction due to engine power differences. Table 8-19 provides noise source specifications, including engine power, length, draft, UTM source coordinates, activity, proxy source and broadband SL for each vessel modelled in this scenario.

Table 8-19 Noise Source Specifications for Scenario 11, Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Support Vessel	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	339406, 5981101	Stand-by	Fu Lai[1]	174.9 dB
Supply Vessel	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	338830, 5980939	Stand-by	Fu Lai[1]	174.9 dB
Anchor Handling Tug 1	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339210, 5981162	Anchor Handling	Britoil 51[2]	193.2 dB
Anchor Handling Tug 2	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339024, 5980876	Anchor Handling	Britoil 51[2]	193.2 dB
Anchor Handling Tug 3	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	338974, 5981111	Holding Position	Maersk Rover[3]	179.1 dB
Anchor Handling Tug 4	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339261, 5980929	Holding Position	Maersk Rover[3]	179.1 dB
Anchor Handling Tug 5	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339129, 5980970	Holding Position	Maersk Rover[3]	179.1 dB
Anchor Handling Tug 6	Propulsion Power = 5750 bhp, Length = 40.4 m, Draft = 5.8 m	339105, 5981067	Holding Position	Maersk Rover[3]	179.1 dB

[1] MacGillivray 2006b
[2] Hannay *et al*. 2004
[3] Austin *et al*. 2005

Scenario 12 - Scour Protection Placement:

Scenario 12 accounts for the noise produced within the wind farm grid during scour protection placement. These activities were represented by a rock dumping barge performing spoil dumping, a dive support vessel operating on dynamic positioning, a marshalling tug holding position in front of dumping operations and an additional tug on standby at the rear of dumping activities. The rock dumping barge was modelled using 1/3-octave band acoustic source levels for a rock dumping vessel, the Pompei (Hannay *et al*. 2004), and the dive support vessel was modelled using acoustic source levels for the Fu Lai (MacGillivray 2006b), a dynamic positioning dive support vessel. Noise levels produced by the support vessel and standby tug were also modelled using 1/3-octave band source levels for the Fu Lai. However, the engine power of the Fu Lai is twice the engine power of the proposed support vessel and standby tug, and therefore 3 dB was subtracted from each band level to account for noise reduction due to engine power differences. Noise source specifications, including vessel engine power, length, draft, UTM source coordinates and activity are summarized in Table 8-20 along with the proxy source and broadband SL used for model input.

Table 8-20 Noise Source Specifications for Scenario 12 Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Marshalling Tug	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	336392, 5980675	Holding Position	Fu Lai[1]	174.9 dB
Rock Dumping Barge	Propulsion Power = 1086 hp, Thruster Power = 939 hp, Length = 65.5 m, Draft = 3.8 m	336686, 5980735	Dumping	Pompei[2]	188.4 dB
Dive Support Vessel	Propulsion Power = 7400 bhp, Thruster Power = 5032 bhp, Length = 107.2 m, Draft = 6.6 m	336884, 5980775	Dynamic Positioning	Fu Lai[1]	177.9 dB
Stand-by Tug	Propulsion Power = 2640 bhp, Length = 31.6 m, Draft = 4.1 m	337077, 5980822	Stand-by	Fu Lai[1]	174.9 dB

[1] MacGillivray 2006b
[2] Hannay *et al*. 2004

Scenario 13 - Rock Dumping at Cable/Pipeline Crossing:

Scenario 13 accounts for noise produced in Chatham Sound during rock dumping necessary to facilitate cable-lay over existing subsea cables/pipelines. These activities were represented by a rock dumping barge performing spoil dumping, and a cable-lay vessel and dive support vessel, both operating on dynamic positioning. The Pompei (Hannay *et al*. 2004), a spoil dumping vessel, provided a suitable proxy source for the rock dumping barge, and therefore, 1/3-octave band acoustic source levels for this vessel were used as model input parameters. The dominant sound during rock dumping will be from the noise of the vessel. To model the cable-lay vessel and dive support vessel, the Fu Lai (MacGillivray 2006b), a dynamic positioning dive support vessel, provided a suitable proxy source. The Fu Lai's 1/3-octave band acoustic source levels were therefore used as model input parameters for both dynamic positioning sources. The engine power, length, draft, UTM source coordinates, activity, proxy source and broadband source level for each noise source are summarized in Table 8-21.

Table 8-21 Scenario 13 Noise Source Specifications, Including Propulsion Power, Length, Draft, Source Location, Activity, Proxy Source and Broadband Source Level (SL).

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Cable-lay Vessel	Propulsion Power = 7200 bhp, Thruster Power = 4000 bhp, Length = 82.5 m, Draft = 6.2 m	408533, 6001144	Dynamic Positioning	Fu Lai[1]	177.9 dB
Dive Support Vessel	Propulsion Power = 7400 bhp, Thruster Power = 5032 bhp, Length = 107.2 m, Draft = 6.6 m	408783, 6001144	Dynamic Positioning	Fu Lai[1]	177.9 dB
Rock Dumping Barge	Propulsion Power = 1086 hp, Thruster Power = 939 hp, Length = 65.5 m, Draft = 3.8 m	408657, 6001268	Dumping	Pompei[2]	188.4 dB

[1] MacGillivray 2006b
[2] Hannay *et al*. 2004

8.4.3.2 Operations

<u>Scenario 14 - Turbine Operations:</u>

Scenario 14 accounts for underwater noise produced by vibration of the WTG towers during normal operations of the wind farm. A total of 110 3.6 MW wind turbines operating within the wind farm grid were modelled for this scenario. The proponent is considering several different turbine models for the Project, however if a larger turbine was used (with greater power than 3.6 MW) then fewer total turbines would be required. The 110 turbine case that has been modelled here represents the greatest expected number of operating turbines and thus is the most conservative noise scenario. 1/3-octave band source levels for the wind turbines were estimated from published measurements of the Utgrunden wind farm in Sweden (Lidell 2003). The wind speed for this model scenario was taken to be 8 m/s. The Utgrunden source levels were increased by 1.8 dB for this modelling scenario in order to account for the greater diameter of the turbines planned for the NaiKun wind farm (107 m versus 70.5 m) under the assumption that emitted underwater noise energy is proportional to turbine diameter. Even though an individual larger diameter turbine would be louder than the individual turbine source level that has been used in this scenario, the chosen layout with the greatest number of turbines will produce a larger noise footprint than would a layout with fewer turbines with higher power rating. Table 8-22 summarizes the wind turbine specifications and wind speed that were assumed for this model scenario.

Table 8-22 Scenario 14 Noise Source Specifications for a Single Wind Turbine Generator, Including Wind Turbine Model, Wind Speed and Broadband Source Level (SL).

Noise Source	Source Description	Locations	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Siemens 3.6 MW Wind Turbine Generator	Turbine Diameter = 107 m Wind Speed = 8 m/s 110 Turbines Total	Distributed throughout wind farm grid	Normal Operations	GE 1.5 MW Wind Speed = 8 m/s Utgrunden Wind Park[1]	156.3 dB

[1] Lidell 2003

Scenario 15 - Turbine Maintenance:

This scenario accounts for the noise produced during WTG maintenance. It is anticipated that the loudest noise source involved in maintenance activities will be the vessel used to transport maintenance staff from the mainland to the wind farm grid. Therefore, turbine maintenance activities were represented using a single crew transfer vessel, which was modelled using 1/3-octave band acoustic source levels for the Suvukti (MacGillivray *et al*. 2002), a similar crew-transfer vessel to the one proposed. Table 8-23 summarizes the engine power, length, draft, UTM source location, activity, proxy source and broadband source level of the noise source modelled in this scenario.

Table 8-23 Scenario 15 noise source specifications including propulsion power, length, draft, source coordinates, activity, proxy source and broadband source level (SL.)

Noise Source	Source Description	Location (m - UTM Zone 9)	Activity	Proxy Source	Modelled Broadband SL (dB re 1μPa·m)
Crew Vessel	Propulsion Power = 420 hp, Length = 11.9 m, Draft = 1.2 m	336686, 5980735	Transiting	Suvukti[1]	174.6 dB

[1] MacGillivray *et al*. 2002

9 UNDERWATER NOISE MODELLING – RESULTS

9.1 SOUND LEVEL CONTOUR MAPS

9.1.1 Construction

Sound propagation modelling was performed using MONM for 13 wind farm construction scenarios (see Section 8.4.3 for scenario details). Figure 9-1 through Figure 9-16 present the geographically-rendered sound level contour maps for each construction scenario. The contours shown in each map represent the maximum modelled sound level over all depths. In addition, each map includes an inset illustrating sound level contours close to the noise source(s). For Scenario 1 and Scenarios 4A through 13 (Figure 9-1 and Figure 9-6 through Figure 9-16 respectively), each contour illustrates the received *rms* SPL (the mean sound pressure level over the measurement period) from 180 dB re 1 µPa down to 90 dB re 1 µPa in 5 dB increments. For Scenarios 2A through 3B (Figure 9-2 through Figure 9-5, respectively), sound level contour maps show SEL (the total sound energy contained in a single pile driving pulse) from 200 dB re 1µPa^{2}s down to 150 dB re 1µPa^2 s in 5 dB increments. Note that the noise contour colour scales for Figure 9-2 through Figure 9-5 are different from those presented on the other maps. This is because the impact piling noise maps show contours of SEL (for impulsive noise) rather than SPL (for continuous noise). Also note that some of the low-level sound contours (< 100 dB re 1 µPa) were truncated where they intersected the limits of the acoustic modelling grid at long range.

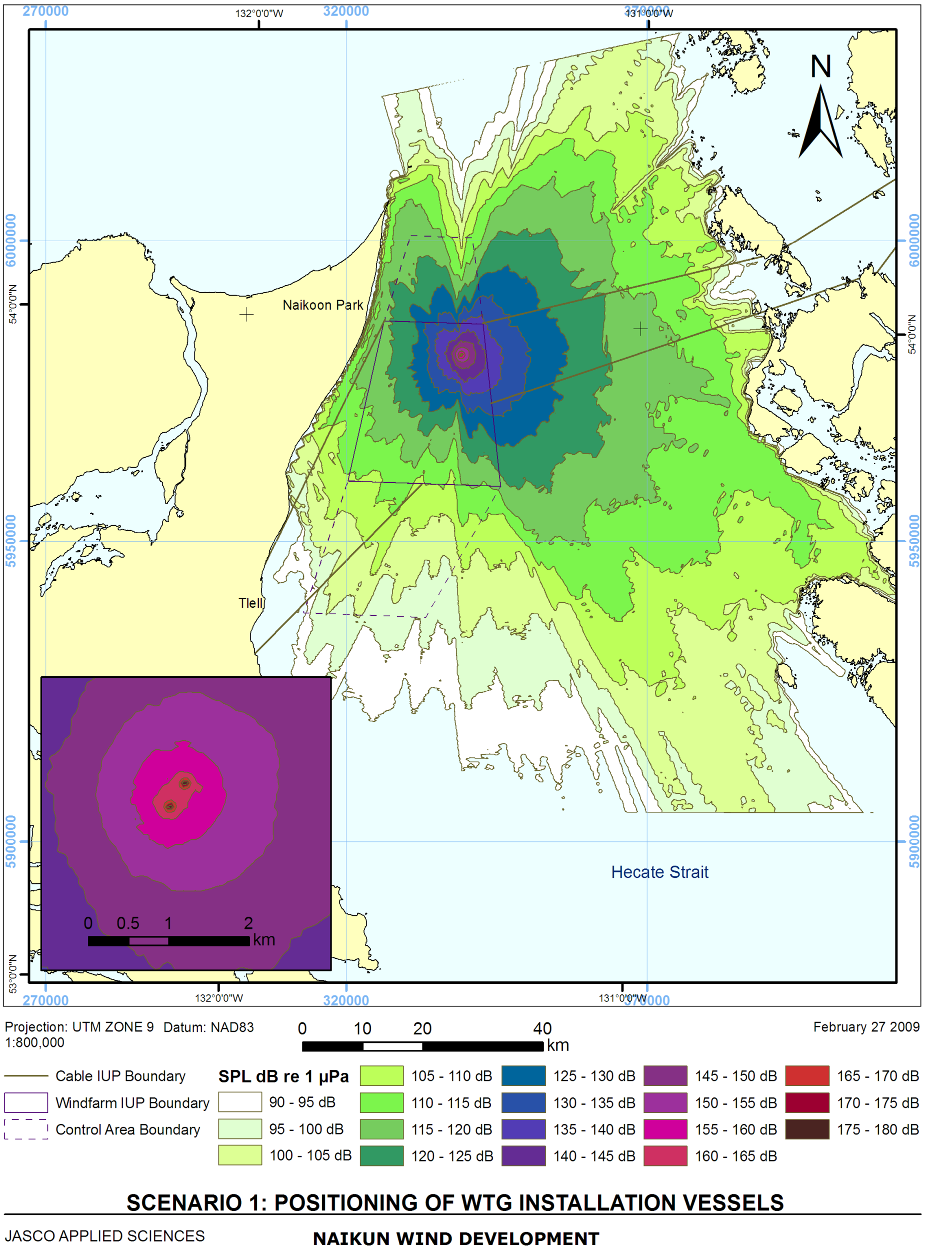


Figure 9-1 Map Showing Modelled Noise Contours from the Positioning of the WTG Installation Vessels Including Two Support Vessels, and Two Anchor Handling Tugs.

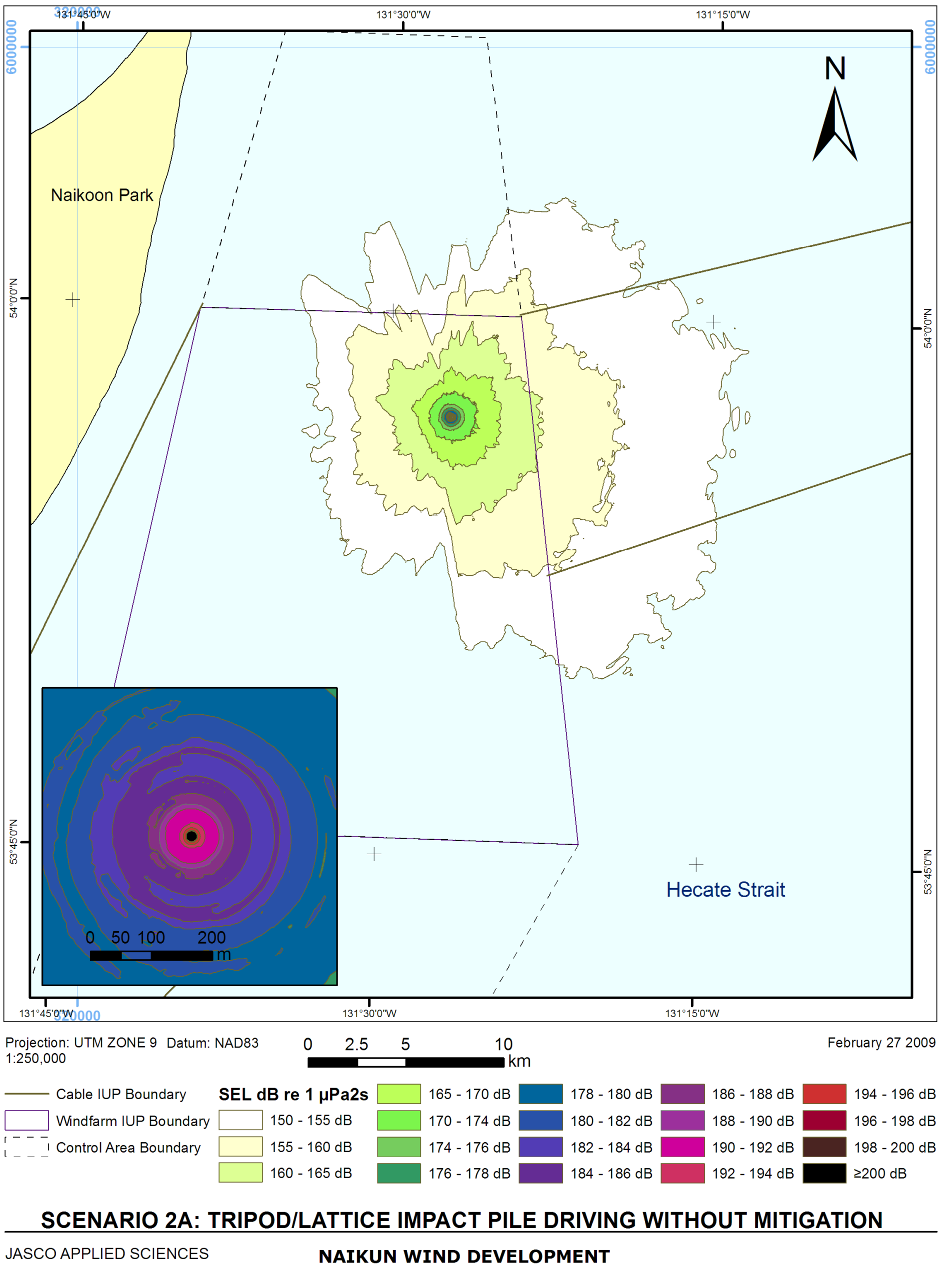


Figure 9-2 Map Showing Modelled Noise Contours for Unmitigated Impact Hammer Pile Driving of a 2-3 m Diameter Steel Pile for the Tripod/Lattice Supports (550 kJ ram Energy).

