Underwater Acoustic Analysis and Exposure Modeling

Revolution Wind: Impact Pile Driving during Foundation Installation

JASCO Applied Sciences (USA) Inc.

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Executive Summary

Revolution Wind, LLC (Revolution Wind), a 50/50 joint venture between Ørsted North America Inc. (Ørsted NA) and Eversource Investment LLC (Eversource), proposes to construct, own, and operate the Revolution Wind Farm (RWF) in the designated Bureau of Ocean Energy Management (BOEM) Renewable Energy Lease Area OCS-A 0486. RWF includes up to 100 foundations consisting of wind turbine generators (WTG) and two offshore substations (OSS), as well as inter-array cables (IAC) connecting the WTG and OSS. The WTG will each be supported by a tapered monopile foundation that is 7 m on top and 12 m diameter at the mudline, while the OSS will be supported by a tapered 7 m (top) to 15 m (mudline) monopile foundation.

Underwater noise associated with the construction of the RWF will predominantly result from the impact pile driving of the monopile foundations. A quantitative assessment of the sounds produced by the impact pile driving of the monopile foundations was undertaken in this study. Other sources of sound, such as dynamic positioning (DP) vessel thrusters used during cable installation and vessel propulsion during transit, were considered here as a qualitative assessment.

WTG monopile foundations consisting of a single pile, tapered from 7 to 12 m in diameter, were modeled at two representative locations in the lease area. Forcing functions for impact pile driving were computed for each pile type using GRLWEAP (GRLWEAP, Pile Dynamics 2010). The resulting forcing functions were used as inputs to JASCO's impact pile driving source model to characterize the sounds generated by the piles. Acoustic sound fields were estimated using JASCO's Marine Operations Noise model (MONM) and Full Wave Range Dependent Acoustic Model (FWRAM). To account for the likely minimum sound reduction resulting from noise abatement systems (NAS) such as bubble curtains, the modeling study included hypothetical broadband attenuation levels of 0, 6, 10, and 15 dB for all impact pile driving acoustic modeling results. Based on a recent analysis of NAS (Bellmann et al. 2020), the 10 dB level was conservatively chosen as an achievable sound reduction level when one NAS is in use during pile driving, and is highlighted in this analysis.

The goal of the study was to determine the number of individual animals that may be impacted and the associated monitoring distances (exposure and acoustic ranges) for mitigation purposes. JASCO's animal movement modeling software, JASMINE, was used to integrate the computed sound fields with species-typical movement (e.g., dive patterns) to estimate received sound levels for the modeled marine mammals and sea turtles that may occur near the construction area. Using the time history of the received levels, exposure estimates and exposure ranges accounting for 95% of exposures above regulatory-defined injury and behavioral disruption thresholds (NMFS 2018, McCauley et al. 2000a, Finneran et al. 2017) were calculated. Fish were considered static receivers, so the acoustic distance to their regulatory thresholds (FHWG Andersson et al. 2007, Wysocki et al. 2007, 2008, Stadler and Woodbury 2009, Mueller-Blenkle et al. 2010, Purser and Radford 2011) were calculated. Exposure ranges (marine mammals) and acoustic ranges (fish) are reported for various levels (0, 6, 10, and 15) of broadband attenuation that could be expected from the use of mitigation systems such as a bubble curtain.

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1. Introduction

1.1. Project Background and Overview of Assessed Activity

Revolution Wind, LLC (Revolution Wind), a 50/50 joint venture between Ørsted North America Inc. (Ørsted NA) and Eversource Investment LLC (Eversource), proposes to construct, own, and operate the Revolution Wind Farm in the designated Bureau of Ocean Energy Management (BOEM) Renewable Energy Lease Area OCS-A 0486 (Lease Area, Figure 1). The Revolution Wind Offshore Windfarm Project (RWF) consists of wind turbine generators (WTGs), offshore substations (OSSs), inter-array cables (IAC), and export cables (ECs). The ECs will connect from the OSSs to landfall in Connecticut and Rhode Island.

Underwater noise may be generated by several activities associated with the Project. Impacts of noise on marine fauna for most of these anthropogenic sound sources is expected to be low or very low. Only pile driving for the installation of WTGs and OSS foundations could be expected to have greater impacts. A quantitative assessment of pile driving activities is undertaken here as the primary source of noise associated with the Project. A qualitative assessment of secondary sound sources associated with other construction and operational activities that contribute non-impulsive (aircraft, dredging, drilling, dynamic positioning [DP] thrusters) and continuous (vessel propulsion, turbine operation) sound to the environment can be found in Appendix C.

For the quantitative acoustic analysis, the potential underwater acoustic impacts resulting from the installation of tapered monopile foundations were modeled. The WTGs will be supported by tapered monopiles which have a diameter of 7 meters (m) (23 feet (ft)) at the waterline and 12 m (39 ft) at the mudline. OSSs will be supported by a monopile foundation. OSS monopiles are tapered, with diameter ranging from 7 m at the waterline to 15 m at the mudline. This underwater noise assessment considers that the currently available information; the precise locations, noise sources, and schedule of the construction and operation scenarios is subject to change as the engineering design progresses.

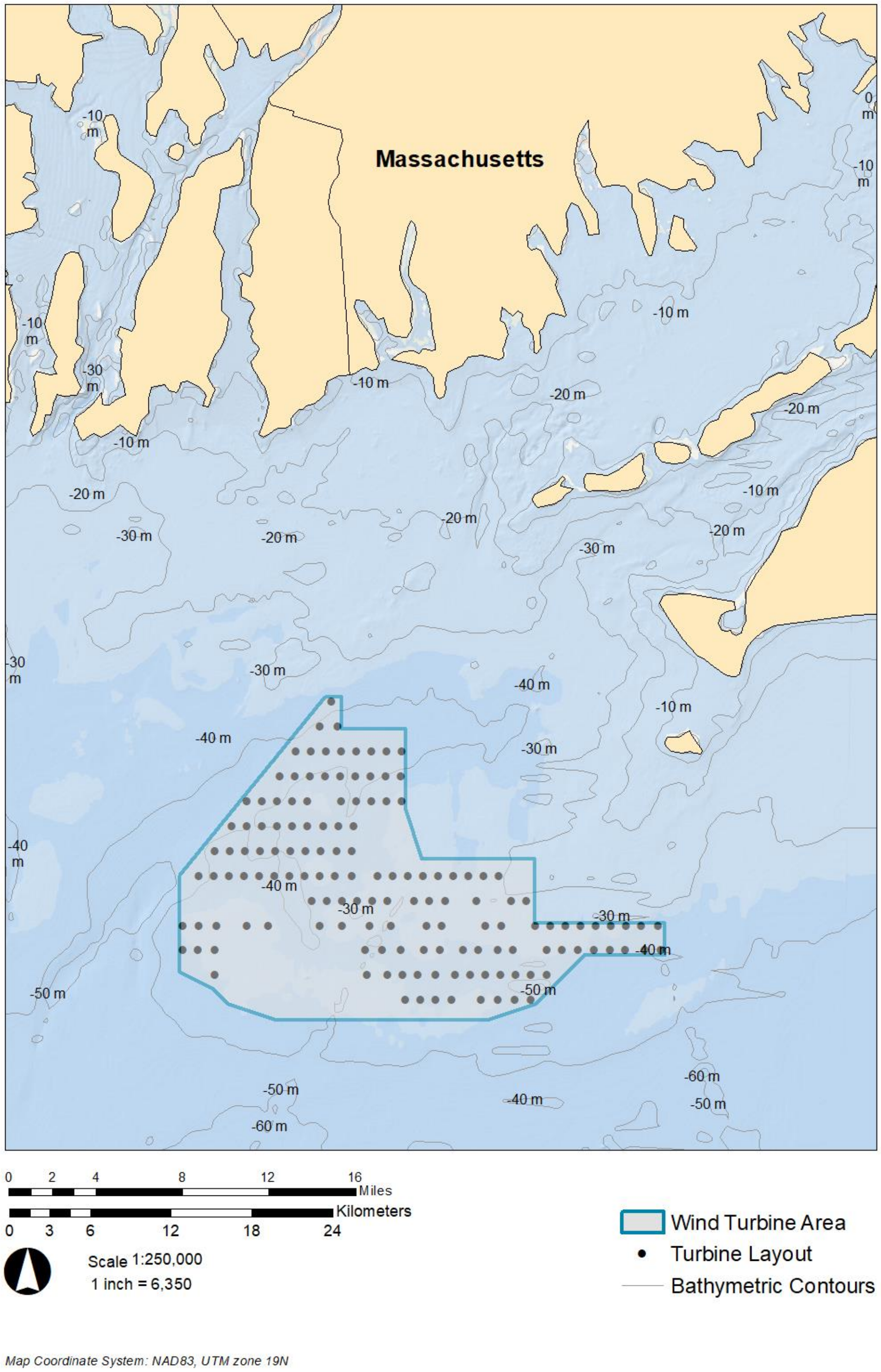

Figure 1. Revolution Wind Offshore Wind Farm Project (RWF).

1.2. Modeling Scope and Assumptions

The objective of the quantitative underwater noise assessment was to determine exposure estimates and exposure ranges from impact pile driving for marine mammals and sea turtle species that occur near the RWF. Exposure ranges and exposure estimates for animals exceeding regulatory acoustic thresholds for injury and behavioral disruption are predicted using animal movement modeling. For fish, acoustic ranges to their regulatory thresholds predicting injury and behavioral disturbance were calculated.

1.2.1. Foundations

A monopile used as a foundation in a wind farm is a single hollow cylinder fabricated from steel that is installed by driving (hammering) it into the seabed. Tapered 7/12 m monopiles (7 m top diameter, 12 m bottom diameter, with a tapered section near the water line) are proposed as the WTG foundations within the project development envelope (PDE). The proposed OSS monopile foundations are single, 7/15 m diameter tapered piles (7 m top diameter, 15 m bottom diameter, and a tapered section near the waterline). Nominal dimensions of the monopiles are shown in Appendix B.

The amount of sound generated during pile driving varies with the energy required to drive piles to the desired depth and depends on the sediment resistance encountered. Sediment types with greater resistance require hammers that deliver higher energy strikes and/or an increased number of strikes relative to installations in softer sediment. Maximum sound levels usually occur during the last stage of impact pile driving, where the greatest resistance is encountered (Betke 2008). The make and model of impact hammer (IHC S-4000 and IHC S-2300) and the representative hammering schedule used in the acoustic modeling effort were provided by Revolution Wind in coordination with potential hammer suppliers. The number of strikes at each hammer energy level needed to drive piles for the foundations can be found in Tables 1 and 2.

Sound fields from 7/12 m WTG monopiles were modeled at two locations: L024-002 in the northwest section of the RWF area and L024-114 in the southeast (L024_002 and L024_114 in Table 3 and Figure 2). The OSS monopile foundations were modeled at three proposed installation locations within the RWF area (OSS1, OSS2, and OSS3 in Table 3 and Figure 2). All piles were assumed to be vertical and driven to a maximum expected penetration depth of 50 m (130 ft) for the 7/12 WTGs monopiles the OSS monopiles. For exposure analysis, it was assumed that 1, 2, or 3 WTG monopiles may be driven in a day, and 1 or 2 OSS monopiles may be driven per day.

Key modeling assumptions for WTG and OSS foundation types are listed in Table 4. Additional modeling details and input parameters are provided in Appendix B.

Table 1. Hammer energy schedule for 7 to 12 m WTG monopile installation. Total strike count is 10,740 and total penetration depth is 50 m.

Energy level (kilojoule [kJ])	Strike count	Pile penetration (m)	Modeled strike rate (min^{-1})
1,000	1,705	0-6	50
2,000	3,590	6-24	
3,000	2,384	24-36	
4,000	3,061	36-50	

Table 2. Hammer energy schedule for 7 to 15 m OSS monopile installation. Total strike count is 11,563 and total penetration depth is 50 m.

Energy level (kilojoule [kJ])	Strike count	Pile penetration (m)	Modeled strike rate (min^{-1})
1,000	954	0-5	50
2,000	2,944	5-17	
3,000	4,899	17-36	
4,000	2,766	36-50	