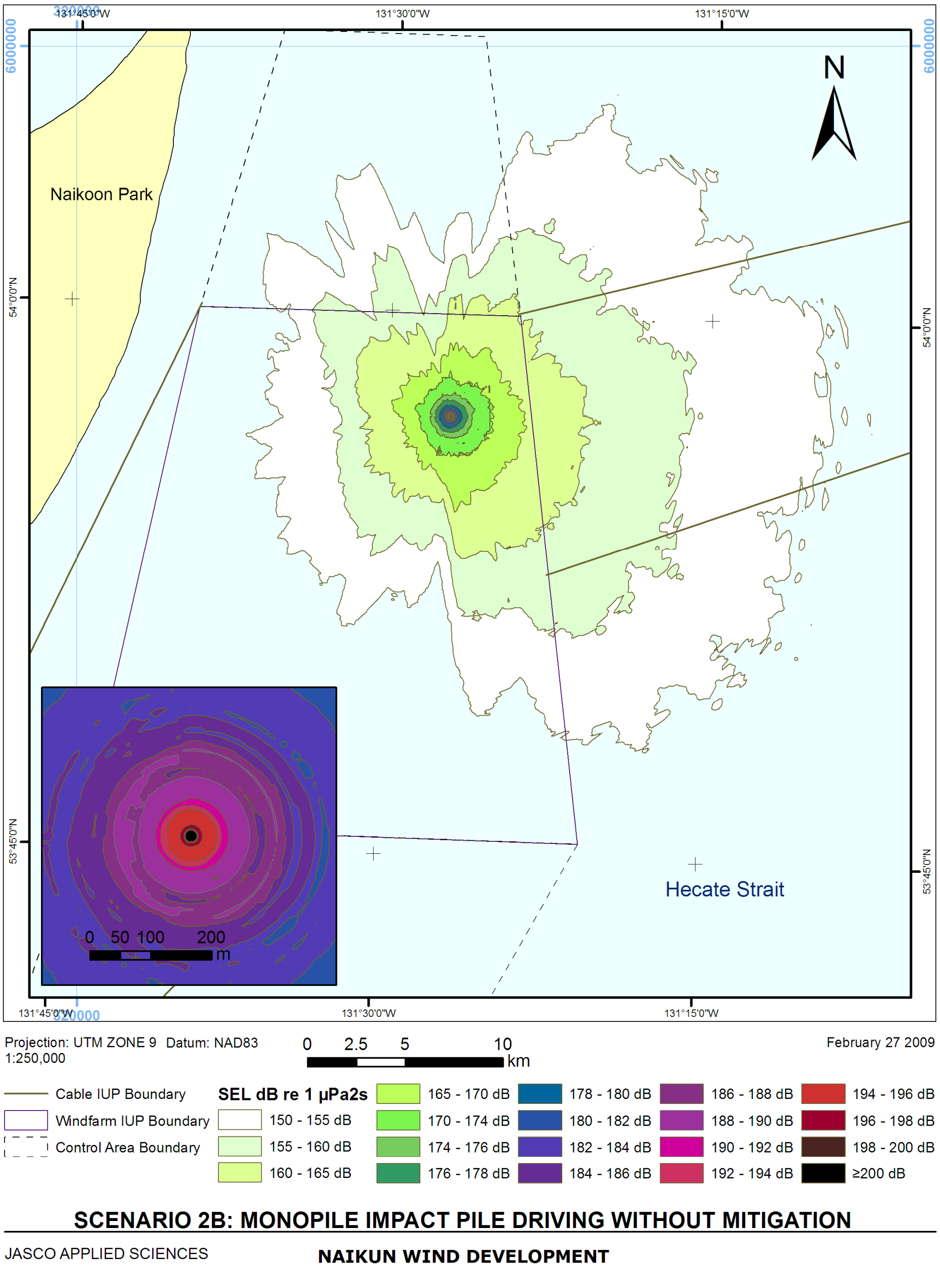


Figure 9-3 **Map Showing Modelled Noise Contours for Unmitigated Impact Hammer Pile Driving of a 4.5-5 m Diameter Steel Pile for the Monopile Supports (1200 kJ ram Energy).**

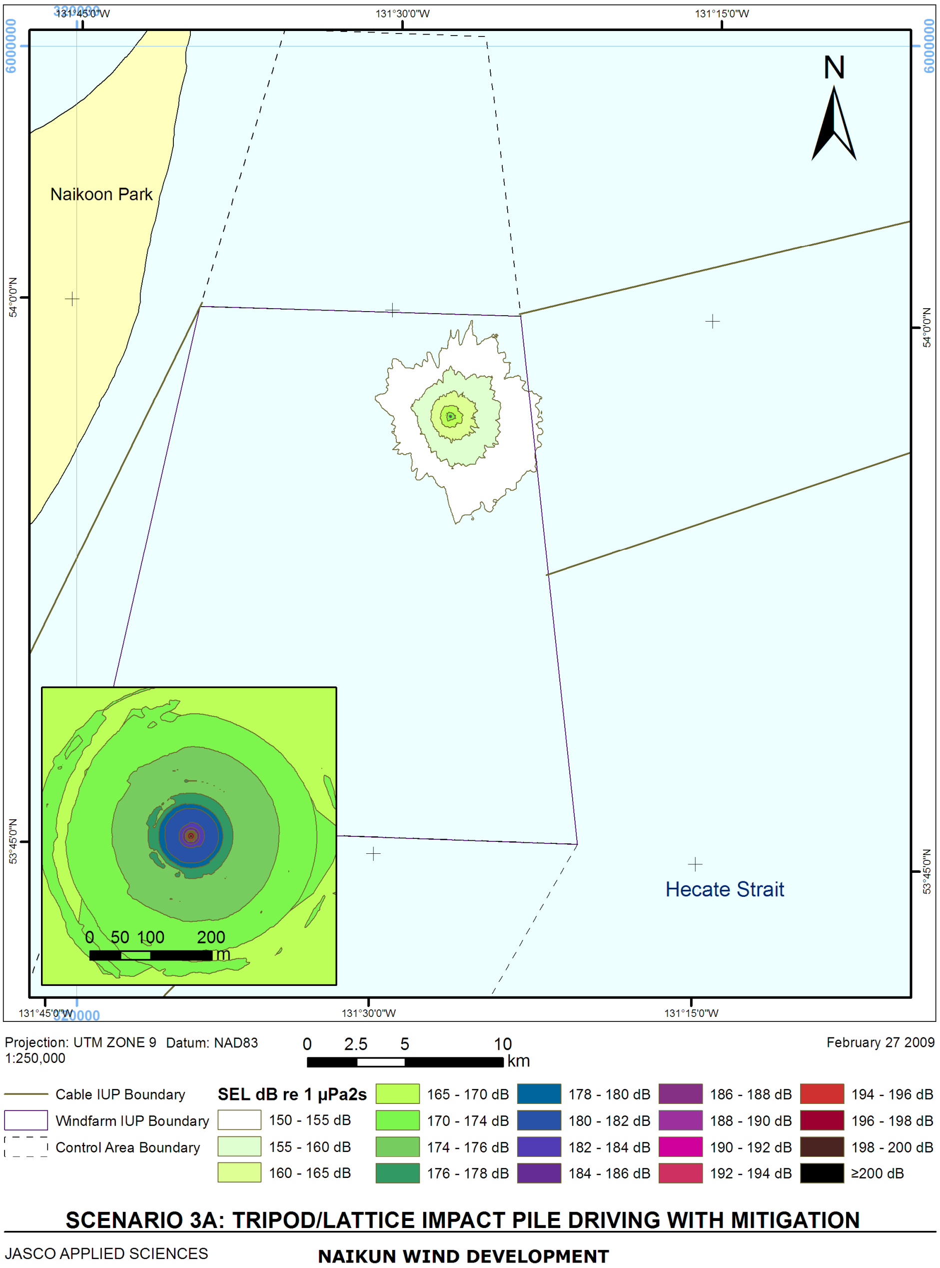


Figure 9-4 Map Showing Modelled Noise Contours for Mitigated Impact Hammer Pile Driving of a 2-3 m Diameter Steel Pile for the Tripod/Lattice Supports (550 kJ ram Energy).

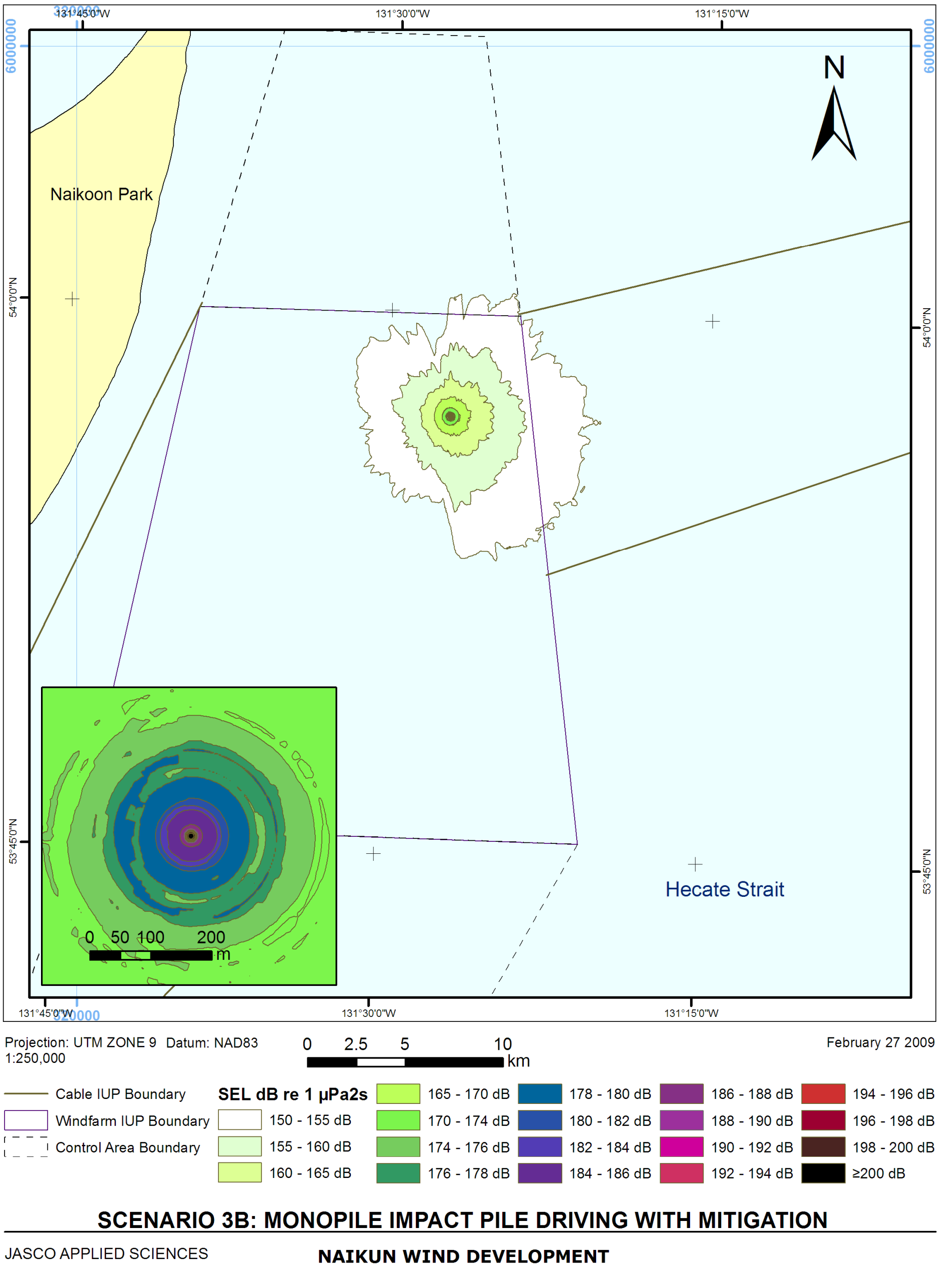


Figure 9-5 **Map Showing Modelled Noise Contours for Mitigated Impact Hammer Pile Driving of a 4.5-5 m Diameter Steel Pile for the Monopile Supports (1200 kJ ram Energy).**

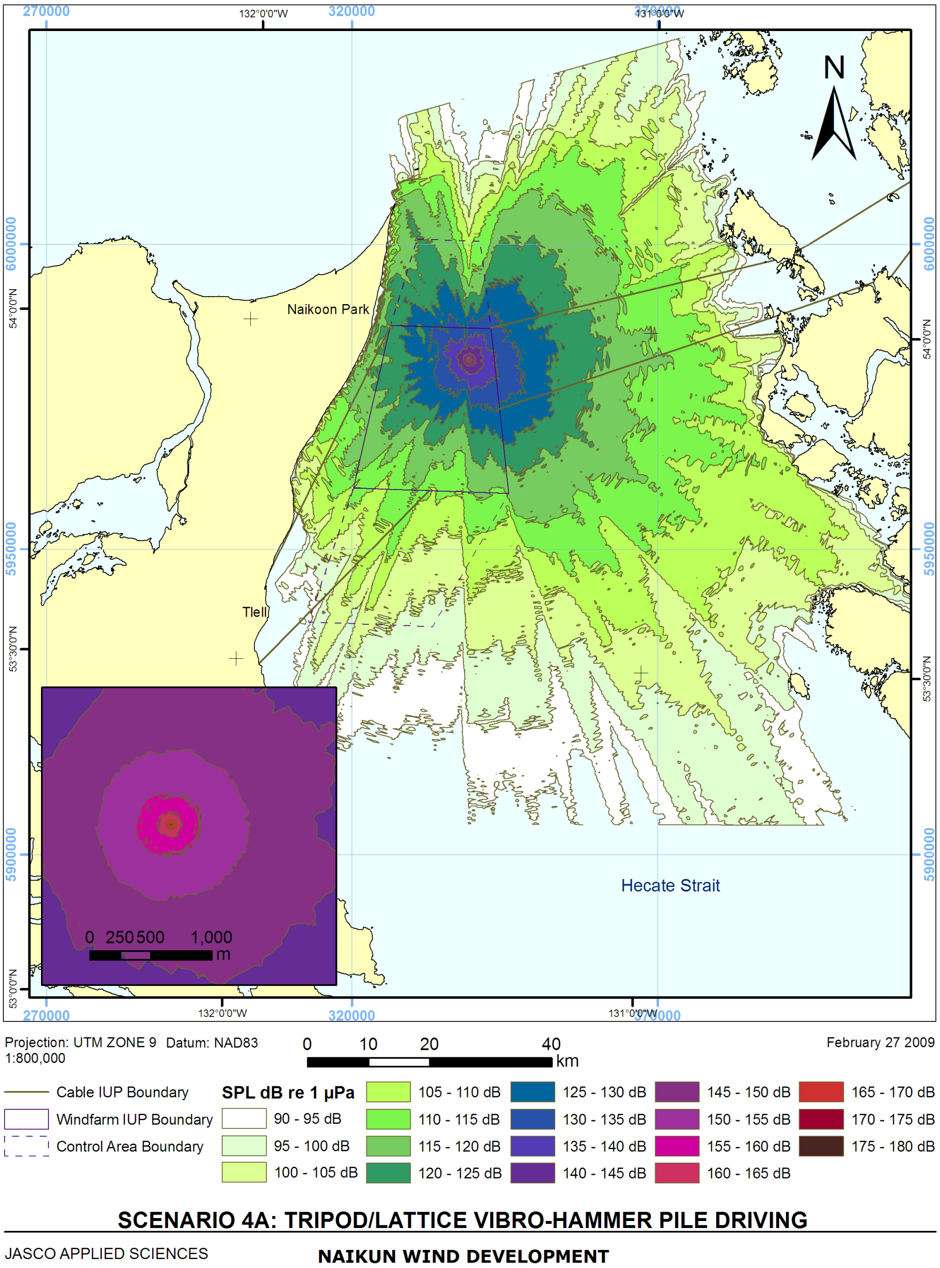


Figure 9-6 Map Showing Modelled Noise Contours for Vibrohammering of a 2-3 m Diameter Steel Pile for the Tripod/Lattice Supports.

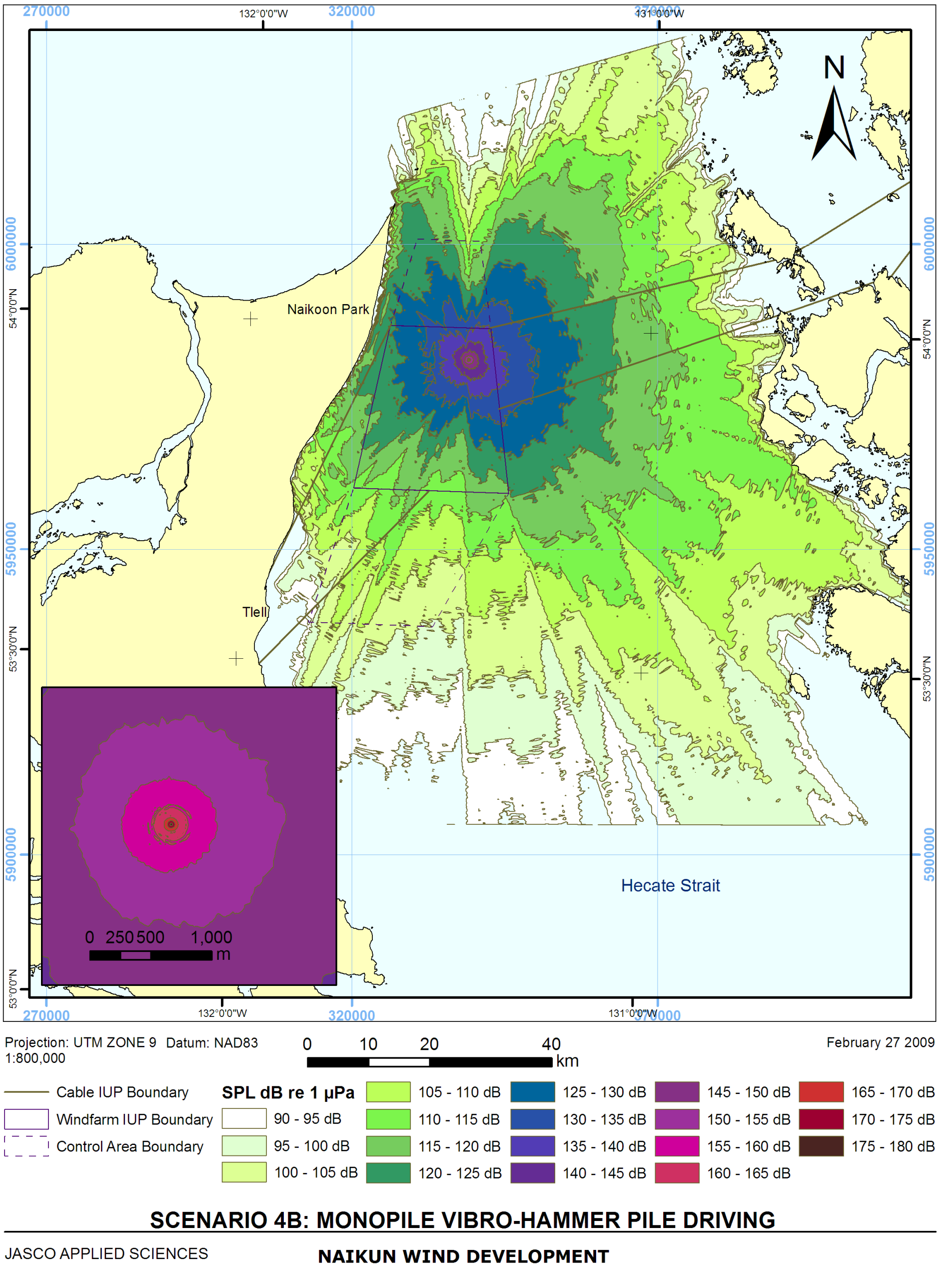


Figure 9-7 Map Showing Modelled Noise Contours for Vibrohammering of a 4.5-5 m Diameter Steel Pile for the Monopile Supports.

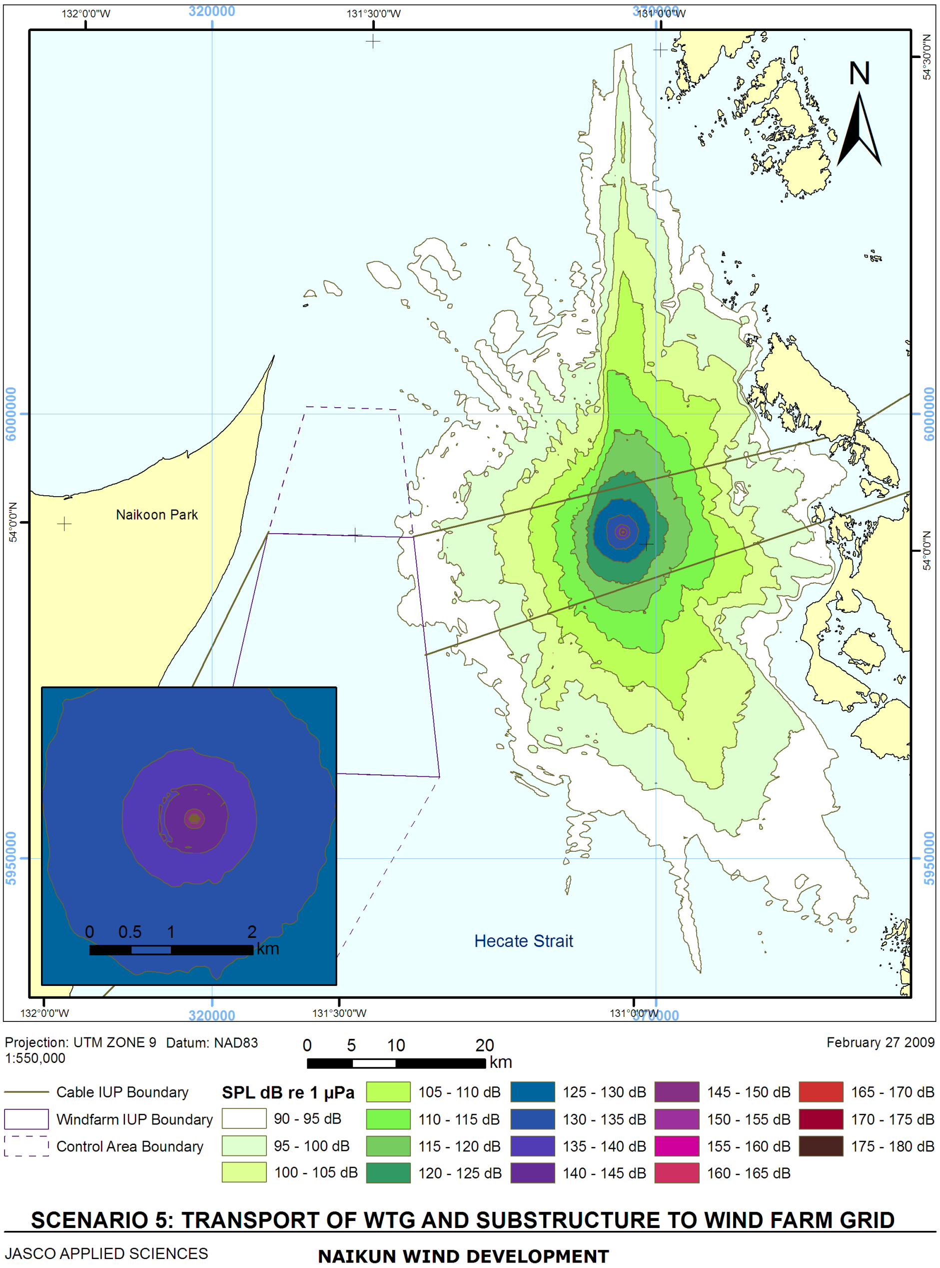


Figure 9-8 Map Showing Modelled Noise Contours from the Transport of the WTG and Substructures to the Wind Farm Grid using a Heavy Lift Transport Vessel.

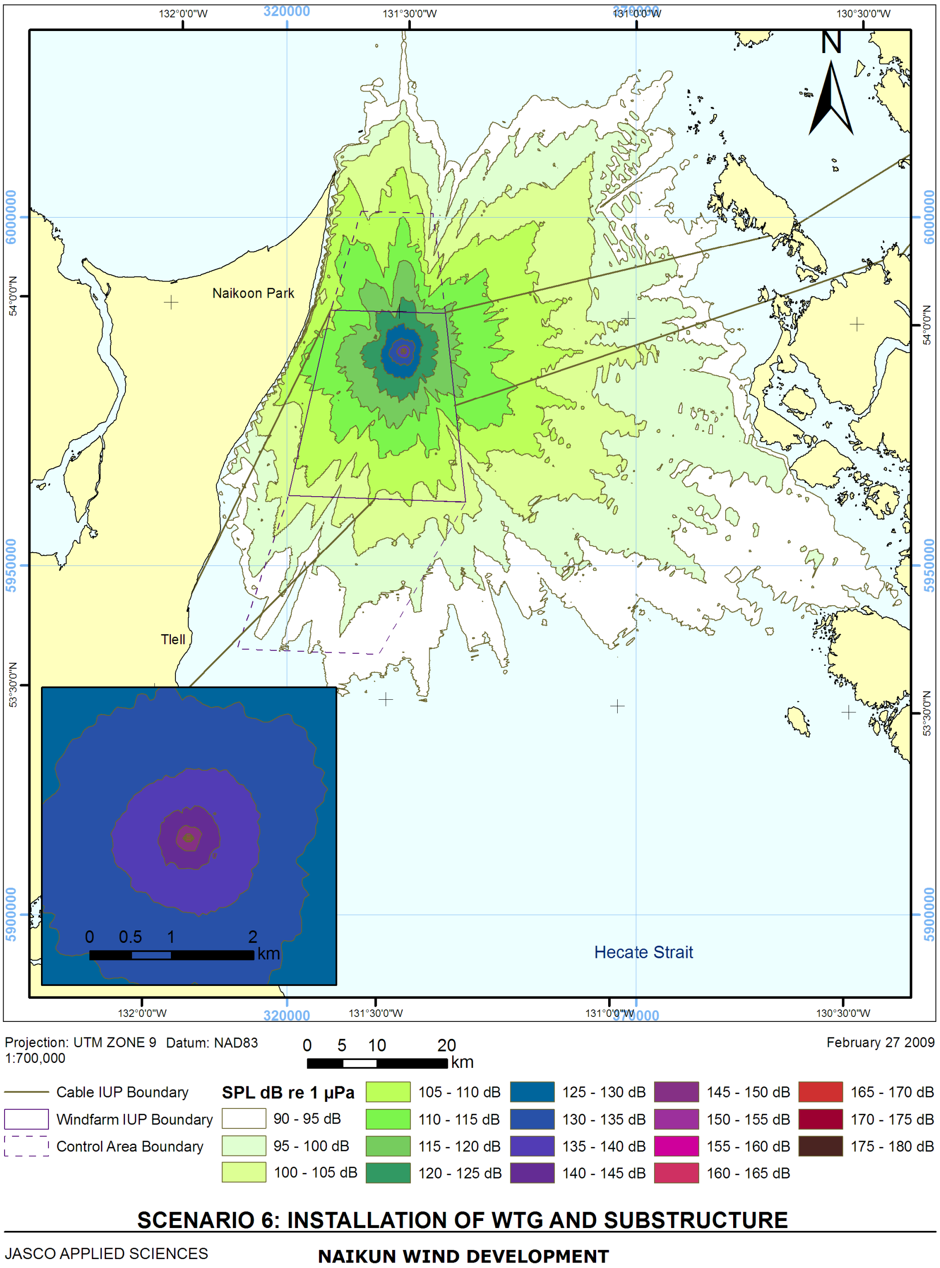


Figure 9-9 Map Showing Modelled Noise Contours from the Installation of a WTG and Associated Substructures using a Heavy Lift Transport Vessel.

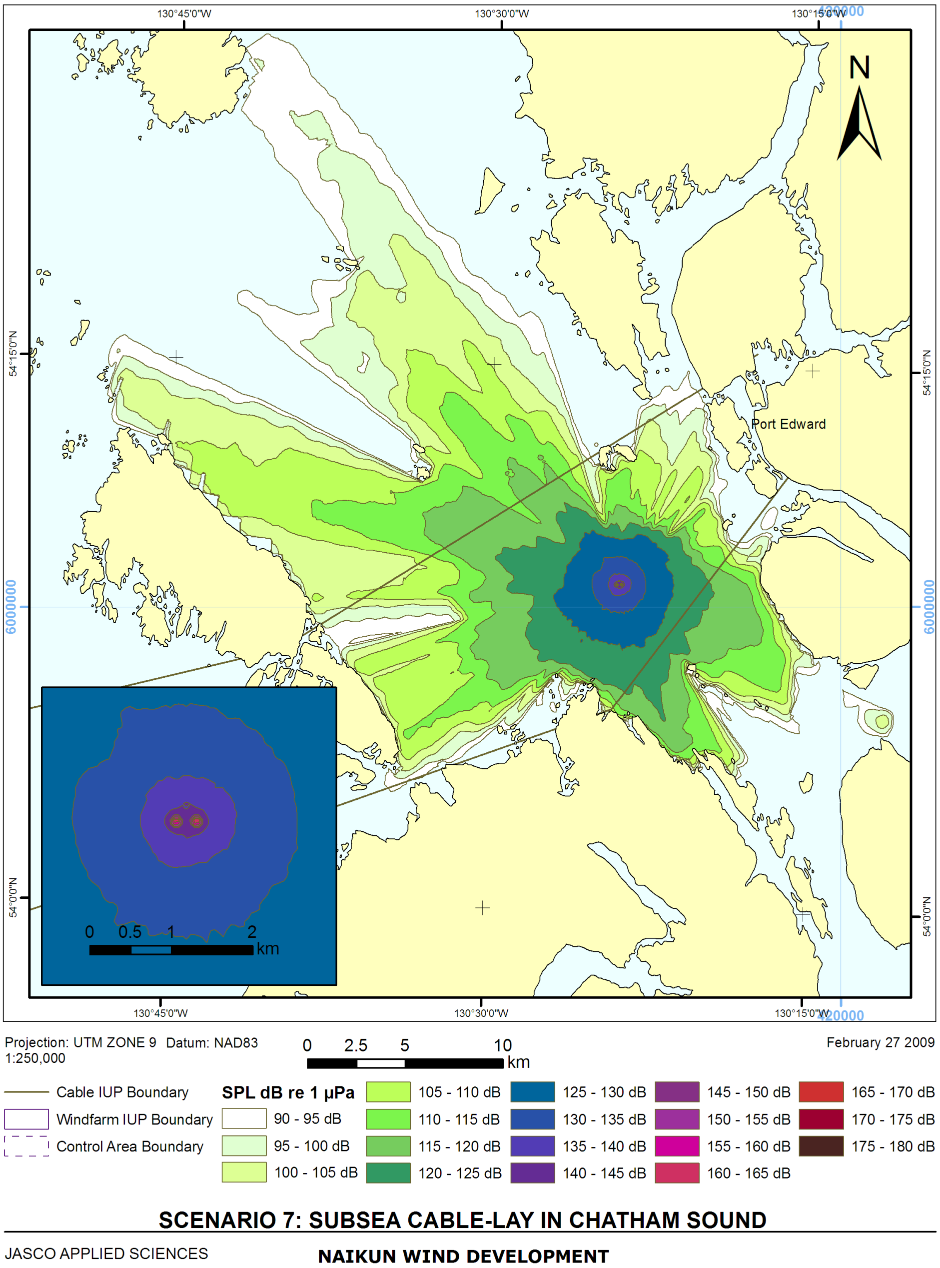


Figure 9-10 Map Showing Modelled Noise Contours from Subsea Cable-Lay in Chatham Sound using a Cable-Lay Vessel, and a Dive Support Vessel.

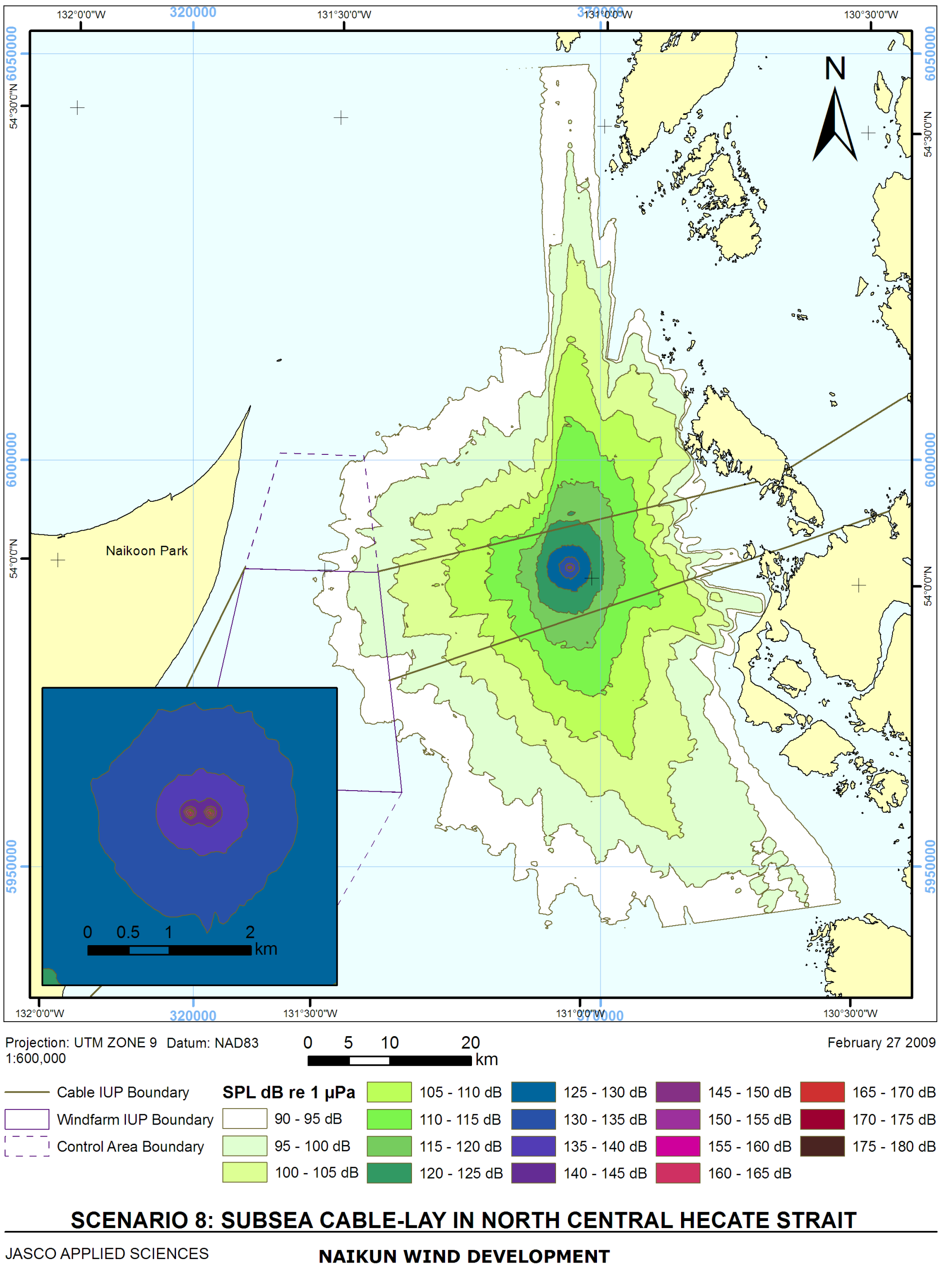


Figure 9-11 Map Showing Modelled Noise Contours from Subsea Cable-lay in North Central Hecate Strait using a Cable-lay Vessel and a Dive Support Vessel.

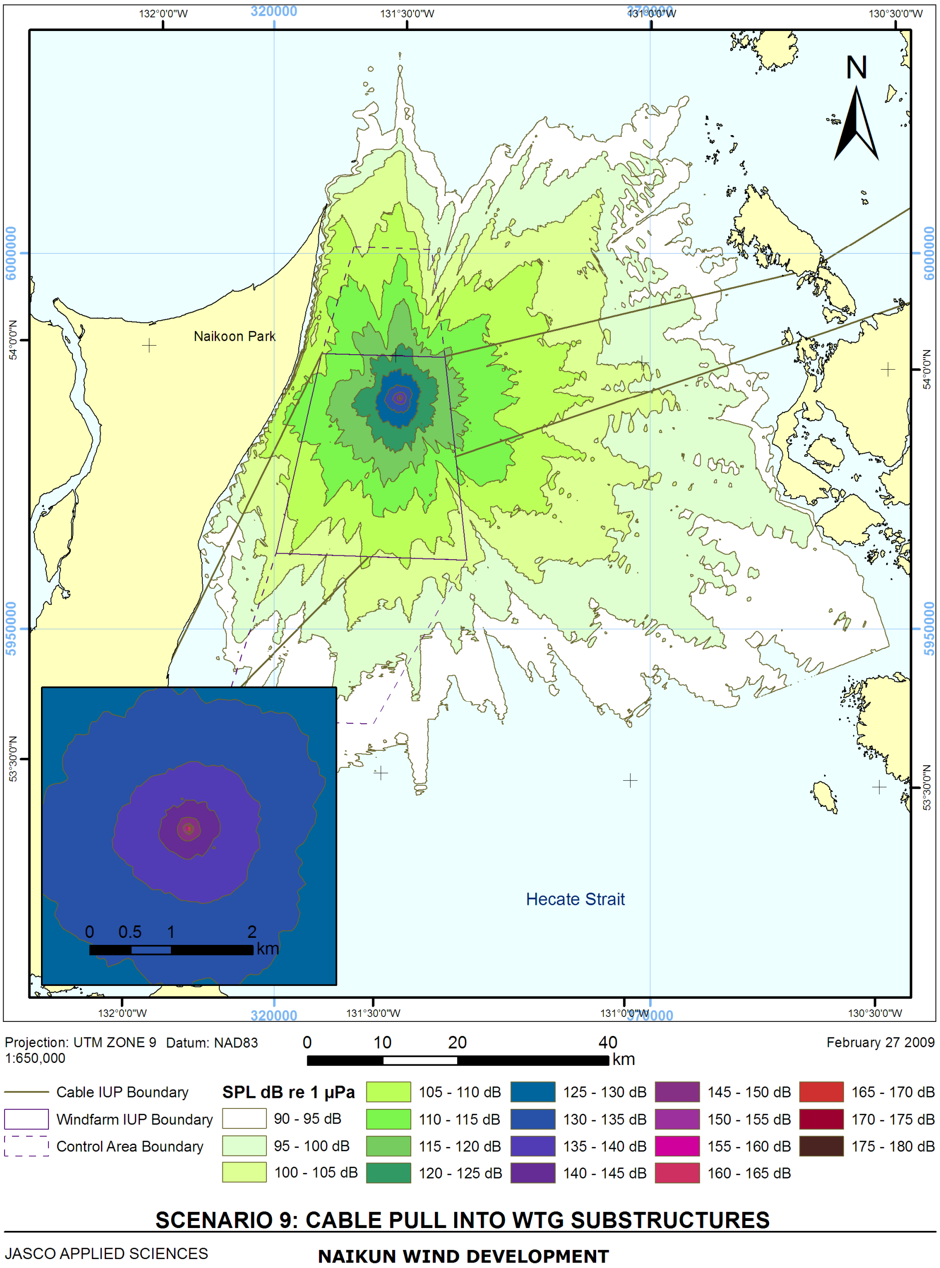


Figure 9-12 Map Showing Modelled Noise Contours from Cable Pull into the WTG Substructures using a Cable-lay Vessel.