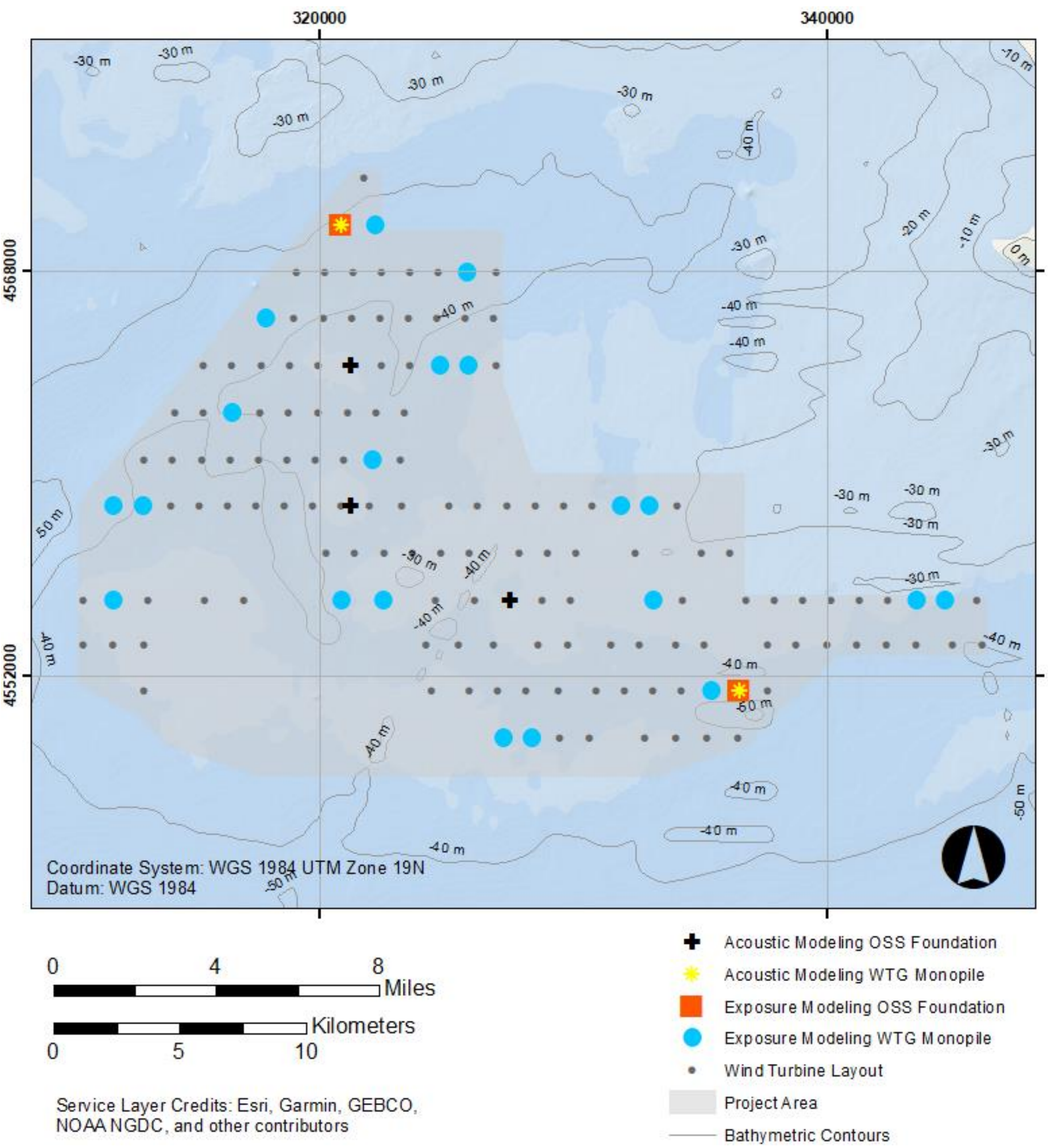

Figure 2. RWF monopile foundation locations with acoustic propagation and animal movement modeling locations.

Table 3. Locations for acoustic modeling of WTG and OSS foundations.

Model site	Location (UTM Zone 19N)		Water depth (m)	Sources	Source type
	Easting	Northing			
L024-002	320793.48	4569669.5	41.3	Monopile Foundations	Impulsive
L024-114	336403.93	4551413.2	36.8		
OSS 1	327480.00	4554999.69	34.2		
OSS 2	321190.00	4564259.69	34.4		
OSS 3	321190.00	4558703.00	33.7		

Table 4. Key piling assumptions used in underwater acoustic modeling.

Foundation type	Modeled maximum impact hammer energy (kJ)	Pile length (m)	Pile diameter (m)	Pile wall thickness (mm)	Seabed penetration (m)	Number of piles per day
WTG Monopile	4000	110	7/12	160	40	1, 2, 3
OSS Monopile	4000	120	7/15	200	50	1, 2

1.2.2. Modeling Scenario and Pile Construction Schedules

Construction schedules cannot be fully predicted because of environmental factors like weather and because of installation variation such as drivability. To estimate the number of animals likely to be exposed above the regulatory thresholds a conservative construction schedule that maximizes activity during the highest density months for each species was assumed – 90 WTG monopiles (3 per day for 30 days) are assumed installed in the highest density month of each species (see Sections 3.1 and 3.3 for details on animal density estimates) and 10 WTG monopiles (3 per day for 3 days and 1 per day for 1 day) are assumed installed during the month with the second highest density. The two OSS monopile foundations (1 per day for 2 days) are assumed installed during the second highest density month. Construction schedule assumptions are summarized in Table 5.

Table 5. Construction schedule assumptions for WTG and OSS foundations. Dashes indicate no piling days.

Foundation type	Configuration	Days of piling	
		Highest density month	2nd highest density month
WTG	Monopile, 3 per day	30	3
WTG	Monopile, 1 per day	-	1
OSS	Monopile, 1 per day		2

2. Methods

The basic modeling approach is to characterize the sound produced by the source, determine how the sound propagates within the surrounding water column, and then estimate species-specific exposure probabilities by combing the computed sound fields with animal movement in simulated representative scenarios.

For impact pile driving sounds, time-domain representations of the acoustic pressure waves generated in the water are required for calculating sound pressure level (SPL), sound exposure level (SEL), and peak pressure level (PK). The source signatures associated with the installation of each of the modeled 7/12 m and 7/15 m monopile locations are predicted using a finite-difference model that calculates the physical vibration of the pile caused by the pile driving equipment. The sound field radiating from the pile is computed using a vertical array of point sources.

For this study, synthetic pressure waveforms were computed using a Full-Waveform Range-dependent Acoustic Model (FWRAM), which is JASCO's acoustic propagation model capable of producing time-domain waveforms. The sound propagation modeling incorporated site-specific environmental data including bathymetry, sound speed in the water column, and seabed geoacoustics in the proposed construction area. Animal movement modeling integrated the estimated sound fields with species-typical behavioral parameters (e.g., dive patterns) to estimate received sound levels for the modeled animals (animats) that may occur in the construction area. Animats that exceed pre-defined acoustic thresholds (e.g., NMFS 2018) are identified and the distance for the exceedances determined. The number of animals expected to exceed the regulatory thresholds is determined by scaling the probability of exposure by the species-specific density of animals in the area.

2.1. Acoustic Environment

The proposed RWF is located in a continental shelf environment characterized by predominantly sandy seabed sediments. Water depths in the construction area vary between 30-45 m. From May through October, the average temperature of the upper (10–15 m) water column is higher than deeper layers, leading to an increased surface layer sound speed. This situation creates a downward-refracting environment in which propagating sound interacts with the seafloor more than in a well-mixed environment. Increased wind mixing, combined with a decrease in solar energy in during winter from December through March, results in a sound speed profile that is more uniform as a function of depth. Separate acoustic propagation model runs were conducted for both average summer and average winter sound speed profiles. See Appendix G.1 for more details on the environmental parameters used in acoustic propagation and exposure modeling.

2.2. Modeling Acoustic Sources

2.2.1. Impact Pile Driving

Piles deform when driven with impact hammers, creating a bulge that travels down the pile and radiates sound into the surrounding air, water, and seabed. This sound may be received as a direct transmission from the sound source to biological receivers (such as marine mammals, sea turtles, and fish) through the water, or as the result of reflected paths from the surface or re-radiated into the water from the seabed (Figure 3). Sound transmission depends on many environmental parameters, such as the sound speeds in water and substrates. It also depends on the sound production parameters of the pile and how it is driven, including the pile material, size (length, diameter, and thickness), and the make and energy of the hammer.