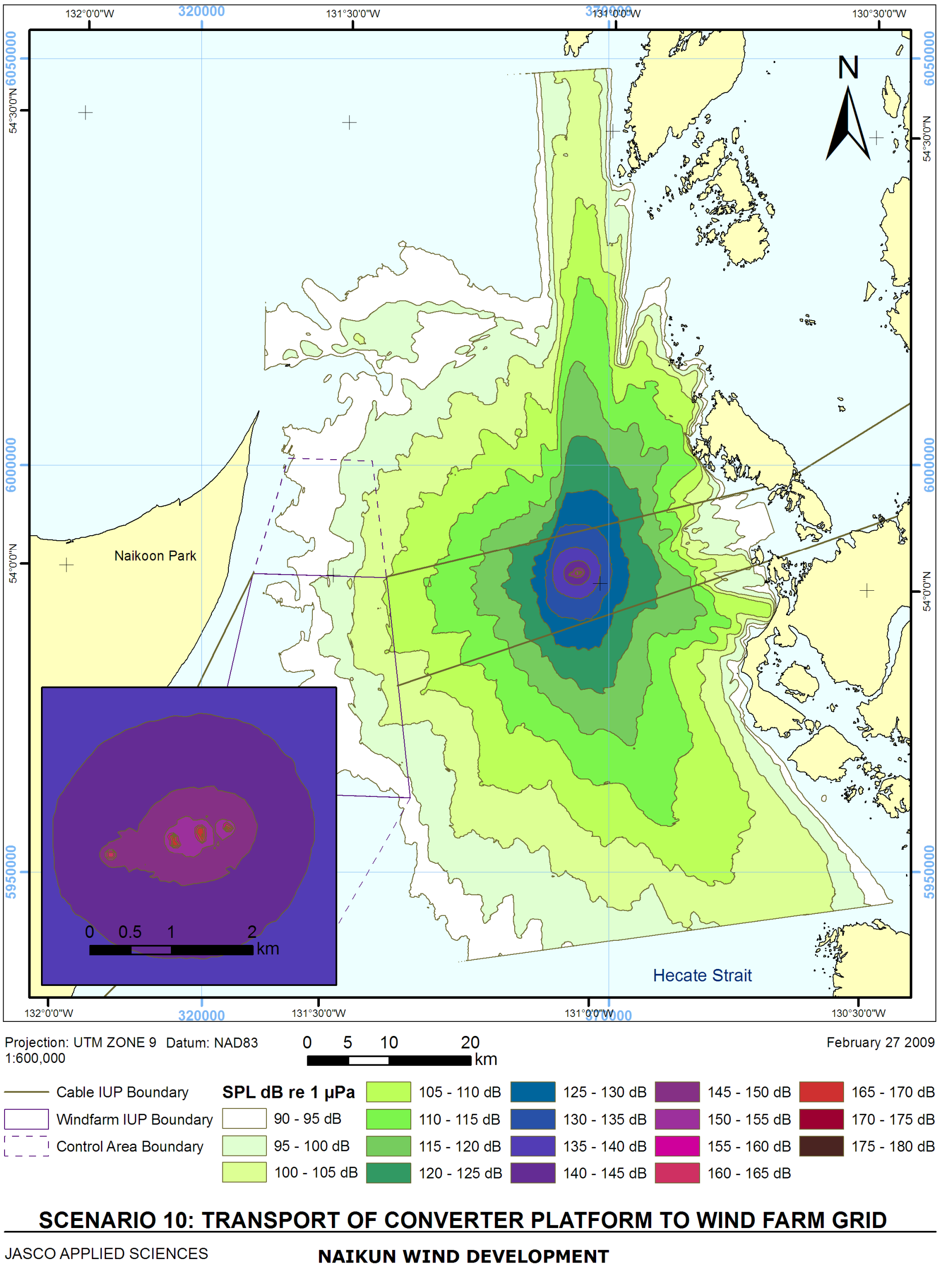


Figure 9-13 Map Showing Modelled Noise Contours from Transporting the Converter Platform to the Wind Farm Grid using a Marshalling Tug, Four Towing Tugs, and a Standby Tug.

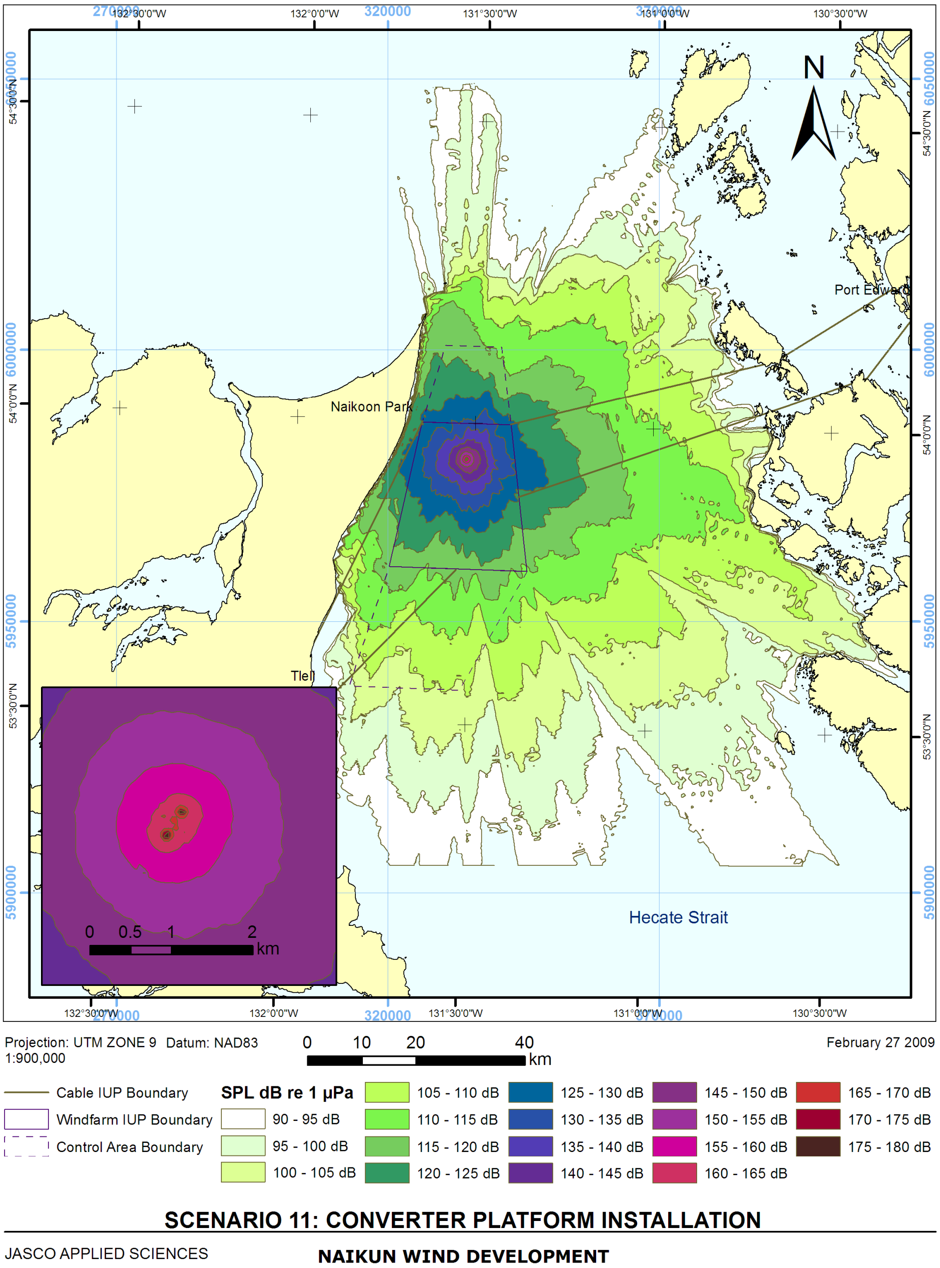


Figure 9-14 Map Showing Modelled Noise Contours from the Installation of the Converter Platform using a Support Vessel and Supply Vessel on Standby, and Six Anchor Handling Tugs.

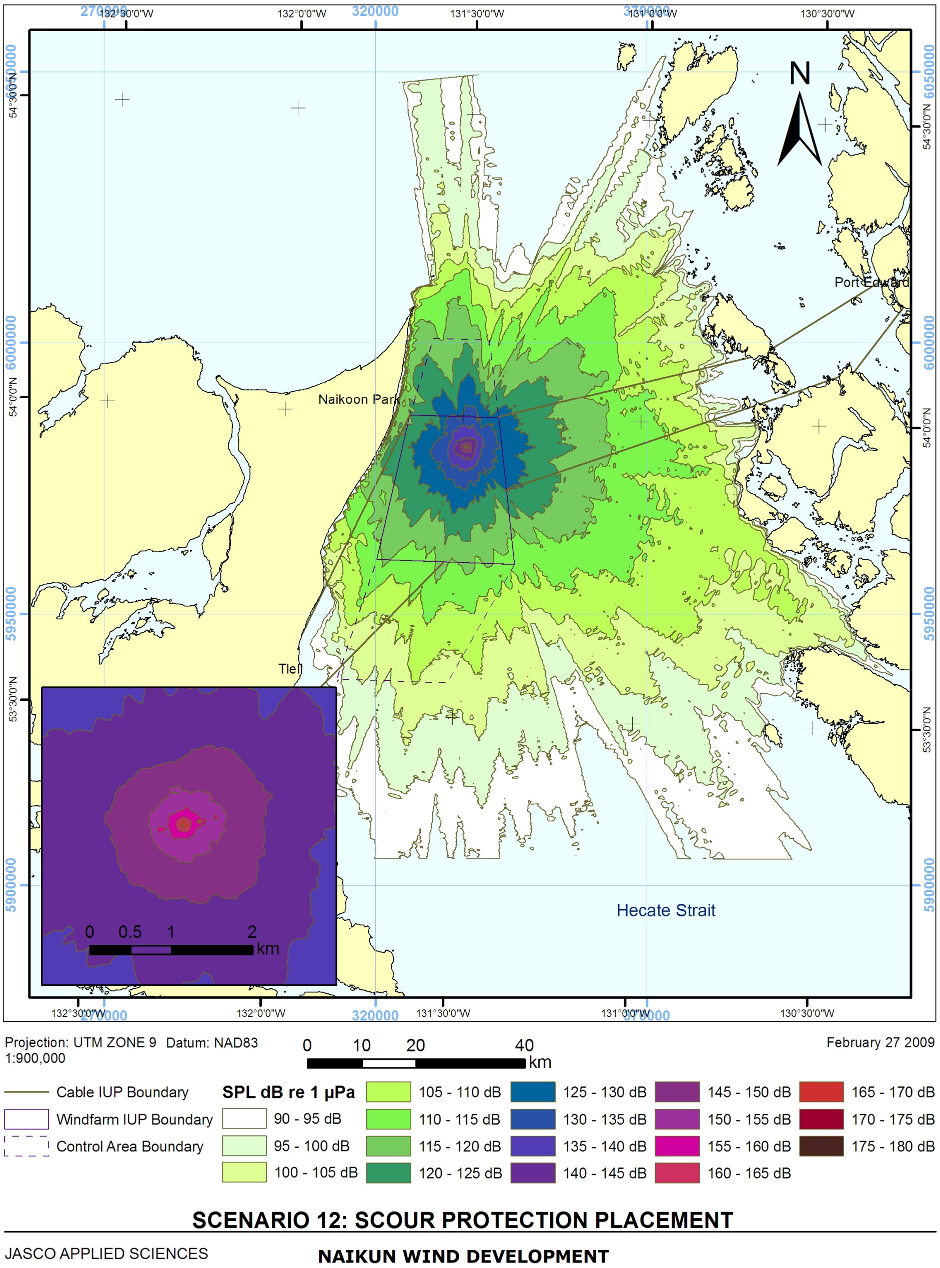
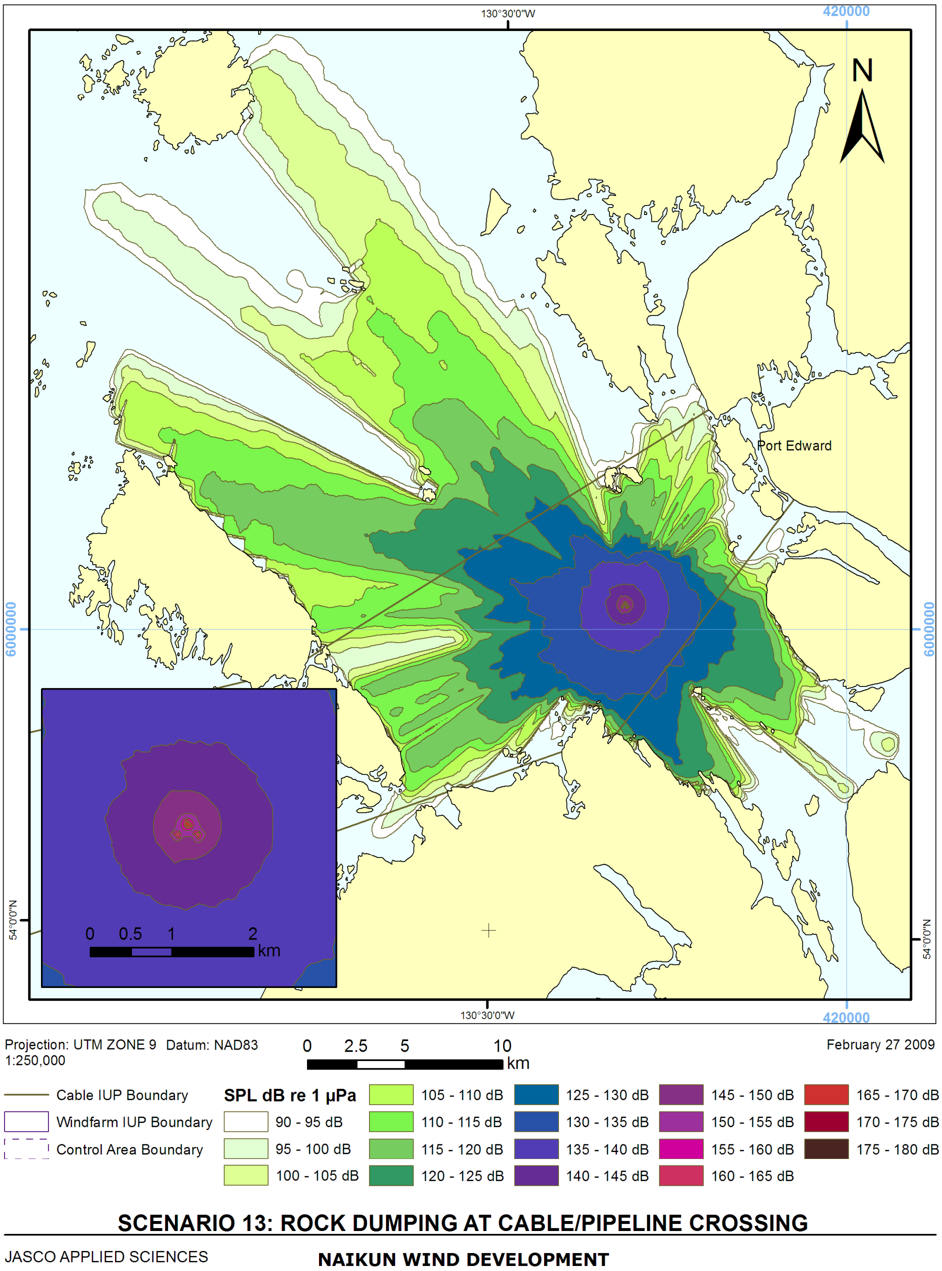


Figure 9-15 Map Showing Modelled Noise Contours from the Placement of Scour Protection using a Marshalling Tug, a Rock Dumping Barge, a Dive Support Vessel and a Standby Tug.



.

Figure 9-16 Map Showing Modelled Noise Contours from Rock Dumping at the Cable / Pipeline Crossing using a Cable Lay Vessel, a Dive Support Vessel and a Rock Dumping Barge.

9.1.2 Operations

Sound propagation modelling of wind farm operations was conducted using MONM for two scenarios: Turbine Operations and Turbine Maintenance (see Section 8.4.3 for operations scenario details). Sound level contour maps for these scenarios are presented in Figure 9-17 and Figure 9-18 below. The contours shown in each map represent the maximum received *rms* SPL (the mean sound intensity over the measurement period) over all depths from 180 dB re 1 µPa down to 90 dB re 1 µPa in 5 dB increments. Insets are included in each map to illustrate sound level contours close to the noise source(s).

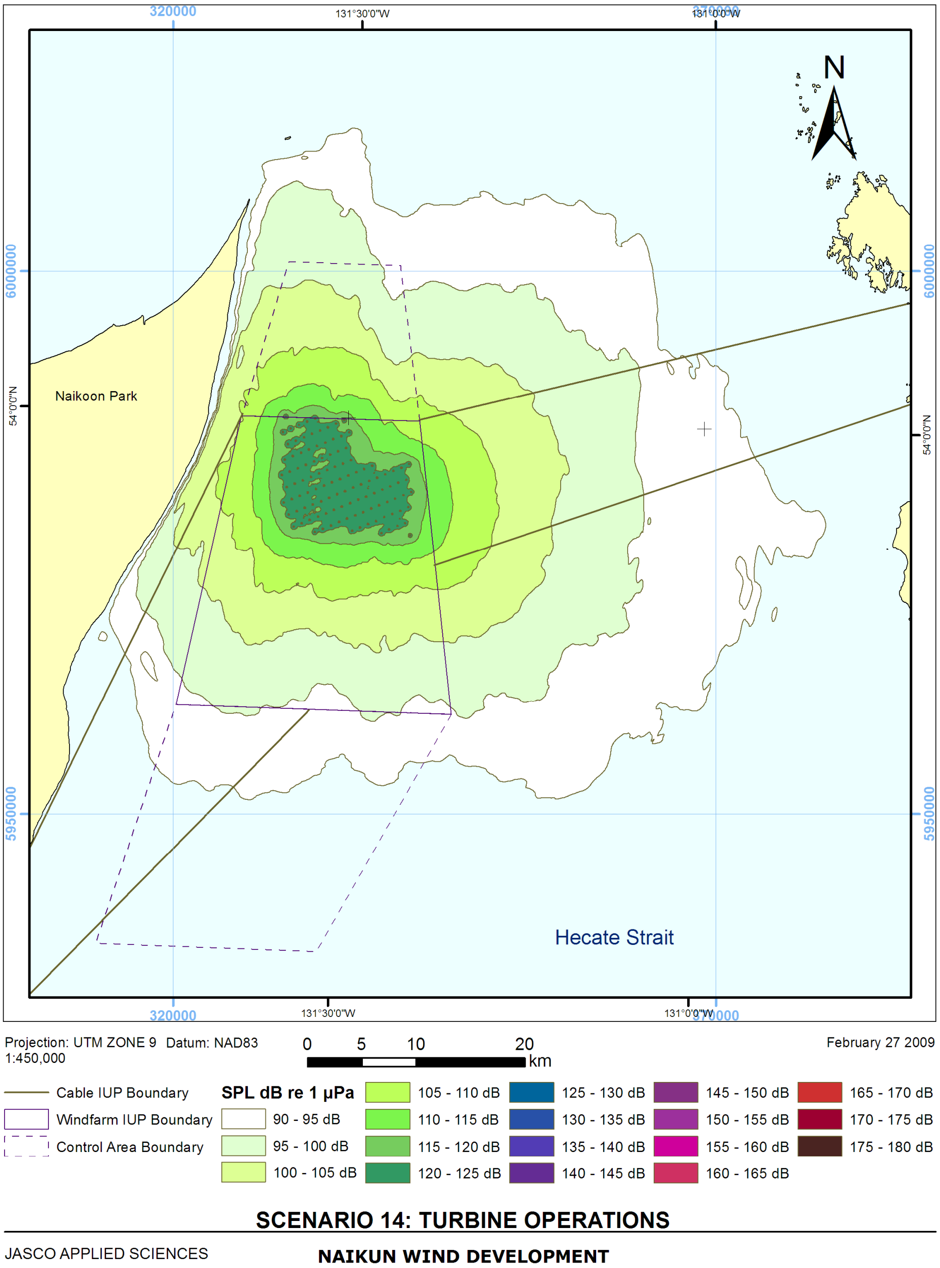


Figure 9-17 Map Showing Modelled Noise Contours for Normal Operations of the WTGs (110 Siemens 3.6 MW turbines) at 8 m/s Wind Speed.

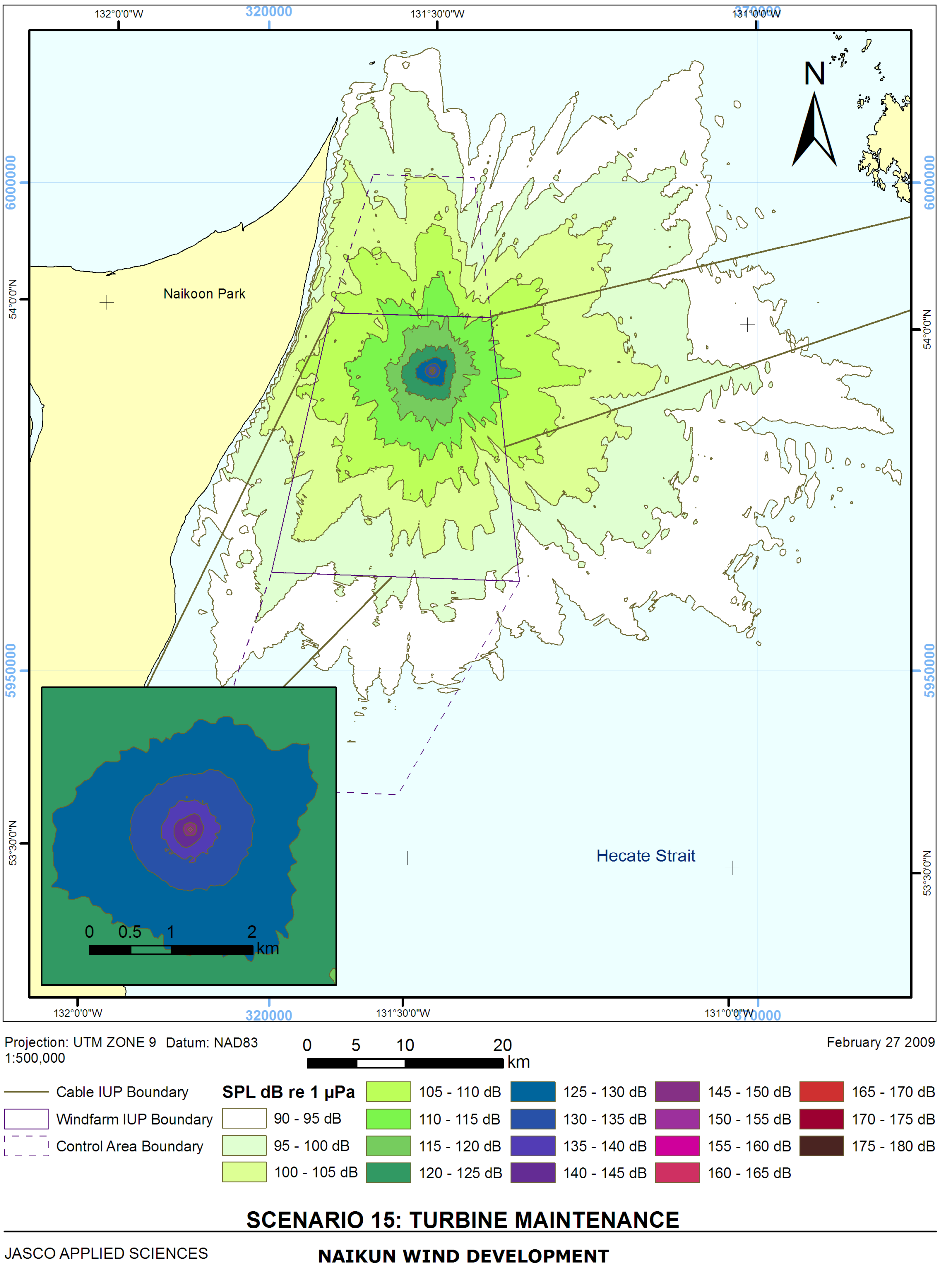


Figure 9-18 Map Showing Modelled Noise Contours from Turbine Maintenance Activities using a Crew Vessel.

9.2 SOUND LEVEL RADII

9.2.1 Construction

For each wind farm construction scenario, 95th percentile ranges to specific noise threshold levels were determined using the sound level contours generated by MONM as described in Section 8.4.1. For scenarios involving multiple noise sources, ranges were computed from the geometric centroid of the source positions for those threshold contours that surrounded all vessels in a spread. At higher noise levels, ranges were computed relative to the location of the single loudest source in the spread. Table 9-1 presents 95th percentile ranges computed for *rms* SPL threshold levels between 90 dB re 1 µPa and 170 dB re 1 µPa for model scenarios 1 and 4-13. The minimum spatial resolution for the model scenarios presented in Table 9-1 was 50 m, therefore the minimum computation range in Table 9-1 was taken to be 100 m (*i.e.*, less than 2 grid points). SPL's greater than 170 dB re 1 µPa were not exceeded beyond 100 m range for any of the modelled scenarios presented in Table 9-1.

For the tripod/lattice impact pile driving model scenarios (2A and 2B) Table 9-2 and presents 95th percentile ranges for *rms* SPLs between 160 dB re 1 µPa^2 s and 220 dB re 1 µPa^2 s, as well as unweighted and M-weighted SELs for single pile driving pulses. M-weighted levels are presented for Mysticetes, mid-frequency Odontocetes and Pinnipeds. Results for the monopile impact hammer pile driving model scenarios (3A and 3B) are presented in Table 9-3. The minimum spatial resolution for the pile driving model scenarios (*i.e.*, in Table 9-1 and Table 9-2) was 5 m, therefore the minimum range for computing SEL was taken to be 10 m. Table 9-4 presents estimated peak SPL threshold ranges for scenarios 2A through 3B in 2 dB increments from 224 dB re 1 µPa to 190 dB re 1 µPa. Table 9-5 presents estimated impulse versus range for scenarios 2A through 3B, in units of Pa·s, at ranges from 10 m to 50 m.

Table 9-1 Modelled 95th percentile *rms* SPL ranges for wind farm construction scenarios 1 and 4-13 computed using MONM.

SPL (dB re 1 µPa)	95 Percentile Sound Level Radius (km)											
	Model Scenario											
	1	4A	4B	5	6	7	8	9	10	11	12	13
90	77.977	76.067	76.741	42.166	57.286	26.852	46.384	56.167	47.218	75.539	74.700	29.841
95	77.315	72.425	74.755	32.569	44.664	23.288	38.451	44.374	46.615	67.353	65.688	28.360
100	72.111	62.091	65.524	26.522	30.875	20.675	28.514	31.031	45.467	58.438	59.369	25.615
105	61.387	52.824	57.008	19.103	22.027	17.615	20.474	22.076	35.329	48.393	48.731	21.746
110	49.387	38.835	44.638	13.258	15.374	11.687	14.439	15.238	27.178	39.014	34.757	19.581
115	34.746	28.407	32.354	9.161	9.975	8.356	9.363	9.890	19.133	26.300	24.838	16.621
120	23.900	20.301	23.738	5.663	6.244	5.275	5.381	6.136	13.629	18.546	16.970	10.026
125	16.341	13.824	16.555	3.354	3.564	2.994	2.717	3.530	8.967	12.518	10.858	6.992
130	10.819	8.391	10.639	1.863	1.889	1.366	1.253	1.831	5.505	8.366	6.539	4.536
135	6.703	4.561	6.091	0.832	0.897	0.565	0.536	0.871	3.030	5.772	3.814	2.273
140	4.026	2.305	3.124	0.428	0.378	0.253	0.232	0.365	1.530	3.823	2.134	1.033
145	2.288	1.297	1.733	0.121	0.159	< 0.100	< 0.100	0.143	0.859	2.376	0.907	0.454
150	1.229	0.597	0.842	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	0.409	1.325	0.461	0.188
155	0.597	0.265	0.379	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	0.713	0.265	< 0.100
160	0.304	0.106	0.164	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	0.355	< 0.100	< 0.100
165	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	0.234	< 0.100	< 0.100
170	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100

Table 9-2 Modelled 95th percentile rms SPL, flat-weighted SEL, and M-weighted SEL ranges for impact pile driving of 2-3 m piles (550 kJ ram energy) for the lattice/tripod supports.

		Scenario 2A: Tripod/Lattice Unmitigated Impact Pile Driving					Scenario 3A: Tripod/Lattice Mitigated Impact Pile Driving				
			M - Weighted 95 Percentile Radius (km)					M – Weighted 95 Percentile Radius (km)			
rms SPL (dB re 1 µPa)	SEL (dB re 1 µPa²•s)	Flat Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds	Flat Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
160	150	13.758	13.750	11.675	10.599	13.181	4.567	4.562	3.541	3.059	4.257
165	155	8.208	8.195	6.624	5.948	7.661	2.463	2.460	1.840	1.611	2.257
170	160	4.567	4.562	3.541	3.059	4.257	1.244	1.245	0.851	0.703	1.084
175	165	2.463	2.460	1.840	1.611	2.257	0.562	0.561	0.395	0.320	0.496
180	170	1.244	1.245	0.851	0.703	1.084	0.239	0.239	0.158	0.143	0.196
185	175	0.562	0.561	0.395	0.320	0.496	0.105	0.105	0.053	0.049	0.094
190	180	0.239	0.239	0.158	0.143	0.196	0.044	0.044	0.020	0.017	0.040
192	182	0.158	0.158	0.140	0.123	0.146	0.021	0.020	0.013	< 0.010	0.017
194	184	0.140	0.140	0.057	0.052	0.131	0.013	0.013	< 0.010	< 0.010	0.010
196	186	0.069	0.069	0.048	0.046	0.056	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
198	188	0.051	0.051	0.042	0.038	0.048	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
200	190	0.044	0.044	0.020	0.017	0.040	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
202	192	0.021	0.020	0.013	< 0.010	0.017	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
204	194	0.013	0.013	< 0.010	< 0.010	0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
206	196	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
208	198	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
210	200	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010

Table 9-3 Modelled 95th percentile *rms* SPL, flat-weighted SEL, and M-weighted SEL ranges for impact pile driving of 4.5-5 m piles (1200 kJ ram energy) for the monopile supports.

rms SPL (dB re 1 μPa)	SEL (dB re 1 μPa²•s)	Scenario 2B: Monopile Unmitigated Impact Pile Driving					Scenario 3B: Monopile Mitigated Impact Pile Driving				
			M - Weighted 95 Percentile Radius (km)					M – Weighted 95 Percentile Radius (km)			
		Flat Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds	Flat Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
160	150	17.893	17.880	15.822	14.640	17.265	6.811	6.802	5.531	4.843	6.401
165	155	11.760	11.749	9.858	8.893	11.219	3.745	3.745	2.863	2.506	3.431
170	160	6.811	6.802	5.531	4.843	6.401	2.020	2.017	1.501	1.261	1.816
175	165	3.745	3.745	2.863	2.506	3.431	0.959	0.958	0.660	0.558	0.840
180	170	2.020	2.017	1.501	1.261	1.816	0.421	0.420	0.286	0.243	0.373
185	175	0.959	0.958	0.660	0.558	0.840	0.175	0.175	0.140	0.105	0.161
190	180	0.421	0.420	0.286	0.243	0.373	0.058	0.058	0.047	0.044	0.053
192	182	0.300	0.299	0.194	0.162	0.264	0.048	0.048	0.040	0.030	0.046
194	184	0.201	0.201	0.146	0.141	0.179	0.041	0.041	0.018	0.015	0.035
196	186	0.148	0.148	0.134	0.069	0.143	0.018	0.018	0.011	< 0.010	0.016
198	188	0.130	0.129	0.054	0.050	0.118	0.011	0.011	< 0.010	< 0.010	< 0.010
200	190	0.058	0.058	0.047	0.044	0.053	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
202	192	0.048	0.048	0.040	0.030	0.046	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
204	194	0.041	0.041	0.018	0.015	0.035	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
206	196	0.018	0.018	0.011	< 0.010	0.016	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
208	198	0.011	0.011	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
210	200	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010

Table 9-4 Estimated peak SPL thresholds for impact pile driving of the lattice/tripod and monopile supports.

Peak SPL (dB re 1 μPa)	Threshold Range (km)			
	Tripod/Lattice Impact Piling		Monopile Impact Piling	
	Scenario 2A: Unmitigated	Scenario 3A: Mitigated	Scenario 2B: Unmitigated	Scenario 3B: Mitigated
190	0.543	0.172	0.794	0.251
192	0.432	0.136	0.631	0.200
194	0.343	0.108	0.501	0.158
196	0.272	0.086	0.398	0.126
198	0.216	0.068	0.316	0.100
200	0.172	0.054	0.251	0.079
202	0.136	0.043	0.200	0.063
204	0.108	0.034	0.158	0.050
206	0.086	0.027	0.126	0.040
208	0.068	0.022	0.100	0.032
210	0.054	0.017	0.079	0.025
212	0.043	0.014	0.063	0.020
214	0.034	0.011	0.050	0.016
216	0.027	< 0.010	0.040	0.013
218	0.022	< 0.010	0.032	0.010
220	0.017	< 0.010	0.025	< 0.010
222	0.014	< 0.010	0.020	< 0.010
224	0.011	< 0.010	0.016	< 0.010
226	< 0.010	< 0.010	0.013	< 0.010
228	< 0.010	< 0.010	0.010	< 0.010

Table 9-5 Estimated acoustic impulse versus range for impact pile driving of the lattice/tripod and monopile supports.

Range (km)	Impulse (Pa·s)			
	Lattice/Tripod Impact Piling		Monopile Impact Piling	
	Scenario 2A: Unmitigated	Scenario 3A: Mitigated	Scenario 2B: Unmitigated	Scenario 3B: Mitigated
0.005	378.2	119.6	558.7	176.7
0.010	189.1	59.8	279.3	88.3
0.015	126.1	39.9	186.2	58.9
0.020	94.6	29.9	139.7	44.2
0.025	75.6	23.9	111.7	35.3
0.030	63.0	19.9	93.1	29.4
0.035	54.0	17.1	79.8	25.2
0.040	47.3	15.0	69.8	22.1
0.045	42.0	13.3	62.1	19.6
0.050	37.8	12.0	55.9	17.7
0.055	34.4	10.9	50.8	16.1
0.060	31.5	10.0	46.6	14.7
0.065	29.1	9.2	43.0	13.6
0.070	27.0	8.5	39.9	12.6
0.075	25.2	8.0	37.2	11.8
0.080	23.6	7.5	34.9	11.0
0.085	22.2	7.0	32.9	10.4
0.090	21.0	6.6	31.0	9.8
0.095	19.9	6.3	29.4	9.3
0.100	18.9	6.0	27.9	8.8

9.2.2 Operations

The 95th percentile ranges for specific noise threshold levels were determined for operations scenarios 14 and 15 based on the sound level contours generated by MONM (see Section 8.4.1 for details). Scenario 14 (turbine operations) included the total noise contribution of 110 individual WTGs operating simultaneously. At long ranges, corresponding to sound level contours of 120 dB re 1 µPa and lower, the noise contours represent the summation of the total noise field from all the operating turbines (c.f., Figure 9-17). At shorter ranges, corresponding to sound level contours of 125 dB re 1 µPa and higher, noise from a single turbine dominates the sound field. Therefore, distances to noise contours at 120 dB and lower were computed from the geometric centroid of all of the source positions. Sound levels of 125 dB re 1 µPa and higher were not exceeded beyond 100 m range from the individual WTGs. For Scenario 15 (turbine maintenance), ranges were computed relative to a single noise source. Table 9-6 presents the 95th percentile ranges computed for *rms* SPL values between 90 dB re 1 µPa and 150 dB re 1 µPa for both operations scenarios.

Table 9-6 Modelled 95th percentile rms SPL ranges for wind farm operations scenarios 14 and 15 computed using MONM.

SPL (dB re 1 µPa)	95th Percentile Sound Level Ranges (km)	
	Scenario 14: Turbine Operations	Scenario 15: Turbine Maintenance
90	35.568	36.311
95	25.990	27.150
100	18.485	19.451
105	13.074	13.148
110	9.428	8.202
115	7.531	4.950
120	6.279	2.940
125	< 0.100	1.589
130	< 0.100	0.742
135	< 0.100	0.363
140	< 0.100	0.206
145	< 0.100	< 0.100

9.3 DECOMMISSIONING

Decommissioning of the Project and associated infrastructure will produce a temporary increase in the amount of underwater noise and vibration in the Hecate Strait area. It is anticipated that most of the decommissioning process will be a reversal of installation procedures (Nedwell and Howell 2004, MMS 2008, Pearson), with similar equipment and vessels used to remove the wind turbine generator (WTG), cables, offshore converter platform, and scour protection (MMS 2008). As a result, noise levels produced during decommissioning of these components will be similar to levels produced during their construction.

The amount of noise and vibration produced during decommissioning of WTG pile foundations will depend on the method of pile removal. Unfortunately, information on WTG foundation disposal is limited as offshore wind energy structures are relatively new developments, with an expected design life of 20 – 50 years (Vella *et al*. 2001, The Marine Institute 2000). However, similarities between pile foundations used for WTGs and offshore oil platforms suggest decommissioning options will be similar to those used by the offshore oil and gas industry (Nedwell and Howell 2004). Currently, these options include total foundation removal, toppling to the sea floor, and leaving the foundation in place (Pulsipher *et al*. 2000, Schroeder *et al*. 2004). Total removal and toppling both require severing the pile foundation at or just below the sea floor using abrasive jet or diamond wire cutting (Nedwell and Howell 2004, Nedwell *et al.* 2003, MMS 2008, Pearson, Diederichs *et al*. 2008, GGOW 2007) or underwater explosives (Nedwell and Howell 2004, Nedwell *et al.* 2003, MMS 2004). In the case of total removal, the severed pieces are transported to shore and recycled or discarded, while for toppling, they are allowed to settle to the ocean floor (Pulsipher *et al*. 2000, Schroeder *et al*. 2004). At the time of writing, noise levels produced by jet cutting are not available (Nedwell and Howell 2004, Diederichs *et al*. 2008). However, underwater explosions have been well documented (MMS 2004, Connor 1990, Keevin and Hempen 1997), and the amount of noise and vibration produced will depend on the type of the explosive and how it is used (Nedwell and Howell 2004). This method of severance will likely produce a loud point source of underwater noise and therefore present a serious risk of tissue or hearing damage to nearby marine mammals (Diederichs *et al*. 2008). As such, determination of impact radii using sound modelling prior to decommissioning is highly advisable. As an alternative to total removal and toppling, the wind project may be left in place and used for other means. No appreciable increase in noise is anticipated by leaving the foundation in place, but this method of decommissioning may raise other environmental concerns.