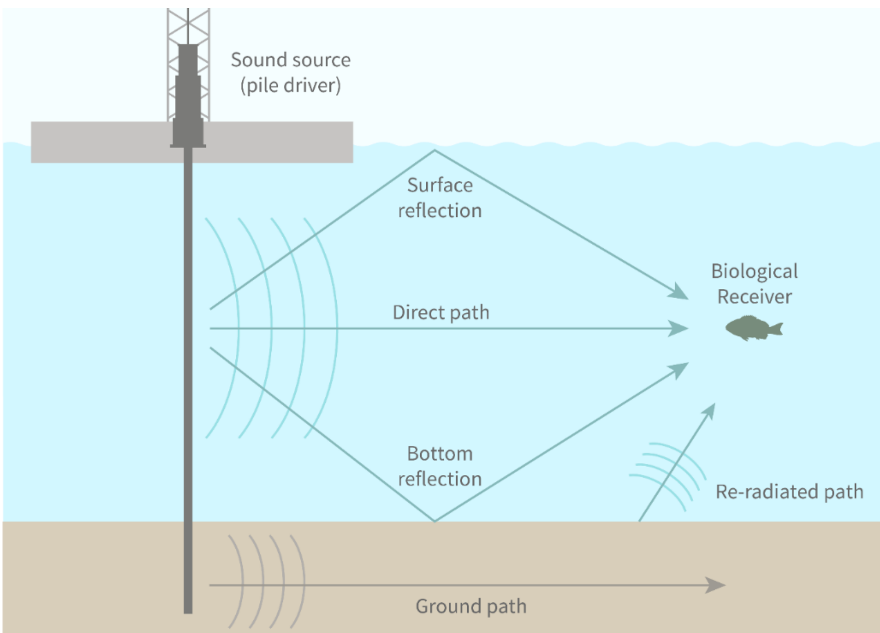

Figure 3. Sound propagation paths associated with impact pile driving (adapted from Buehler et al. 2015).

JASCO's physical model of pile vibration and near-field sound radiation (MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010) to predict sound levels associated with impact pile driving activities. Piles are modeled as a vertical installation using a finite-difference structural model of pile vibration based on thin-shell theory. The sound radiating from the pile itself was simulated using a vertical array of discrete point sources. These models account for several parameters that describe the operation—pile type, material, size, and length—, the pile driving equipment, and approximate pile penetration depth. See Appendix F for a more detailed description.

Forcing functions were computed for the 7/12 m and 7/15 m monopile using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010). The model assumed direct contact between the representative hammers, helmets, and piles (i.e., no cushion material). The forcing functions serve as the inputs for the pile driving source model (PDSM) used to estimate equivalent acoustic source characteristics detailed in Appendix F. Decidecade spectral source levels for each pile type, hammer energy, and modeled location, using an average summer sound speed profile provided in Appendix G. Additionally, to ensure a conservative impact estimate for the 7/15 m OSS monopiles, a 2 dB factor was added to their source levels.

Acoustic propagation modeling used JASCO's Marine Operations Noise Model (MONM) and FWRAM that combine the outputs of the source model with the spatial and temporal environmental context (e.g., location, oceanographic conditions, and seabed type) to estimate sound fields. The lower frequency bands were modeled using MONM and FWRAM, which are based on the parabolic equation method of acoustic propagation modeling. For higher frequencies, additional losses resulting from absorption were added to the propagation loss model. See Appendix D for a more detailed description.

2.3. Noise Mitigation

Noise abatement systems (NASs) are often used to decrease the sound levels in the water near a source by inserting a local impedance change that acts as a barrier to sound transmission. A variety of technologies can achieve attenuation by impedance change, including bubble curtains, evacuated sleeve systems (e.g., IHC-Noise Mitigation System (NMS)), encapsulated bubble systems (e.g., HydroSound Dampers (HSD)), and Helmholtz resonators (AdBm NMS). The effectiveness of each system is frequency-dependent and may be influenced by local environmental conditions such as current and depth. For example, the size of the bubbles determines the effective frequency band of an air bubble curtain, with larger bubbles needed for lower frequencies.

Small bubble curtains (bubble curtains positioned within a small radius around the pile) have been measured to reduce sound levels from ~10 dB to more than 20 dB but are highly dependent on water depth, current, and how the curtain is configured and operated (Koschinski and Lüdemann 2013, Bellmann 2014, Austin and Li 2016). Larger bubble curtains tend to perform better and more reliably, particularly when deployed with two rings (Koschinski and Lüdemann 2013, Bellmann 2014, Nehls et al. 2016). A California Department of Transportation (CalTrans) study tested several small, single, bubble-curtain systems and found that the best attenuation systems resulted in 10–15 dB of attenuation. Buehler et al. (2015) concluded that attenuation greater than 10 dB could not be reliably predicted from small, single, bubble curtains because sound transmitted through the seabed and re-radiated into the water column is the dominant source of sound in the water for bubble curtains deployed immediately around (10 m [32 ft]) the pile (Buehler et al. 2015).

A recent analysis by Bellmann et al. (2020) of NASs performance measured during impact driving for wind farm foundation installation provides expected performance for common NASs configurations. Measurements with a single bubble curtain and an air supply of 0.3 m^3/min resulted in 7 to 11 dB of broadband attenuation for optimized systems in up to 131 ft (40 m) water depth. Increased air flow (0.5 m^3/min) may improve the attenuation levels up to 11 to 13 dB (M. Bellmann, personal communication, 2019). Double bubble curtains add another local impedance change and, for optimized systems, can achieve 15 to 16 dB of broadband attenuation (measured in up to 131.25 ft [40 m] water depth). The IHC-NMS can provide 15 to 17 dB of attenuation but is currently limited to piles <8 m diameter. Other NASs such as the AdBm NMS achieved 6 to 8 dB (M. Bellmann, personal communication, 2019), but HSDs were measured at 10 to 12 dB attenuation and are independent of depth (Bellmann et al. 2020). Systems may be deployed in series to achieve higher levels of attenuation.

The NAS must be chosen, tailored, and optimized for site-specific conditions. NAS performance of 10 dB broadband attenuation was chosen for this study as an achievable reduction of sound levels produced during pile driving when one NAS is in use, noting that a 10 dB decrease means the sound energy level is reduced by 90%. For exposure modeling, several levels of attenuation were included for comparison purposes.

2.4. Acoustic Criteria for Marine Fauna

The acoustic criteria used for this study were derived from the current US regulatory acoustic criteria and are summarized below (further details on these criteria are in Sections 2.4.1 and 2.4.2):

1. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) were derived from the US National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for marine mammal injury thresholds.
2. Sound pressure level (SPL; L_{p}) for marine mammal behavioral thresholds were based on the unweighted NOAA (2005) and the frequency-weighted Wood et al. (2012) criteria.
3. Injury thresholds (PK and SEL) for fish were derived from the Fisheries Hydroacoustic Working Group (FHWG 2008) and Stadler and Woodbury (2009) for fish that are equal, greater than, or less than 2 g.
4. Injury thresholds (PK and SEL) for fish were obtained from Popper et al. (2014) for fish without swim bladders, fish with swim bladders not involved in hearing, and fish with swim bladders involved in hearing.
5. Behavioral thresholds for fish were developed by the NOAA Fisheries Greater Atlantic Regional Fisheries Office (GARFO) (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011)
6. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) were used for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in sea turtles.
7. Behavioral response thresholds for sea turtles were obtained from McCauley et al. (2000a), which was confirmed in Finneran et al. (2017).

2.4.1. Acoustic Criteria-Marine Mammals

The Marine Mammal Protection Act (MMPA) prohibits the take of marine mammals. The term "take" is defined as: to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal. MMPA regulations define harassment in two categories relevant to the Project construction and operations. These are:

- **Level A**: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild, and
- **Level B**: Any act of pursuit, torment or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild (16 U.S.C. 1362).