9.4 NOISE MITIGATION OPTIONS

9.4.1 Pile Driving

Pile driving is expected to produce the highest intensity underwater noise levels associated with the Project. Mitigation of piling noise is desirable in order to reduce the impact of piling activities on VECs. Two technical reports prepared for the UK's COWRIE organization provide an up-to-date review of available piling noise mitigation technologies (Nehls *et al*. 2007, Thomsen *et al*. 2006). Based on a review of the available literature, the following have been identified as the most promising methods for mitigating the impacts of piling noise for the Project:

1. Implementing ramp-up/soft-start procedures
2. Using biologist observers
3. Using sonar to detect VECs
4. Utilising hammer technology that minimizes noise (eg vibrohammer)
5. Scheduling activities at times of low usage by or presence of VECs to minimize impacts
6. Using bubble curtains
7. Using air-filled or foam-filled pile sheaths and/or
8. Acoustic monitoring

Other mitigation methods, such as modifying the pile driving ram or mantling the hammer with damping material were rejected as impractical, since they would be costly to implement and have not been proven to be effective (Thomsen *et al*. 2006).

Hydraulic powered vibratory hammers drive piles by a series of rapid, low-intensity strikes, as opposed to the large, high-intensity blows produced by an impact hammer. Vibratory hammers generate lower intensity, continuous noise rather than the high intensity impulsive noise from an impact hammer. The resultant overall noise footprint associated with a vibratory hammer is reduced in comparison to that for an impact hammer. Additionally, it is expected that exposure to noise of a vibratory hammer is very unlikely to induce injury due to the much reduced peak pressure levels associated with the vibratory hammer. The US National Marine Fisheries Service (Alaska) determined that fish are likely to avoid sounds similar to those produced by vibratory hammers (NMFS, 2005). The impulses associated with impact hammering, however, are too brief in duration and do not contain enough sound energy in the infrasound range for perception and response by fish. Fish are therefore less likely to avoid noise from an impact hammer and are more likely to remain within potentially injurious range of impact hammer noise.

Ramp-up (also called soft-start) is a mitigation method that involves gradually increasing the hammer energy at the start of pile driving over a period of several minutes. The gradual increase in noise levels associated with ramp-up gives VECs the opportunity to move away from the pile driving, thus reducing the risk of an injurious exposure (Richardson *et al*. 1995). Ramp-up procedures can be implemented alongside other mitigation strategies, such as bubble curtains or pile sleeves.

Bubble curtains are commonly used to dampen noise from pile driving. A bubble curtain works by saturating the water surrounding a pile with sound-attenuating air bubbles. A bubble curtain typically consists of one or more aerating tubes, fitted around the pile, which inject a continuous flow of bubbles into the water. The bubble curtain is supplied by an air compressor that is connected to the aerating tubes via air hoses. The broadband noise reducing capabilities of bubble curtains have been reported to be as high as 20 dB (*e.g*., MacGillivray *et al*. 2006) and as low as 3 dB (*e.g*., Vagle 2003). The sound attenuation of a bubble curtain depends on the volume of airflow, the size of the air bubbles, as well as on the design of the bubble curtain itself (Vagle 2003). Ocean currents can reduce the effectiveness of bubble curtains; however the effect of currents can be mitigated by placing a fabric mantle around the pile to confine the bubbles. At present, the degree of effectiveness of bubble curtains cannot be reliably predicted and must be measured *in situ* during actual piling operations.

In 2007, bubble curtain technology was successfully deployed at the proponent's wind farm grid site during installation of the meteorological mast support piles, albeit with a much smaller pile. Underwater sound measurements showed that the bubble curtain achieved 13 dB attenuation of the peak levels from the piling (Racca *et al.* 2007) as measured at 10m range. The bubble curtain was constructed by the pile driving contractor, Fraser River Pile and Dredge (FRPD). It consisted of a single ~3 foot diameter aerating ring made of a 1 inch diameter rubber air hose. The aerating ring was perforated with 1/8 inch air holes spaced four inches apart. The bubble curtain was supplied by an air compressor at a rate of 175 CFM (cubic feet per minute). A diver deployed the bubble curtain ring at the pile base prior to hammering. Although a similar bubble curtain could be deployed during hammering of the WTG substructure support piles, the time required to install the bubble curtain significantly adds to the overall duration of the pile driving process.

A promising alternative to bubble curtains is the use of air-filled or foam-filled pile sleeves. A pile sleeve consists of two concentric tubular sheaths, surrounding the pile, with a gap between them that may be either air-filled or foam-filled. The sleeve must be long enough to extend from the seabed to the water surface but must not be so long as to interfere with the action of the pile driving hammer. A crane is typically used to lower the sleeve over the pile, prior to pile driving. Recent tests of air-filled and foam-filled pile sleeves performed for Washington State Ferries showed broadband noise attenuation in excess of 20 dB at close range (MacGillivray *et al*. 2006). However, pile sheath mitigation is expected to be significantly more difficult to implement than bubble curtain mitigation, due to the sizable dimensions of the sleeves that would be needed for surrounding large diameter steel piles.

It is recommended that *in situ* acoustic monitoring should be used to measure underwater sound levels from pile driving and to verify the effectiveness of any sound level mitigation that is adopted. Acoustic monitoring can also be used to verify, and adjust if appropriate, the ranges to threshold zones and exclusion zones for marine mammals and fish. Acoustic monitoring of pile driving would only need to be conducted at a limited number of locations because water depth and seabed conditions are fairly uniform throughout the wind farm area. Trained observers should be employed during the piling operations to ensure that no marine mammals enter into designated exclusion zones and to verify whether any fish mortality in the area is caused by the piling operations. Deploying sonar could enhance the effectiveness of observers. If marine mammals are observed inside of the designated exclusion zones (either visually or using sonar) then the operations should be shut down until the animals are once again outside of the exclusion zone. Finally, careful planning and scheduling of piling activities can also be used as an effective mitigation strategy. If feasible, pile driving should be scheduled to coincide with periods when VECs are not present (Richardson *et al*. 2005).

9.4.2 Vessel Operations

Predominant sources of underwater noise during construction operations will include vessels performing barge towing, cable-laying, material dumping, structure installation, and anchor handling. The types of vessels involved in the construction operations are ocean going tugs, crane vessels, dynamic-positioning (DP) vessels, and barges. In particular, tugs under propulsion during towing and anchor handling are generally at high power and so have the potential to create substantial underwater noise. At high propulsion levels the predominant noise source with most vessels is propeller cavitation. Noise from cranes is expected to be intermittent and unlikely to propagate substantially into the water. Barges are not under their own power and do not contribute substantially to the underwater noise levels. Dynamic positioning vessels will use thrusters, which are known to be substantial contributors of noise.

The following options have been identified as the best available methods for mitigating the impacts of vessel noise emissions for the Project:

1. Regular inspection and maintenance of propellers and thrusters
2. Minimize vessel speed and acceleration during operations
3. Eliminate non-essential noise sources on board vessels
4. Vessels to standby when not in use
5. Navigation restrictions to avoid VEC high-use areas
6. Scheduling activities to minimize VEC impacts
7. Acoustic monitoring

Propeller tip vortex cavitation is one of the primary sources of sub-surface acoustic noise from shipping, and is generally the strongest in terms of overall sound pressure. The cause of cavitation is low-pressure cavities created by a loaded propeller. These low-pressure cavities fall below the vapour pressure of the water, causing the water to change phase from liquid to gas. Collapse of these cavities results in high amplitude broadband acoustic events occurring at a frequency of the shaft speed multiplied by the number of blades. Due to the intrinsic relationship of cavitation and the pressure differentials created by the propeller, the only avenue to mitigate cavitation noise is to lower the pressure differential. This can only be achieved by reducing the loading on the propeller or altering the geometry of the propeller to reduce the pressure differentials under the same loading conditions.

Operational mitigation is best achieved by the minimization of ship propulsion noise. Propeller cavitation, once it begins, will be the dominant noise source. All propellers will cavitate if sufficiently loaded. The high load may be due to high installed power, rapid increase in revolutions, crash stops or violent manoeuvres. However, proper propeller design will avoid cavitation under normal operation and raise cavitation speed as high as possible. It is important that the propeller remains in good condition, as damage will increase the propensity to cavitate. Reduction of cavitation requires monitoring and maintenance of propeller condition, since damaged propellers create more noise. In addition, many custom propeller shapes have been developed to combat cavitation. In particular “high skew” propellers are well suited to minimizing cavitation and are readily available from many manufacturers.

Other operational mitigation procedures for vessels which could be used are speed reduction, engine power reduction, time management, and navigation/route planning. Using a larger number of tugs at lower power may produce less noise than fewer tugs under higher power. Minimizing the use of thrusters would reduce noise levels. Implementation of policies that maintain support vessels off-station when unnecessary would lessen overall worksite noise. Ensuring unnecessary machinery is inactive aboard support vessels would further minimize radiated noise. With all construction operations, careful planning and scheduling of activities can be used as an effective mitigation strategy. Navigation restrictions can be imposed on construction vessel traffic in order to avoid VEC high-use areas. If feasible, construction operations should be scheduled to coincide with periods when VECs are not present. In situ acoustic measurements can be used to quantify noise emissions from construction operations and to verify the effectiveness of any mitigation strategies that are adopted.

9.5 DISCUSSION

9.5.1 Pile Driving Impact

The highest intensity noise levels from construction activities associated with the Project are expected to be from impact hammer pile driving of the WTG substructure support piles (Scenarios 2A through 3B from Section 8.4.3). Impact pile driving generates pulsed noise, as opposed to continuous noise, and so the pulsed noise impact criteria from Section 8.3.1 apply to this source. In terms of the old US NMFS “Level A” SPL impact criteria for cetaceans, the modelling predicts that noise from unmitigated impact hammer pile driving will reach 180 dB re 1 µPa *rms* level at approximately 1.2 km range for the tripod/lattice foundation and 2.0 km range for the monopile foundation (c.f. Table 9-2 and Table 9-3, respectively). For mitigated piling, assuming a 10 dB reduction in the broadband levels can be achieved, the range to the 180 dB re 1 µPa threshold level is predicted to be reduced by 80% to 239 m for the tripod/lattice foundation and by 79% to 421 m for the monopile foundation. Ranges to the 160 dB re 1 µPa *rms* SPL threshold ("Level B" Harassment) for marine mammals are predicted to be approximately 13.8 km and 17.9 km for unmitigated piling of tripod/lattice and monopile foundations respectively, while for mitigated piling, these values are reduced to 4.6 km and 6.8 km (c.f. Table 9-2 and Table 9-3, respectively).

According to the more recent noise exposure criteria of Southall *et al.* (2007), the injury threshold for cetaceans (onset of PTS) corresponds to M-weighted SELs above 198 dB re 1 µPa^2 s and the injury threshold for pinnipeds (onset of PTS) corresponds to M-weighted SELs above 186 dB re 1 µPa^2 s. Unlike the peak or *rms* SPL, the SEL is a cumulative metric and so the range at which this threshold would be exceeded depends on the total number of sound pulses generated by the pile driving. This is because the "dosage" of sound energy received by an animal increases with the number of pulses. Table 9-7 shows the range at which the Southall *et al.* (2007) M-weighted SEL criteria would be exceeded for a specified number of strikes from the pile driving hammer. The ranges in Table 9-7 were computed for a stationary receiver. Note that, the anticipated number of pile driver strikes per hour is approximately 1800 (~2 s between blows) for both tripod/lattice and monopile foundations, and the total time to drive a single pile is anticipated to be approximately 2 hours. According to Table 9-7, the threshold ranges for mid-frequency odontocetes are shorter than for mysticetes, because noise from the pile driving is concentrated at lower frequencies where the hearing sensitivity of odontocetes is poorer. The threshold ranges are longer for pinnipeds, because the SEL injury threshold is lower for pinnipeds than for cetaceans. Note that, according to Southall *et al.* (2007), the SEL should be "reset" after 24 hours to account for the recovery of the auditory system after exposure to noise. Finally, according to the modelling, the SEL injury thresholds would be exceeded at longer ranges than the peak SPLs for pile driving. Therefore, given the dual criterion nature for impact thresholds in Southall *et al*. (2007), the SEL threshold should be applied rather than the peak SPL threshold for evaluating impacts for this source.

Injury threshold ranges for fish may also be estimated based on the modelled pile driving levels from this study. According to the peak level estimates in Table 9-4, the 210 dB re 1 µPa peak SPL threshold criterion, corresponding to the current BC Marine and Pile Driving Contractor's Association guidelines for marine pile driving, would be exceeded at 54 m and 79 m for the unmitigated lattice/tripod and monopile scenarios, respectively. For the mitigated piling, the 210 dB re 1 µPa peak threshold would be exceeded at 17 m and 25 m for the lattice/tripod and monopile scenarios, respectively. Ranges based on the interim injury criteria of the Fisheries Hydroacoustic Working Group (2008) are higher. The 206 dB re 1 µPa peak SPL interim threshold criterion would be exceeded at 86 m and 126 m for the unmitigated lattice/tripod and monopile scenarios respectively. For the mitigated piling, the 206 dB re 1 µPa peak threshold would be exceeded at 27 m and 40 m for the tripod/lattice and monopile scenarios, respectively. Table 9-2 shows the ranges at which the SEL based injury threshold for fish would be reached for a specified number of strikes from the pile driving hammer. These ranges were computed for a stationary receiver. Injury threshold ranges are greater for fish with smaller body mass since smaller fish are more susceptible to injury from exposure to pile driving noise. Note that, according to Carlson *et al*. (2007), the SEL should be "reset" after 18 hours to account for the recovery of the auditory system after exposure to noise. Impact ranges for invertebrates are assumed shorter than those for fish, given that invertebrates are expected less susceptible to acoustic injury.

Pile driving injury thresholds for birds may be estimated based on the estimated acoustic impulse values presented in Table 9-5. For the unmitigated piling, the no-injury impulse threshold for birds, corresponding to Φ=41 Pa·s, would be exceeded at ranges less than 50 m and 70 m for the tripod/lattice and monopile scenarios respectively. For the mitigated piling, the no-injury impulse threshold would be exceeded at ranges less than 15 m and 25 m for the tripod/lattice and monopile scenarios, respectively. Note that the impulse threshold for onset of slight, recoverable injuries for marine birds is over three times greater than the no-injury threshold (*c.f.* Section 8.3.3).

Table 9-7: Modelled ranges at which the Southall *et al.* (2007) injury criteria for marine mammals (M-weighted SEL) would be exceeded for a specified number of pile driving strikes. Ranges were computed for a stationary receiver. The total number of pile driving strikes per hour is approximately 1800-2400 and the total time for driving a single pile is approximately 2 hours.

	Scenario 2B: Unmitigated Monopile Impact Piling				Scenario 3B: Mitigated Monopile Impact Piling			
Number of Piling Strikes	Mysticete PTS Threshold 198 dB re 1 µPa^{2}s	Mid-freq Odontocete PTS Threshold 198 dB re 1 µPa^{2}s	High-freq Odontocete PTS Threshold 198 dB re 1 µPa^{2}s	Pinniped PTS Threshold 186 dB re 1 µPa^{2}s	Mysticete PTS Threshold 198 dB re 1 µPa^{2}s	Mid-freq Odontocete PTS Threshold 198 dB re 1 µPa^{2}s	High-freq Odontocete PTS Threshold 198 dB re 1 µPa^{2}s	Pinniped PTS Threshold 186 dB re 1 µPa^{2}s
1	0.011 km	< 0.010 km	< 0.010 km	0.143 km	< 0.010 km	< 0.010 km	< 0.010 km	0.016 km
10	0.129 km	0.054 km	0.050 km	0.747 km	0.011 km	< 0.010 km	< 0.010 km	0.143 km
100	0.635 km	0.436 km	0.369 km	3.109 km	0.129 km	0.054 km	0.050 km	0.747 km
1000	2.708 km	2.046 km	1.759 km	10.256 km	0.635 km	0.436 km	0.369 km	3.109 km
2000	3.751 km	2.868 km	2.512 km	13.650 km	0.960 km	0.662 km	0.559 km	4.626 km
4000	5.592 km	4.475 km	3.918 km	17.300 km	1.598 km	1.168 km	0.983 km	6.422 km
8000	7.822 km	6.423 km	5.678 km	22.453 km	2.373 km	1.782 km	1.518 km	9.322 km

Table 9-8: Modelled ranges at which the Fisheries Hydroacoustic Working Group (2008) SEL injury criterion for listed fish species would be exceeded for a specified number of pile driving strikes. Ranges were computed for a stationary receiver. The total number of pile driving strikes per hour is approximately 1800-2400 and the total time for driving a single pile is approximately 2 hours.

	Lattice/Tripod Impact Piling				Monopile Impact Piling			
	Scenario 2A: Unmitigated		Scenario 3A: Mitigated		Scenario 2B: Unmitigated		Scenario 3B: Mitigated	
Number of Piling Strikes	Fish Injury (>2g) Threshold 187 dB re 1µPa^{2}s	Fish Injury (<2g) Threshold 183 dB re 1µPa^{2}s	Fish Injury (>2g) Threshold 187 dB re 1µPa^{2}s	Fish Injury (<2g) Threshold 183 dB re 1µPa^{2}s	Fish Injury (>2g) Threshold 187 dB re 1µPa^{2}s	Fish Injury (<2g) Threshold 183 dB re 1µPa^{2}s	Fish Injury (>2g) Threshold 187 dB re 1µPa^{2}s	Fish Injury (<2g) Threshold 183 dB re 1µPa^{2}s
1	0.060 km	0.149 km	< 0.010 km	0.017 km	0.139 km	0.250 km	0.014 km	0.045 km
10	0.433 km	0.835 km	0.060 km	0.149 km	0.744 km	1.383 km	0.139 km	0.250 km
100	1.976 km	3.305 km	0.433 km	0.835 km	3.055 km	4.971 km	0.744 km	1.383 km
1000	6.751 km	10.427 km	1.976 km	3.305 km	9.780 km	14.213 km	3.055 km	4.971 km
2000	9.329 km	13.772 km	2.888 km	4.574 km	12.999 km	17.912 km	4.364 km	6.820 km
4000	12.671 km	17.787 km	4.155 km	6.766 km	16.692 km	23.390 km	6.210 km	9.800 km
8000	16.467 km	22.612 km	6.045 km	9.352 km	21.589 km	29.779 km	8.821 km	13.025 km

9.5.2 Pile Refusal

Pile "refusal" occurs when a pile begins to encounter significant resistance and no longer penetrates into the substrate. As a pile approaches refusal, the hammer energy required for driving the pile increases, as do the concomitant underwater noise emissions. A recent study of impact hammer piling noise was conducted in the UK that measured underwater noise levels during refusal of a test-pile (Robinson et al. 2007). Published measurements from this study show that, as the test-pile pile approached refusal, the SPL and SEL increased with the hammer energy in a predictable, linear fashion (~3 dB per doubling of energy). Furthermore, at refusal, the pulse period became more erratic and the variability in the measured sound levels increased substantially. Noise level predictions in the current study were based on precautionary estimates of the typical hammer energies that would be required for driving piles within the wind farm. It is anticipated that the single pulse noise estimates from this study could be exceeded for a limited period of time, in the case of pile refusal. However, noise generated by the majority of pile strikes is expected to be at, or below, the modelled levels provided in the current study. Furthermore, since pile refusal represents only a small fraction of the total number of strikes required to drive a pile, the cumulative SEL estimates provided in the previous section are not expected to be exceeded in the case that pile refusal is encountered.