To assess the potential impacts of the underwater sound in the RWF, it is first necessary to establish the acoustic exposure criteria used by United States regulators to estimate marine mammal takes. In 2016, National Oceanographic and Atmospheric Administration (NOAA) Fisheries issued a Technical Guidance document that provides acoustic thresholds for onset of PTS in marine mammal hearing for most sound sources, which was updated in 2018 (NMFS 2016, 2018). The Technical Guidance document also recognizes two main types of sound sources: impulsive and non-impulsive. Non-impulsive sources are further broken down into continuous or intermittent categories.

NMFS also provided guidance on the use of weighting functions when applying Level A harassment criteria. The Guidance recommends the use of a dual criterion for assessing Level A exposures, including a PK (unweighted/flat) sound level metric and a cumulative SEL metric with frequency weighting. Both acoustic criteria and weighting function application are divided into functional hearing groups (low-, mid-, and high-frequency and phocid pinnipeds) that species are assigned to based on their respective hearing distances. The acoustic analysis applies the most recent sound exposure criteria utilized by NMFS to estimate acoustic harassment (NMFS 2018).

Based on observations of mysticetes (Malme et al. 1983, 1984, Richardson et al. 1986, 1990b), sound levels thought to elicit disruptive behavioral response are described using the SPL metric (NMFS and NOAA 2005). NOAA Fisheries (NMFS) currently uses a behavioral response threshold of 160 dB re 1 µPa for marine mammals exposed to impulsive sounds, with the modification that 120 dB re 1 µPa be used for migrating mysticetes (NOAA 2005). 120 dB re 1 µPa is used for all marine mammals exposed to non-impulsive sounds (NMFS 2018). Alternative thresholds used in acoustic assessments include a graded probability of response approach and take into account the frequency-dependence of animal hearing sensitivity (Wood et al. 2012). The 160 dB threshold is used in this assessment as per NOAA guidance (2019).

The publication of ISO 18405 Underwater Acoustics–Terminology (ISO 2017) provided a dictionary of underwater bioacoustics (the previous standard was [ANSI] American National Standards Institute and [ASA] Acoustical Society of America S1.1-2013). In the remainder of this report, we follow the definitions and conventions of ISO (2017) except where stated otherwise (Table 6).

Table 6. Summary of relevant acoustic terminology used by US regulators and in the modeling report.

Metric	NMFS (2018)	ISO (2017)	
		Main text	Equations/tables
Sound pressure level	n/a	SPL	L_p
Peak pressure level	PK	PK	L_{pk}
Cumulative sound exposure level	SEL_{cum} [a]	SEL	L_E

[a] The SEL_{cum} metric used by NOAA Fisheries (NMFS) describes the sound energy received by a receptor over a period of 24 h. Accordingly, following the ISO standard, this will be denoted as SEL in this report, except for in tables and equations where L_E will be used.

2.4.1.1. Marine Mammal Hearing Groups

Current data and predictions show that marine mammal species differ in their hearing capabilities, in absolute hearing sensitivity as well as frequency band (Richardson et al. 1995, Wartzok and Ketten 1999, Southall et al. 2007, Au and Hastings 2008). While hearing measurements are available for a small number of species based on captive animal studies, there are no direct measurements of many odontocetes or any mysticetes. As a result, hearing distances for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods including anatomical studies and modeling (Houser et al. 2001, Parks et al. 2007, Tubelli et al. 2012, Cranford and Krysl 2015); vocalizations (see reviews in Richardson et al. 1995, Wartzok and Ketten 1999, Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990, see review in Reichmuth et al. 2007). In 2007, Southall et al. proposed that marine mammals be divided into hearing groups. This division was updated in 2016 and 2018 by NOAA Fisheries using more recent best available science (Table 7).

Southall et al. (2019) published an updated set of Level A sound exposure criteria (including the onset of temporary threshold shift [TTS] and permanent threshold shift [PTS] in marine mammals). While the authors propose a new nomenclature and classification for the marine mammal functional hearing groups, the proposed thresholds and weighting functions do not differ in effect from those proposed by NOAA Fisheries (2018). The new hearing groups proposed by Southall et al. (2019) have not yet been adopted by NOAA. The NOAA Fisheries (NMFS 2018) hearing groups presented in Table 7 are used in this analysis.

Table 7. Marine mammal hearing groups (Sills et al. 2014, NMFS 2018).

Faunal group	Generalized hearing range [a]
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid pinnipeds in water (PPW)	50 Hz to 86 kHz
Phocid pinnipeds in air (PPA)[b]	50 Hz to 36 kHz

[a] The generalized hearing range is for all species within a group. Individual hearing will vary.

[b] Sound from piling will not reach NOAA Fisheries thresholds for behavioral disturbance of seals in air (90 dB [rms] re 20 µPa for harbor seals and 100 dB [rms] re 20 µPa for all other seal species) at the closest land-based sites where seals may spend time out of the water. Thus in-air hearing is not considered further.

2.4.1.2. Marine Mammal Auditory Weighting Functions

The potential for anthropogenic sound to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well, unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal's ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS thresholds expressed in metrics that consider what is known about marine mammal hearing (e.g., SEL) (Southall et al. 2007, Erbe et al. 2016a, Finneran 2016). Marine mammal auditory weighting functions for all hearing groups (Table 7) published by Finneran (2016) are included in the NMFS (2018) Technical Guidance for use in conjunction with corresponding permanent threshold shift (PTS [Level A]) onset acoustic criteria (Table 8). (See Appendix E for a detailed description of the weighting functions.)

The application of marine mammal auditory weighting functions emphasizes the importance of taking measurements and characterizing sound sources in terms of their overlap with biologically important frequencies (e.g., frequencies used for environmental awareness, communication, and the detection of predators or prey), and not only the frequencies that are relevant to achieving the objectives of the sound producing activity (i.e., context of sound source; NMFS 2018).

2.4.1.3. Marine Mammal Auditory Injury Exposure Criteria

Injury to the hearing apparatus of a marine mammal may result from a fatiguing stimulus measured in terms of SEL, which considers the sound level and duration of the exposure signal. Intense sounds may also damage hearing independent of duration, so an additional metric of peak pressure (PK) is used to assess acoustic exposure injury risk. A PTS in hearing may be considered injurious, but there are no published data on the sound levels that cause PTS in marine mammals. There are data that indicate the received sound levels at which temporary threshold shift, TTS, occurs, and PTS onset may be extrapolated from TTS onset level and an assumed growth function (Southall et al. 2007). The NMFS (2018) criteria incorporate the best available science to estimate PTS onset in marine mammals from sound energy accumulated over 24 h (SEL), or very loud, instantaneous peak sound pressure levels. These dual threshold criteria of SEL and PK are used to calculate marine mammal exposures (Table 8). If a non-impulsive sound has the potential to exceed the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

Table 8. Summary of relevant permanent threshold shift (PTS) onset acoustic thresholds for marine mammal hearing groups (NMFS 2018).