9.5.3 Vessel Noise Impact

The highest noise levels for the vessel-based construction activities are expected to be from positioning of the WTG installation vessels and installation of the converter platform (model scenarios 1 and 11, respectively). Both of these construction scenarios involve the use of ocean going tugs performing anchor handling operations. In both cases, the anchor handling tugs are the dominant contributors to the noise field from the vessel spread. Noise levels down to 120 dB re 1 µPa *rms* SPL for these scenarios, corresponding to the lower estimated behavioural response threshold for mysticetes from Southall *et al.* (2007), are estimated to extend to 24.0 km and 18.5 km range, respectively.

Levels down to 90 dB re 1 µPa *rms* SPL, corresponding to the lower estimated behavioural response threshold for odontocetes from Southall *et al*. (2007), are estimated to extend beyond 70 km range for these scenarios. One should note however that ambient noise measurements carried out by JASCO during 2008 showed that background noise levels in Hecate Strait regularly exceeded 90 dB re 1 µPa in all decade bands from 10 Hz to 10 kHz (see the results section of the ambient study chapter of this volume). Furthermore, noise generated by ships is primarily concentrated a low frequencies < 1 kHz which is at the lower hearing range of most odontocetes (*c.f.*, NRC 2003 Fig 1-1). Thus, vessel noise at these ranges is expected to be at the lower detectable limit for most odontocetes in Hecate Strait.

Neither the vessel-based construction activities nor the vibro-hammering are expected to generate injurious levels of noise exposure over a 24 hour period, based on the Southall *et al.* (2007) injury criteria for marine mammals exposed to continuous noise. There are no data on impact thresholds for fish, invertebrates and marine birds exposed to continuous noise. Vessel-noise impact on these animals was therefore could not be determined.

9.5.4 Turbine Operating Noise

The modelling shows that noise levels from the operating wind farm (model scenario 14) are strongly tied to the total number of operating wind turbines. That is, the collective underwater noise emission from 110 turbines will be substantially greater than for a single turbine. This is partly due to the additive effect of multiple noise sources operating concurrently and also partly due to the large area over which the noise sources are distributed. The main contribution to the underwater noise emitted from the wind turbines is expected to be from acoustic coupling of the vibrations of the substructure into the water rather than from transmission of in-air noise from the turbines into the water (Lidell 2005). Sound pressure levels greater than 120 dB re 1 µPa *rms* SPL are predicted to occur at ranges less than 8.5 km (c.f. Table 9-6). This is the distance to the centre of the wind farm grid and not to a single turbine. Noise levels of the operating wind farm are too low to cause injury in marine mammals and the ranges to the injury thresholds for continuous noise were not computed from the model results. There is no data on impact thresholds for fish, invertebrates and marine birds exposed to continuous noise. Turbine operating noise impact on these animals was therefore not modelled.

9.5.5 Model Uncertainties

It is important to note that, while the modelling results presented here are expected to provide a precautionary estimate of noise levels produced by construction and operation of the NaiKun wind farm, there are several sources of uncertainty associated with the modelling that must be taken into consideration. Proxy source levels for each of the modelling scenarios presented in this report were derived from underwater source measurements of similar equipment operating in different environments. Actual source levels may be different. In particular, there are large variations in reported source levels for impact hammer pile driving (see *e.g.*, Nehls *et al*. 2007, Table 2-1). The acoustic source level of pile driving is expected to be site-specific, since the efficiency (and therefore the loudness) of impact piling depends on the resistance of the substrate, as well as on the hammer energy and pile size. Furthermore, ocean going vessels all have unique acoustic signatures and published source level measurements of many classes of vessels are sparse or absent. More accurate model estimates would require *in situ* source level measurements for the actual construction and operational noise sources that are intended to be employed by the proponent. However, no such measurements were available at the time of writing and therefore proxy sources were used for the modelling.

Another source of uncertainty is that the model, by necessity, presents a static representation of the noise emissions from any given construction or operational scenario. In reality, noise from mechanical sources like vessels, pile driving and wind turbines changes dynamically with time. For example, the noise emissions from an operation like anchor handling will depend on the propulsion force employed by the different tugs in the spread. Vessel propulsion depends on winds and currents, as well as on innumerable operational considerations, which are beyond the capability of noise modelling to capture. Modelled levels presented in this report represent a mean snapshot of the noise emissions from any given operation.

Another source of uncertainty in the modelling is the limited available knowledge regarding the acoustic environment at the construction and operation sites. The most important environmental parameters that affect sound propagation are the sound speed profile, the bathymetry and the geoacoustics, as described in Section 8.4.2. In addition, roughness of the sea-surface and sea-bottom has a strong influence on sound propagation at higher frequencies. Uncertainties in environmental parameters are either due to lack of data or lack of forecasting ability. An example of the former source of uncertainty is the limited knowledge of the geoacoustic properties of the sub-bottom at the modelling sites. An example of the latter source of uncertainty is not being able to know the exact sound speed profile conditions and sea-state when a particular operation is going to be conducted. As with other sources of uncertainty, the modelling provides a best estimate, subject to the limitations of the available environmental data. Given the various sources of uncertainty in the modelling, it is recommended that *in situ* acoustic measurements be conducted in order to verify underwater noise emissions from those operations which have the greatest potential to impact VECs (*e.g.*, such as the pile driving).

9.6 CONCLUSIONS

This section of the Noise and Vibration Study has presented the results from a modelling study that was carried out in order to forecast underwater noise levels from construction and operational activities associated with the Project. The purpose of this noise modelling study was to help evaluate the potential impacts of project activities on VECs in the surrounding environment, and to identify various underwater noise mitigation options. Numerical acoustic modelling techniques were employed in order to estimate underwater noise levels from project activities based on the best available source level and environmental data. Activities that were modelled as part of this study included pile driving, turbine installation, converter platform installation and cable-laying, as well as the normal operation of the Wind Turbine Generators. A total of 13 different construction scenarios and two different operational scenarios were modelled. In addition, a review of anticipated noise sources associated with wind farm decommissioning was presented. Thematic maps of modelled noise level contours as well as tables of modelled noise threshold ranges were presented for each one of the 15 model scenarios considered in the present study.

The highest underwater noise levels associated with this project were predicted to be from impact hammer pile driving of the turbine substructure support piles. Noise level predictions were generated for three different turbine substructure support designs: monopile (1 pile), tripod (3 piles), and lattice (4 piles). In addition, the influence of sound barrier mitigation (*e.g.*, bubble curtain or pile sheath) on the sound levels was also modelled. Impact threshold ranges were substantially reduced for mitigated pile driving. It is anticipated that a 10 dB reduction in piling noise levels could be achieved using bubble curtain mitigation during pile driving operations. Pile sleeves were identified as another promising mitigation technology that could provide potentially greater reductions in overall noise levels. The highest underwater noise levels from vessel-based construction activities were predicted to be from positioning of the WTG installation vessels and installation of the converter platform. Both of these construction activities involved powerful ocean going tugs performing anchor handling operations. In order to mitigate vessel noise as much as reasonably feasible, it is recommended that vessel propellers and thrusters be maintained in good condition (with the potential use of cavitation-reducing propellers) and that vessel speed and acceleration be limited when operating near VEC high-use areas. Several other vessel noise mitigation options were presented as part of this study (see Section 9.4.2).

Although the noise modelling methods employed in this study are known to be accurate for predicting noise levels in the vicinity of industrial operations, inevitable uncertainty remains in the acoustic source levels and environmental parameters used as model inputs. The major sources of uncertainty in the modelling were the limited available source level data for many types of offshore equipment, and also limited knowledge regarding *e.g.*, geoacoustic parameters of the seabed in Hecate Strait. Therefore, it is recommended that *in situ* noise measurements be conducted during the loudest construction operations, such as during pile driving and platform installation, in order to better constrain the potential for noise impacts on VECs from project activities.

References

Austin, M. 2008. Detailed Study Design for Noise and Vibration. Technical report prepared for NaiKun Wind Development by JASCO Research Ltd. 25pp.

Austin, M., A.O. MacGillivray, and D. Hannay. 2005. Maersk Rover Acoustic Sound Level Measurements. Technical report prepared for Sakhalin Energy Investment Company by JASCO Research Ltd. Document Number: 0000-S-90-04-P-7058-00

Arveson, P.T. and D.J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. Journal of the Acoustical Society of America 107(1).

Baird, T. 2008. Project Description. Technical report prepared for NaiKun Wind Development by ODE Ltd. Document Number: 9131-PM.

Barrie, J.V., J. L. Luternauer, K.W. Conway and A. Caltagirone. 1990. Surficial Geology of the Queen Charlotte Basin. GSC Open Files 2193, 2195, 2196, 2197, Geological Survey of Canada.

BC Marine and Pile Driving Contractors Association. 2003. Best management practices for pile driving and related operations. BC Marine and Pile Driving Contractors Association.

California Department of Transportation (Caltrans). 2001. San-Francisco Oakland Bay Bridge east span seismic safety project pile installation demonstration project: Marine mammal impact assessment Appendix D. PIDP EA 012081, Caltrans contract 04A0148, Task order 205.10.90.

Carlson, T., M. Hastings, and A. Popper. 2007. Memorandum to Deborah McKee (California Department of Transportation) and Paul Wagner (Washington Department of Transportation) in July of 2007.

Collins, M.D. 1993. A split-step Pade solution for the parabolic equation method. Journal of the Acoustical Society of America. 93(4).

Connor Jr., J.G. 1990. Underwater Blast Effects from Explosive Severance of Offshore Platform Legs and Well Conductors. Naval Service Warfare Center. Document Number: NAVSWC TR 90-532.

Diederichs, A., G. Nehls, M. Dähne, S. Adler, S. Koschinski and U. Verfuß. 2008. Methodologies for measuring and assessing potential changes in marine mammal behaviour, abundance or distribution arising from the construction, operation and decommissioning of offshore windfarms. Technical report prepared by BioConsult SH, German Oceanographic Museum, and University of Rostock for COWRIE Ltd.

Greater Gabbard Offshore Winds Ltd (GGOW). 2007. Decommissioning Programme Greater Gabbard Offshore Wond Farm Project. Document No. 577000/403 – MGT100 – GGR – 107.

Hannay, D., A. MacGillivray, M. Laurinolli and R. Racca. 2004. Source Level Measurements from 2004 Acoustics Program. Technical report prepared for Sakhalin Energy Investment Company by JASCO Research Ltd.

Hannay, D., and R. Racca. 2005. Acoustic Model Validation. Technical report prepared for Sakhalin Energy Investment Company by JASCO Research Ltd. Document Number: 0000-S-90-04-T-7006-00-E.

Illingsworth & Rodkin Inc., 2001. Noise and vibration measurements associated with the pile installation demonstration project for the San Francisco-Oakland Bay Bridge East Span.

ISO 266-1975. 1995. Acoustics - Preferred frequencies for measurements. International Standards Organization.

Fisheries Hydroacoustic Working Group. 2008. Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities. FHWG Agreement in Principle Technical/Policy Meeting Vancouver, WA. June 11, 2008.

Keevin T.M., and G. L. Hempen. 1997. The environmental effects of underwater explosions with methods to mitigate impacts. U.S. Army Corps of Engineers.

Lidell, H. 2003. Utgrunden off-shore wind farm: Measurements of underwater noise. Technical report prepared for Airicole, GE Wind Energy and SEAS/Energi/E2 by Ingemansson Technology AB, Goteborg, Sweden.

MacGillivray, A., D. Hannay and S. Carr. 2002. Acoustic Monitoring, 2001. P3-1 to 3-51 In: Miller, G.W. and R.A. Davis (eds.). 2002. Marine mammal and acoustical monitoring of Anderson Exploration Ltd.'s open-water seismic program in the southeastern Beaufort Sea. Final report by LGL Ltd. and JASCO Research Ltd for Devon Canada Corporation. Document Number: TA2618-1.

MacGillivray, A., E. Ziegler, and J. Laughlin, 2006. Underwater acoustic measurements from Washington State Ferries 2006 Mukilteo Ferry Terminal Test Pile Project. Technical report prepared by JASCO Research Ltd., Victoria BC, for Washington State Ferries and Washington State Department of Transportation.

MacGillivray, A.O. 2006a. An Acoustic Modelling Study of Seismic Airgun Noise in Queen Charlotte Basin. University of Victoria Masters Thesis.

MacGillivray, A. 2006b. Underwater Acoustic Source Level Measurements of Castoro Otto and Fu Lai. Technical report prepared for Sakhalin Energy Investment Company by JASCO Research Ltd, Victoria BC.

Malme CI, Miles PR, Clark CW, Tyack P, Bird JE. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behaviour. BBN Rep. 5366. Rep from Bolt Beranek and Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. NTIS PB86-174174.

Malme CI, Miles PR, Clark CW, Tyack P, Bird JE. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behaviour. Phase II: January 1984 migration. Bolt Beranek and Newman Report No 5586 submitted to Minerals Management Service, U.S. Dept. of the Interior.

The Marine Institute. 2000. Assessment of Impact of Offshore Wind Energy Structures on the Marine Environment. Technical report prepared for The Marine Institute by Byrne Ó Cléirigh Ltd, Ecological Consultancy Services Ltd (EcoServe), and the School of Ocean and Earth Sciences, University of Southampton. Document Number: 303-X001.

Minerals Management Service. 2004. Explosive Removal of Offshore Structures-Information Synthesis Report. Technical report prepared by Continental Shelf Associates, Inc. for the U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region. Document Number: MMS 2003-070.

Minerals Management Service (MMS). 2008. Cape Wind Energy Project-Draft Environmental Impact Statement January 2008. Document Number: 2007-024

Naval Oceanographic Office (NOO). 2003. Database Description for the Generalized Digital Environmental Model – Variable Resolution (GDEM – V) (U).

National Research Council. 2003. Ocean Noise and Marine Mammals. National Academies Press, Washington D.C. 220 pp.

Nedwell, J., and D. Howell. 2004. A review of offshore windfarm related underwater noise sources. Technical report prepared by Subacoustech Ltd for COWRIE. Report Number 544 R 0308.

Nedwell, J., J. Langworthy and D. Howell. 2003. Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise. Technical report prepared by Subacoustech Ltd for COWRIE. Report Number: 544 R 0424.

Nehls, G., K. Betke, S. Eckelmann, and M. Ros. 2007. Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms. Technical report prepared by BioConsult SH, Husum Germany, for COWRIE Ltd. UK. Report number ENG-01-2007.

Pearson, D. Decommissioning Wind Turbines in the UK Offshore Zone. http://www.owen.eru.rl.ac.uk/Default.htm.

Popper, A.N., T.J. Carlson, A.D. Hawkins, B.L. Southall, and R.L. Gentry. 2006. Interim Criteria for Injury of Fish Exposed to Pile Driving Operations: A White Paper.

Pulsipher, A.G., and W. B. Daniel IV. 2000. Onshore disposition of offshore oil and gas platforms: Western politics and international standards. Ocean & Coastal Management. 43(12).

Racca, R., A. MacGillivray and M. Laurinolli. 2007. NaiKun meteo mast installation: Underwater sound level monitoring of pile driving operations. Technical report prepared for NaiKun Wind Development by JASCO Research Ltd, Victoria BC.

Richardson WJ, Wursig B, Greene CR Jr. 1986. Reactions of bowhead whales, Balaena mysticetus, to seismic exploration in the Canadian Beaufort Sea. J Acoust Soc Am 79: 1117-1128.

Richardson W.J., C. R. Greene, Jr., C. I. Malme, and D. H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego, CA.

Robinson, S.P. Lepper, P.A. and Ablitt, J. 2007. The measurement of the underwater radiated noise from marine piling including characterisation of a "soft start" period. Proceedings: Oceans 2007 – Europe. pp. 1-6.

Schroeder, D. M. and M. S. Love. 2004. Ecological and political issues surrounding decommissioning of offshore oil facilities in the Southern California Bight. Ocean & Coastal Management. 47(1 - 2).

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene Jr., D. Kastak, D.K. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas, and P.L.Tyack. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Special Issue of Aquatic Mammals, 33(4): 412-522.

Thomsen, F., K. Ludemann, R. Kafemann, and W. Piper, 2006. Effects of offshore wind farm noise on marine mammals and fish. Technical report prepared by Biola, Hamburg Germany, for COWRIE Ltd. UK.

Vagle, S, 2003. On the impact of underwater pile-driving noise on marine life. Technical report prepared by Institute of Ocean Sciences, DFO/Pacific, Ocean Science and Productivity Division.

Vella, G., I. Rushforth, E. Mason, A. Hough, R. England, P. Styles, T. Holt and P. Thorne. 2001. Assessment of the effects of noise and vibration from offshore wind farms on marine wildlife. Crown, United Kingdom. Centre for Marine and Coastal Studies Environmental Research and Consultancy.

Yelverton, J. T., D. R. Richmond, E. R. Fletcher, and R. K. Jones. 1973. Safe distances from underwater explosions for mammals and birds. Report from Lovelace Foundations Medical Education Research, Albuquerque, for Defense Nuclear Agency, Washington. 67 pp.

Zykov, M., I. Gaboury and D. Hannay. 2007. Estimates of Underwater Noise Levels from Pile Driving on Dogfish Banks, Hecate Strait. Technical report prepared for NaiKun Wind Development by JASCO Research Ltd, Victoria BC.

Appendix 8-1 Source levels

Noise Sources: Self-Propelled Vessel (Holding Position), Cable-Lay Vessel (Dynamic Positioning), Dive Support Vessel (Dynamic Positioning) Broadband Level: 177.9 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	157.9
12.5	155.0
16.0	150.8
20.0	147.2
25.0	149.2
31.5	152.8
40.0	161.0
50.0	155.2
63.0	158.3
80.0	159.1
100.0	158.6
125.0	164.2
160.0	163.6
200.0	163.8
250.0	166.2
315.0	167.4
400.0	167.9
500.0	168.3
630.0	168.1
800.0	167.7
1000.0	164.3
1250.0	160.8
1600.0	160.1
2000.0	162.4
2500.0	161.7
3150.0	162.3
4000.0	163.6
5000.0	163.4
Proxy source levels presented in this table were based on measurements of the Dive Support Vessel Fu Lai (MacGillivray 2006) operating on dynamic positioning.	