Faunal group	Impulsive signals [a]		Non-impulsive signals
	Unweighted L_{pk} (dB re 1 µPa)	Frequency weighted $L_{E,\,24h}$ (dB re 1 µPa^2·s)	Frequency weighted $L_{E,\,24h}$ (dB re 1 µPa^2·s)
Low-frequency (LF) cetaceans	219	183	199
Mid-frequency (MF) cetaceans	230	185	198
High-frequency (HF) cetaceans	202	155	173
Phocid seals in water (PW)	218	185	201

[a] Dual metric acoustic threshold for impulsive sounds: The largest range of the two criteria is used for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds have also been considered.

2.4.1.4. Marine Mammal Behavioral Response Exposure Criteria

Numerous studies on marine mammal behavioral responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioral reactions. It is recognized that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison et al. 2012). Due to the complexity and variability of marine mammal behavioral responses to acoustic exposure, NOAA has not yet released technical guidance for determining potential behavioral responses of marine mammals exposed to sounds (NMFS 2018). NOAA's National Marine Fisheries Service (NMFS) currently uses a step function to assess behavioral impact (NOAA 2005). The step function sets an SPL of 160 dB re 1 µPa as the behavioral disruption threshold based on the 50% response rate of collated responses in the HESS (1999) report. An SPL of 120 dB re 1 µPa was set as the behavioral disruption threshold for migrating mysticetes (NOAA 2005), which was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983, 1984). The HESS team recognized that behavioral responses to sound may occur at lower levels, but substantial responses were only likely to occur above an SPL of 140 dB re 1 µPa.

An extensive review of behavioral responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions. In 2012, Wood et al. proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric. Wood et al. (2012) also designated behavioral response categories for sensitive species (including harbor porpoises and beaked whales) and for migrating mysticetes. For this analysis, both the unweighted NOAA (2005) and the frequency-weighted Wood et al. (2012) criteria are used to estimate Level B exposures to impulsive pile-driving sounds (Table 9).

Table 9. Acoustic sound pressure level (SPL) thresholds used to evaluate potential behavioral impacts to marine mammals. Probabilities are not additive

Marine mammal group	Frequency weighted probabilistic response (L_p; dB re 1 µPa)				Unweighted probabilistic response
	>120	>140	>160	>180	160
Beaked whales and harbor porpoises	50%	90%			100%
Migrating mysticete whales	10%	50%	90%		
All other species		10%	50%	90%	

[a] Wood et al. (2012)
[b] NOAA (2005)

2.4.2. Acoustic Criteria for Fish and Sea Turtles

In a cooperative effort between Federal and State transportation and resource agencies, interim criteria were developed to assess the potential for injury to fish exposed to pile driving sounds (Stadler and Woodbury 2009) and described by the Fisheries Hydroacoustic Working Group (FHWG 2008). Injury and behavioral response thresholds were based on past literature that was compiled and listed in the NOAA Fisheries Greater Atlantic Regional Fisheries Office acoustics tool (GARFO 2020) for assessing the potential effects to Endangered Species Act (ESA) listed animals exposed to elevated levels of underwater sound from pile driving. Dual acoustic thresholds for physiological injury included in the tool are 206 dB re 1 µPa PK and either 187 dB re 1 µPa^2·s SEL (>2 grams [g] fish weight) or 183 dB SEL (<2 g fish weight) (FHWG 2008, Stadler and Woodbury 2009) (Table 10). The behavioral threshold for fish is ≥150 dB SPL (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011).

A technical report by an American National Standards Institute (ANSI) registered committee (Popper et al. 2014) reviewed available data and suggested metrics and methods for estimating acoustic impacts for fish. Their report includes thresholds for potential injury but does not define sound levels that may result in behavioral response, though it does indicate a high likelihood of response near impact pile driving (tens of meters), a moderate response at intermediate distances (hundreds of meters), and a low response far (thousands of meters) from the pile (Popper et al. 2014).

Injury, impairment, and behavioral thresholds for sea turtles were developed for use by the US Navy (Finneran et al. 2017) based on exposure studies (e.g., McCauley et al. 2000a). Dual criteria (PK and SEL) have been suggested for PTS and TTS, along with auditory weighting functions published by Finneran et al. (2017) used in conjunction with SEL thresholds for PTS and TTS . The behavioral threshold recommended in the GARFO acoustic tool (GARFO 2020) is an SPL of 175 dB re 1 µPa (McCauley et al. 2000a, Finneran et al. 2017) (Table 10).

Table 10. Acoustic metrics and thresholds for fish and sea turtles currently used by NMFS GARFO and Bureau of Ocean Energy Management (BOEM) for impulsive pile driving.

Faunal group	Injury		Impairment		Behavior
	PTS		TTS		
	L_{pk}	$L_{E,\ 24hr}$	L_{pk}	$L_{E,\ 24hr}$	L_p
Fish equal to or greater than 2 g [a,b]	206	187	-	-	150
Fish less than 2 g [a,b]		183	-	-	
Fish without swim bladder [c]	213	216	-	-	-
Fish with swim bladder not involved in hearing [c]	207	203	-	-	-
Fish with swim bladder involved in hearing [c]	207	203	-	-	-
Sea turtles [d,e]	232	204	226	189	175

L_{pk} – peak sound pressure (dB re 1 µPa), L_E – sound exposure level (dB re 1 µPa^2·s), L_p – root mean square sound pressure (dB re 1 µPa).

PTS = permanent threshold shift; TTS = temporary threshold shift, which are recoverable hearing effects.

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

[d] Finneran et al. (2017).

[e] McCauley et al. (2000a).

2.5. Animal Movement Modeling and Exposure Estimation

JASMINE was used to estimate the probability of exposure of animals to sound arising from pile driving operations during construction of the RWF. Sound exposure models such as JASMINE use simulated animals (animats) to sample the predicted 3-D sound fields with movement rules derived from animal observations (Appendix J, Figure 4). The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, and surface times) were determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species (Appendix J). The predicted sound fields were sampled by the model receiver in a way that real animals are expected to by programming animats to behave like marine species that may be present near the RWF. The output of the simulation is the exposure history for each animat within the simulation. An individual animat's sound exposure levels are summed over a specified duration, i.e., 24 h (Appendix J.1.1), to determine its total received acoustic energy (SEL) and maximum received PK and SPL. These received levels are then compared to the thresholds described in Section 2.4 within each analysis period. Appendix J provides a fuller description of animal movement modeling and the parameters used in the JASMINE simulations.

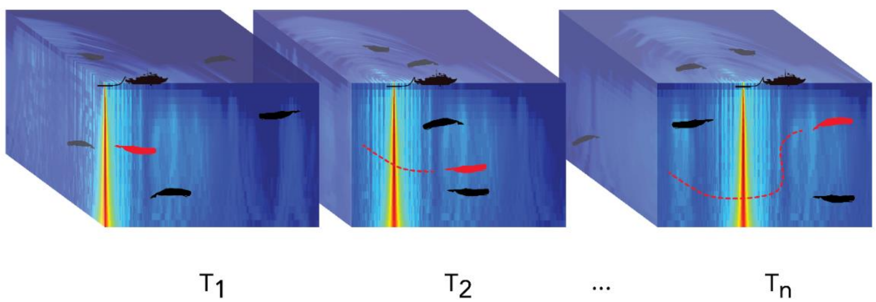

Figure 4. Depiction of animats in an environment with a moving sound field. Example animat (red) shown moving with each time step. The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

2.6. Estimating Monitoring Zones for Mitigation

Monitoring zones used for mitigation purposes have traditionally been estimated by determining the distance to injury and behavioral thresholds based only on acoustic information (see Appendix G.5). This traditional method tacitly assumes that all receivers (animals) in the area remain stationary for the duration of the sound event. Because both where an animal is in a sound field, and the pathway it takes through the sound field, determine the received level of the animal, treating animals as stationary may not produce realistic estimates for monitoring zones.

Animal movement modeling can be used to account for the movement of receivers when estimating distances for monitoring zones. The closest point of approach (CPA) for each of the species-specific animats (simulated animals) in a simulation is recorded and then the CPA distance that accounts for 95% of the animats that exceed an acoustic impact threshold is determined (Figure 5). The $ER_{95\%}$ (95% exposure range) is the horizontal distance that includes 95% of the CPAs of animats exceeding a given impact threshold. $ER_{95\%}$ is reported for marine mammals and sea turtles. If used as an exclusion zone, keeping animals farther away from the source than the $ER_{95\%}$ will reduce exposure estimates by 95%.

Unlike marine mammals and sea turtles for which animal movement modeling was performed, fish were considered static (not moving) receivers, so exposure ranges were not calculated. Instead, the acoustic ranges to fish impact criteria thresholds were calculated by determining the isopleth at which thresholds could be exceeded.

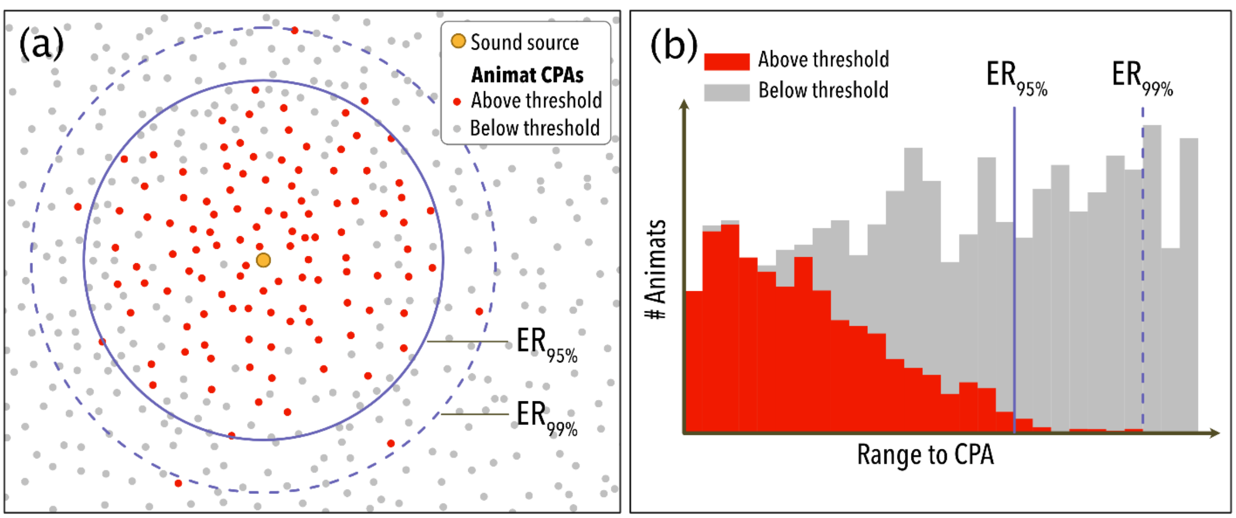

Figure 5. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animats near a sound source. Panel (b) shows a stacked bar plot of the distribution of ranges to animat CPAs. The 95% and 99% Exposure Ranges ($ER_{95\%}$ and $ER_{99\%}$) are indicated in both panels.

3. Marine Fauna Included in the Acoustic Assessment

Marine fauna included in the acoustic assessment are marine mammals (cetaceans and pinnipeds), sea turtles, and fish.

All marine mammal species are protected under the MMPA. Some marine mammal stocks may be designated as Strategic under the MMPA, which requires the jurisdictional agency (NMFS for the Atlantic offshore species considered in this application) to impose additional protection measures. A stock is considered *Strategic* if:

- Direct human-caused mortality exceeds its Potential Biological Removal (PBR) level (defined as the maximum number of animals, not including natural mortality, which can be removed from the stock while allowing the stock to reach or maintain its optimum sustainable population level);
- It is listed under the ESA;
- It is declining and likely to be listed under the ESA; or
- It is designated as *Depleted* under the MMPA.

A depleted species or population stock is defined by the MMPA as any case in which:

- The Secretary, after consultation with the Marine Mammal Commission and the Committee of Scientific Advisors on Marine Mammals established under MMPA Title II, determines that a species or population stock is below its optimum sustainable population;
- A State, to which authority for the conservation and management of a species or population stock is transferred under Section 109 of the MMPA, determines that such species or stock is below its optimum sustainable population; or
- A species or population stock is listed as an endangered or threatened species under the ESA. Some species are further protected under the ESA.

Under the ESA, a species is considered endangered if it is “in danger of extinction throughout all or a significant portion of its range.” A species is considered threatened if it “is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” Five marine mammal species know to occur in the Northwest Atlantic OCS region are ESA listed (Table 11). All four species of sea turtles (Table 13) as well as four fish species (Section 3.3) occurring in the Northwest Atlantic OCS region are also ESA listed.

3.1. Marine Mammals that may Occur in the Area

Thirty-nine marine mammal species (whales, dolphins, porpoise, seals and manatees) comprising 39 stocks have been documented as present (some year–round, some seasonally, and some as occasional visitors) in the Northwest Atlantic Outer Continental Shelf (OCS) region (CeTAP 1982, USFWS 2014, Roberts et al. 2016a, Hayes et al. 2022). All 39 marine mammal species identified in Table 11 are protected by the MMPA and some are also listed under the ESA. The five ESA-listed marine mammal species known to be present year-round, seasonally, or occasionally in southern New England waters are the sperm whale (*Physeter macrocephalus*), NARW (*Eubalaena glacialis)*, fin whale (*Balaenoptera physalus*), blue whale (*Balaenoptera musculus*), and sei whale (*Balaenoptera borealis*). The humpback whale (*Megaptera novaeangliae*), which may occur year-round, has been delisted as an endangered species.

Southern New England waters (including the Project Area (Figure 1) are primarily used as opportunistic feeding areas or habitat during seasonal migratory movements that occur between the feeding areas located farther north and the breeding areas located farther south that are typically used by some of these large whale species. The modeling used in this assessment considered minke and sei whales to be migratory in the region.

The four species of phocids (true seals) that have ranges overlapping the Project Area are harbor seals (*Phoca vitulina*), gray seals (*Halichoerus grypus*), harp seals (*Pagophilus groenlandicus*), and hooded seals (*Cystophora cristata*) (Hayes et al. 2022). None of these are ESA listed, but all are protected under the MMPA. One species of sirenian, the Florida manatee (*Trichechus manatus latirostris*), is an occasional visitor to the region during summer (USFWS 2019). The manatee is listed as Threatened under the ESA and is protected under the MMPA.