Noise Sources: Support Vessel (Stand-by), Supply Vessel (Stand-by), Marshalling Tug (Holding Position), Stand-by Tug (Stand-by) Broadband Level: 174.9 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	154.9
12.5	152.0
16.0	147.8
20.0	144.2
25.0	146.2
31.5	149.8
40.0	158.0
50.0	152.2
63.0	155.3
80.0	156.1
100.0	155.6
125.0	161.2
160.0	160.6
200.0	160.8
250.0	163.2
315.0	164.4
400.0	164.9
500.0	165.3
630.0	165.1
800.0	164.7
1000.0	161.3
1250.0	157.8
1600.0	157.1
2000.0	159.4
2500.0	158.7
3150.0	159.3
4000.0	160.6
5000.0	160.4
Proxy source levels presented in this table were based on measurements of the Dive Support Vessel Fu Lai (MacGillivray 2006) operating on dynamic positioning. Levels were reduced by 3 dB to account for engine power differences between the modelled vessels and the proxy source.	

Noise Source: Anchor Handling Tugs (Anchor Handling) BB Level: 193.2dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	176.6
12.5	171.4
16.0	168.5
20.0	165.0
25.0	164.4
31.5	165.2
40.0	164.7
50.0	171.6
63.0	180.7
80.0	183.2
100.0	184.2
125.0	183.1
160.0	182.4
200.0	183.4
250.0	186.3
315.0	178.7
400.0	177.3
500.0	178.7
630.0	175.2
800.0	175.3
1000.0	174.7
1250.0	175.2
1600.0	175.3
2000.0	173.5
2500.0	170.0
3150.0	169.1
4000.0	168.7
5000.0	169.8
Proxy source levels presented in this table were based on measurements of the Anchor Handling Supply Tug Britoil 51 (Hannay *et al*. 2004) performing anchor handling.	

Noise Sources: Pulling Tugs (Transiting), Pushing Tugs (Transiting), Stand-by Tug (Transiting) Broadband Level: 184.9 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	170.9
12.5	168.8
16.0	165.1
20.0	161.4
25.0	160.2
31.5	166.8
40.0	175.1
50.0	168.4
63.0	169.3
80.0	166.0
100.0	167.3
125.0	171.1
160.0	175.0
200.0	176.4
250.0	174.1
315.0	173.8
400.0	170.8
500.0	168.1
630.0	166.2
800.0	168.0
1000.0	166.4
1250.0	169.9
1600.0	171.4
2000.0	171.5
2500.0	167.7
3150.0	165.7
4000.0	164.6
5000.0	164.5
Proxy source levels presented in this table were based on measurements of the Anchor Handling Supply Tug Britoil 51 (Hannay *et al*. 2004) transiting at half-speed.	

Noise Source: Marshalling Tug (Transiting) Broadband Level: 181.9 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	167.9
12.5	165.8
16.0	162.1
20.0	158.4
25.0	157.2
31.5	163.8
40.0	172.1
50.0	165.4
63.0	166.3
80.0	163.0
100.0	164.3
125.0	168.1
160.0	172.0
200.0	173.4
250.0	171.
315.0	170.8
400.0	167.8
500.0	165.1
630.0	163.2
800.0	165.0
1000.0	163.4
1250.0	166.9
1600.0	168.4
2000.0	168.5
2500.0	164.7
3150.0	162.7
4000.0	161.6
5000.0	161.5
Proxy source levels presented in this table were based on measurements of the Anchor Handling Supply Tug Britoil 51 (Hannay *et al*. 2004) transiting at half-speed. Levels were reduced by 3 dB to account for engine power differences between the noise source and the proxy source.	

Noise Source: Overseas Harriette (Transiting) Broadband Level: 183.6 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	168.4
12.5	164.8
16.0	169.2
20.0	166.4
25.0	175.7
31.5	168.1
40.0	173.5
50.0	177.4
63.0	175.9
80.0	171.2
100.0	169.1
125.0	168.5
160.0	165.5
200.0	163.5
250.0	162.1
315.0	164.0
400.0	164.5
500.0	161.2
630.0	159.9
800.0	159.6
1000.0	159.3
1250.0	157.4
1600.0	156.0
2000.0	155.0
2500.0	153.5
3150.0	152.5
4000.0	151.4
5000.0	149.8
Proxy source levels presented in this table were based on measurements of the cargo ship Overseas Harriot (Arveson *et al*. 2000), travelling at 12 kts.	

Noise Sources: Anchor Handling Tugs (Holding Position) Broadband Level: 179.0 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	148.2
12.5	146.8
16.0	145.9
20.0	155.1
25.0	162.3
31.5	157.9
40.0	171.2
50.0	164.3
63.0	165.
80.0	165.6
100.0	163.0
125.0	163.4
160.0	165.9
200.0	166.4
250.0	165.9
315.0	166.5
400.0	167.4
500.0	166.7
630.0	167.3
800.0	165.7
1000.0	166.2
1250.0	164.4
1600.0	163.6
2000.0	161.1
2500.0	161.4
3150.0	160.2
4000.0	159.1
5000.0	158.3
Proxy source levels presented in this table were based on measurements of the Anchor Handling Supply Tug Maersk Rover (Austin *et al*. 2005) performing anchor handling. Levels were reduced by 3 dB to account for engine power differences between the modelled noise source and the proxy source.	

Noise Source: Rock Dumping Barge (Dumping) Broadband Level: 188.4 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	162.1
12.5	159.4
16.0	155.2
20.0	154.1
25.0	155.4
31.5	153.2
40.0	151.3
50.0	151.7
63.0	156.5
80.0	161.7
100.0	170.6
125.0	173.5
160.0	173.0
200.0	177.0
250.0	175.5
315.0	176.1
400.0	180.7
500.0	180.9
630.0	176.7
800.0	180.1
1000.0	177.4
1250.0	174.0
1600.0	173.2
2000.0	169.8
2500.0	167.4
3150.0	165.3
4000.0	160.7
5000.0	158.4
Proxy source levels presented in this table were based on measurements of the Rock Dumping Barge Pompei (Hannay *et al*. 2004) performing spoil dumping.	

Noise Source: Crew Vessel Broadband Level: 174.6 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	127.9
12.5	130.0
16.0	128.3
20.0	139.9
25.0	133.6
31.5	135.5
40.0	148.1
50.0	145.7
63.0	158.5
80.0	159.7
100.0	154.2
125.0	160.7
160.0	155.2
200.0	162.1
250.0	166.8
315.0	163.8
400.0	162.4
500.0	162.9
630.0	160.2
800.0	161.0
1000.0	161.2
1250.0	161.7
1600.0	160.3
2000.0	160.8
2500.0	161.7
3150.0	161.1
4000.0	161.5
5000.0	161.8
Proxy source levels presented in this table were based on measurements of the crew vessel Suvukti (MacGillivray *et al*., 2002) during transiting.	

Noise Source: Wind Turbine (Underwater) Broadband Level: 156.3 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
3.2	142.0
4.0	146.5
5.0	150.3
6.3	142.7
8.0	140.7
10.0	137.2
12.5	128.3
16.0	125.2
20.0	120.7
25.0	131.1
31.5	143.3
40.0	131.6
50.0	140.7
63.0	146.7
80.0	140.1
100.0	140.9
125.0	139.3
160.0	146.4
200.0	142.7
250.0	133.8
315.0	136.1
400.0	137.7
500.0	138.1
630.0	142.1
800.0	136.5
1000.0	132.1
1250.0	131.5
1600.0	132.8
Proxy source levels presented in this table were based on measurements of GE 1.5 MW turbines obtained at the Utgrunden Wind Park (Lidell 2003).	

Noise Source: Tripod/Lattice Impact Hammer Pile Driving (Underwater) Broadband Level: 215.3 dB	
Frequency (Hz)	Band Level (dB re 1µPa^2 s @ 1 m)
10.0	177.9
12.6	177.9
15.8	177.9
20.0	177.9
25.1	177.9
31.6	177.9
39.8	177.9
50.1	177.9
63.1	174.9
79.4	191.9
100.0	196.8
125.9	205.1
158.5	205.4
199.5	202.4
251.2	203.7
316.2	211.2
398.1	204.8
501.2	202.1
631.0	204.1
794.3	198.2
1000.0	199.5
1258.9	192.2
1584.9	191.6
1995.3	190.1
2511.9	187.7
3162.3	187.3
3981.1	186.0
5011.9	183.9
Proxy source levels presented in this table were based on measurements of a 1000 kJ impact hammer obtained from the 2001 San-Francisco Oakland Bay Bridge pile installation project (Caltrans 2001).	

Noise Source: Monopile Impact Hammer Pile Driving (Underwater) Broadband Level: 218.7 dB	
Frequency (Hz)	Band Level (dB re 1µPa^2 s @ 1 m)
10.0	181.3
12.6	181.3
15.8	181.3
20.0	181.3
25.1	181.3
31.6	181.3
39.8	181.3
50.1	181.3
63.1	178.3
79.4	195.3
100.0	200.2
125.9	208.5
158.5	208.8
199.5	205.8
251.2	207.1
316.2	214.6
398.1	208.2
501.2	205.5
631.0	207.5
794.3	201.6
1000.0	202.9
1258.9	195.6
1584.9	195.0
1995.3	193.5
2511.9	191.1
3162.3	190.7
3981.1	189.4
5011.9	187.3
Proxy source levels presented in this table were based on measurements of a 1000 kJ impact hammer obtained from the 2001 San-Francisco Oakland Bay Bridge pile installation project (Caltrans 2001).	

Noise Source: Tripod/Lattice Vibro-hammer Pile Driving (Underwater) Broadband Level: 192.1 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	152.6
12.6	148.3
15.8	163.8
20.0	149.8
25.1	145.2
31.6	162.1
39.8	164.4
50.1	169.4
63.1	166.1
79.4	169.8
100.0	170.8
125.9	173.8
158.5	172.5
199.5	174.1
251.2	173.2
316.2	176.3
398.1	178.0
501.2	177.3
631.0	178.9
794.3	179.3
1000.0	181.5
1258.9	181.8
1584.9	182.7
1995.3	181.6
2511.9	180.4
3162.3	179.4
3981.1	179.7
5011.9	179.3
Proxy source levels presented in this table were based on measurements of an APE 300 vibro-hammer with 1842 kN centrifugal force, driving a 0.9 m diameter pile, obtained during installation of the meteorological mast support tower at the NaiKun Wind Farm site (Racca 2007). These source levels were increased by 5.2 dB (corresponding to a doubling in intensity) in order to account for the increased force necessary for driving larger diameter piles.	

Noise Source: Monopile Vibro-hammer Pile Driving (Underwater) Broadband Level: 194.4 dB	
Frequency (Hz)	Band Level (dB re 1µPa @ 1m)
10.0	154.8
12.6	150.6
15.8	166.1
20.0	152.0
25.1	147.4
31.6	164.4
39.8	166.6
50.1	171.6
63.1	168.4
79.4	172.0
100.0	173.0
125.9	176.1
158.5	174.7
199.5	176.4
251.2	175.5
316.2	178.6
398.1	180.3
501.2	179.5
631.0	181.1
794.3	181.5
1000.0	183.8
1258.9	184.0
1584.9	185.0
1995.3	183.8
2511.9	182.6
3162.3	181.6
3981.1	182.0
5011.9	181.5
Proxy source levels presented in this table were based on measurements of an APE 300 vibro-hammer with 1842 kN centrifugal force, driving a 0.9 m diameter pile, obtained during installation of the meteorological mast support tower at the NaiKun Wind Farm site (Racca 2007). These source levels were increased by 7.4 dB (corresponding to a doubling in intensity) in order to account for the increased force necessary for driving larger diameter piles.	

Appendix 9-1 Contour Areas

Scenario 1: Positioning of WTG Installation Vessels	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	8275.436
95	7398.041
100	6361.725
105	4898.940
110	3565.335
115	2177.307
120	1119.716
125	534.529
130	242.346
135	102.824
140	38.375
145	13.881
150	4.412
155	1.120
160	0.216
165	< 0.01
170	< 0.01

Scenario 2a: Tripod/Lattice Impact Pile Driving Without Mitigation						
SEL (dB)	SPL (dB)	Area (km^2)				
		Flat-Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
150	160	369.155	368.610	278.300	237.077	341.496
155	165	147.928	147.584	104.375	85.210	132.814
160	170	50.795	50.643	31.629	24.332	44.297
165	175	15.806	15.791	9.026	7.012	13.241
170	180	4.360	4.352	2.159	1.522	3.431
175	185	0.964	0.961	0.423	0.283	0.739
180	190	0.147	0.147	0.075	0.059	0.113
182	192	0.079	0.079	0.045	0.020	0.064
184	194	0.045	0.045	0.011	< 0.0001	0.033
186	196	0.015	0.015	< 0.0001	< 0.0001	0.010
188	198	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
190	200	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
192	202	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
194	204	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
196	206	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
198	208	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
200	210	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

9.7

Scenario 2b: Monopile Impact Pile Driving Without Mitigation						
SEL (dB)	SPL (dB)	Area (km^2)				
		Flat-Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
150	160	632.846	631.955	505.591	440.034	594.822
155	165	276.942	276.470	208.365	173.852	255.941
160	170	107.955	107.734	73.290	57.468	96.351
165	175	34.649	34.565	21.417	16.561	29.725
170	180	10.625	10.590	6.131	4.389	8.846
175	185	2.735	2.717	1.336	0.943	2.123
180	190	0.586	0.584	0.245	0.148	0.454
182	192	0.285	0.285	0.109	0.081	0.195
184	194	0.123	0.123	0.064	0.050	0.092
186	196	0.069	0.068	0.032	0.012	0.055
188	198	0.035	0.035	0.010	< 0.0001	0.021
190	200	0.011	0.011	< 0.0001	< 0.0001	< 0.0001
192	202	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
194	204	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
196	206	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
198	208	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
200	210	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Scenario 3a: Tripod/Lattice Impact Pile Driving With Mitigation						
SEL (dB)	SPL (dB)	Area (km^2)				
		Flat-Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
150	160	50.795	50.643	31.629	24.332	44.297
155	165	15.806	15.791	9.026	7.012	13.241
160	170	4.360	4.352	2.159	1.522	3.431
165	175	0.964	0.961	0.423	0.283	0.739
170	180	0.147	0.147	0.075	0.059	0.113
175	185	0.028	0.028	< 0.0001	< 0.0001	0.020
180	190	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
182	192	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
184	194	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
186	196	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
188	198	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
190	200	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
192	202	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
194	204	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
196	206	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
198	208	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
200	210	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Scenario 3b: Monopile Impact Pile Driving With Mitigation						
SEL (dB)	SPL (dB)	Area (km^2)				
		Flat-Weighted	Mysticetes	Mid-frequency Odontocetes	High-frequency Odontocetes	Pinnipeds
150	160	107.955	107.734	73.290	57.468	96.351
155	165	34.649	34.565	21.417	16.561	29.725
160	170	10.625	10.590	6.131	4.389	8.846
165	175	2.735	2.717	1.336	0.943	2.123
170	180	0.586	0.584	0.245	0.148	0.454
175	185	0.094	0.093	0.047	0.028	0.072
180	190	0.011	0.011	< 0.0001	< 0.0001	< 0.0001
182	192	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
184	194	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
186	196	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
188	198	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
190	200	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
192	202	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
194	204	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
196	206	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
198	208	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
200	210	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Scenario 4a: Tripod/Lattice Vibro-hammer Pile Driving	
SPL (dB)	Area (km^2)
90	8200.148
95	7209.607
100	5800.162
105	4393.159
110	2991.863
115	1875.288
120	1013.809
125	462.473
130	166.774
135	52.066
140	14.334
145	4.988
150	1.173
155	0.203
160	0.028
165	< 0.001
170	< 0.001

Scenario 4b: Monopile Vibro-hammer Pile Driving	
SPL (dB)	Area (km^2)
90	8557.058
95	7667.859
100	6423.512
105	4998.439
110	3597.368
115	2333.343
120	1370.966
125	676.099
130	265.442
135	91.236
140	25.250
145	8.762
150	2.259
155	0.463
160	0.070
165	0.010
170	< 0.001

Scenario 5: Transport of WTG and Substructure to Wind Farm Grid	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	2583.913
95	1676.676
100	1056.116
105	620.335
110	350.330
115	183.998
120	85.374
125	35.362
130	10.892
135	2.175
140	0.546
145	0.045
150	< 0.01
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 6: Installation of WTG and Substructure	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	4932.493
95	3473.436
100	2117.187
105	1225.417
110	622.986
115	258.728
120	99.650
125	34.545
130	10.648
135	2.528
140	0.456
145	0.077
150	< 0.01
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 7: Subsea Cable-Lay in Chatham Sound	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	559.819
95	478.465
100	398.103
105	295.653
110	195.125
115	129.163
120	67.143
125	26.750
130	6.114
135	1.031
140	0.162
145	< 0.01
150	< 0.01
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 8: Subsea Cable-Lay in North Central Hecate Strait	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	3060.505
95	2159.644
100	1340.165
105	771.513
110	401.576
115	182.750
120	78.132
125	24.001
130	5.019
135	0.906
140	0.137
145	< 0.01
150	< 0.01
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 9: Cable Pull into WTG Substructures	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	4953.678
95	3503.376
100	2155.692
105	1241.977
110	627.685
115	259.127
120	98.344
125	33.881
130	10.010
135	2.362
140	0.405
145	0.070
150	< 0.01
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 10: Transport of Converter Platform to Wind Farm Grid	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	4453.042
95	3688.513
100	2873.803
105	1923.333
110	1198.883
115	678.867
120	355.525
125	167.691
130	78.477
135	29.783
140	7.626
145	1.566
150	< 100 m
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 11: Converter Platform Installation	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	8817.742
95	7164.228
100	5579.306
105	4076.029
110	2733.786
115	1624.256
120	908.348
125	449.003
130	204.799
135	93.793
140	39.905
145	15.918
150	5.624
155	1.642
160	0.348
165	< 0.01
170	< 0.01

Scenario 12: Scour Protection Placement	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	8631.987
95	6962.536
100	5421.565
105	4012.681
110	2539.239
115	1494.655
120	763.950
125	322.635
130	118.090
135	39.994
140	12.304
145	2.422
150	0.468
155	0.088
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 13: Rock Dumping at Cable/Pipeline Crossing	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	653.161
95	593.957
100	517.134
105	438.251
110	351.193
115	254.186
120	163.449
125	98.134
130	51.048
135	16.764
140	3.294
145	0.584
150	0.093
155	< 0.01
160	< 0.01
165	< 0.01
170	< 0.01

Scenario 14: Turbine Operations	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	3261.377
95	2010.425
100	1209.585
105	702.342
110	399.164
115	239.540
120	149.008
125	66.303
130	30.719
135	0.055
140	< 0.007
145	< 0.007
150	< 0.007
155	< 0.007
160	< 0.007
165	< 0.007
170	< 0.007

Scenario 15: Turbine Maintenance	
$SPL_{Max\ Over\ depth}$ (dB)	Area (km^2)
90	2778.450
95	1743.815
100	986.121
105	481.028
110	187.234
115	65.899
120	23.724
125	6.853
130	1.716
135	0.396
140	0.115
145	<100