The expected occurrence of each marine mammal species in the Project Area is listed in Table 11. Many of these marine mammal species do not commonly occur in this region of the Atlantic Ocean. For this assessment, species presence was categorized as:

- Common – Occurring consistently in moderate to large numbers;
- Uncommon – Occurring in low numbers or on an irregular basis; and
- Rare – There are limited species records for some years; range includes the US Atlantic waters but due to habitat preferences and distribution information, species are generally not expected to occur in the Project Area, though rare sightings are a possibility. Records may exist for adjacent waters.

Marine mammal species considered c*ommon* and *uncommon* (Table 11) were selected for quantitative assessment by acoustic impact analysis and exposure modeling. Quantitative assessment of bottlenose dolphins (*Tursiops truncatus*) presumed all impacted individuals belong to the Western North Atlantic Offshore stock because the northern limit of the range of the coastal stock does not extend into the Project Area. Quantitative assessment of *rare* species was not conducted because impacts to those species approach zero due to their low densities. The modeled species are identified in Table 11. The likelihood of incidental exposure for each species based on its presence, density, and overlap of proposed activities is described in Section 4.3.1.

Table 11. Marine mammals potentially occurring within the regional waters of the Western North Atlantic Outer Continental Shelf and Project Area (Sources: NOAA Fisheries n.d.[a], 2020b; USFWS 2019).

Species	Scientific name	Stock	Regulatory Status [a]	Relative occurrence in RWF	Abundance [b]
Baleen whales (Mysteceti)					
Blue whale	*Balaenoptera musculus*	Western North Atlantic	ESA Endangered MMPA Depleted and Strategic	Rare	402
Fin whale *	*Balaenoptera physalus*	Western North Atlantic	ESA Endangered MMPA Depleted and Strategic	Common	6,802
Humpback whale *	*Megaptera novaeangliae*	Gulf of Maine	MMPA Non-strategic	Common	1,396
Minke whale *	*Balaenoptera acutorostrata*	Canadian Eastern Coastal	MMPA Non-strategic	Common	21,968
North Atlantic right whale *	*Eubalaena glacialis*	Western	ESA Endangered MMPA Depleted and Strategic	Common	368 [c]
Sei whale *	*Balaenoptera borealis*	Nova Scotia	ESA Endangered MMPA Depleted and Strategic	Common	6,292
Toothed Whales and Dolphins (Odontoceti)					
Atlantic spotted dolphin *	*Stenella frontalis*	Western North Atlantic	MMPA Non-strategic	Uncommon	39,921
Atlantic white-sided dolphin*	*Lagenorhynchus acutus*	Western North Atlantic	MMPA Non-strategic	Common	93,233
Bottlenose dolphin	*Tursiops truncatus*	Western North Atlantic, offshore* [d]	MMPA Non-strategic	Common	62,851
	Tursiops truncatus	Western North Atlantic, Northern Migratory Coastal	MMPA Depleted and Strategic	Rare	6,639
Clymene dolphin	*Stenella clymene*	Western North Atlantic	MMPA Non-strategic	Rare	4,237
Common dolphin*	*Delphinus delphis*	Western North Atlantic	MMPA Non-strategic	Common	172,974
False killer whale	*Pseudorca crassidens*	Western North Atlantic	MMPA Non-strategic	Rare	1,791
Fraser's dolphin	*Lagenodelphis hosei*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Killer whale	*Orcinus orca*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Melon-headed whale	*Peponocephala electra*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Pan-tropical spotted dolphin	*Stenella attenuata*	Western North Atlantic	MMPA Non-strategic	Rare	6,593
Pilot whale, long-finned*	*Globicephala melas*	Western North Atlantic	MMPA Non-strategic	Uncommon	39,215
Pilot whale, short-finned *	*Globicephala macrorhynchus*	Western North Atlantic	MMPA Non-strategic	Uncommon	28,924
Pygmy killer whale	*Feresa attenuata*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Risso's dolphin *	*Grampus griseus*	Western North Atlantic	MMPA Non-strategic	Uncommon	35,215
Rough-toothed dolphin	*Steno bredanensis*	Western North Atlantic	MMPA Non-strategic	Rare	136
Sperm whale *	*Physeter macrocephalus*	North Atlantic	ESA Endangered MMPA Depleted and Strategic	Uncommon	4,349
Spinner dolphin	*Stenella longirostris*	Western North Atlantic	MMPA Non-strategic	Rare	4,102
Striped dolphin	*Stenella coeruleoalba*	Western North Atlantic	MMPA Non-strategic	Rare	67,036

Beaked whales (Ziphiidae)					
Cuvier's beaked whale	*Ziphius cavirostris*	Western North Atlantic	MMPA Non-strategic	Rare	5,744
Blainville's beaked whale	*Mesoplodon densirostris*	Western North Atlantic	MMPA Non-strategic	Rare	10,107 [e]
Gervais' beaked whale	*Mesoplodon europaeus*	Western North Atlantic	MMPA Non-strategic		
Sowerby's beaked whale	*Mesoplodon bidens*	Western North Atlantic	MMPA Non-strategic		
True's beaked whale	*Mesoplodon mirus*	Western North Atlantic	MMPA Non-strategic		
Northern bottlenose whale	*Hyperoodon ampullatus*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Dwarf and pygmy sperm whales (Kogiidae)					
Dwarf sperm whale	*Kogia sima*	Western North Atlantic	MMPA Non-strategic	Rare	7,750 [f]
Pygmy sperm whale	*Kogia breviceps*	Western North Atlantic	MMPA Non-strategic	Rare	7,750 [f]
Porpoises (Phocoenidae)					
Harbor porpoise *	*Phocoena phocoena*	Gulf of Maine/ Bay of Fundy	MMPA Non-strategic	Common	95,543
Earless seals (Phocidae)					
Gray seal *	*Halichoerus grypus*	Western North Atlantic	MMPA Non-strategic	Common	27,300 [g]
Harbor seal *	*Phoca vitulina*	Western North Atlantic	MMPA Non-strategic	Common	61,336
Harp seal *	*Pagophilus groenlandicus*	Western North Atlantic	MMPA Non-strategic	Uncommon	Unknown [h]
Hooded seal	*Cystophora cristata*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Sirenia					
Florida manatee	*Trichechus manatus latirostris*	Florida	ESA Threatened MMPA Depleted and Strategic	Rare	4,834

* = modeled species

[a] Denotes the highest federal regulatory classification. A strategic stock is defined as any marine mammal stock: 1) for which the level of direct human-caused mortality exceeds the potential biological removal level; 2) that is declining and likely to be listed as threatened under the ESA; or 3) that is listed as threatened or endangered under the ESA or as depleted under the MMPA (NOAA Fisheries 2019).

[b] Best available abundance estimate is from NOAA Fisheries Stock Assessment Reports (Hayes et al. 2022).

[c] Best available abundance estimate is from NOAA Fisheries Stock Assessment (Hayes et al. 2022). NARW consortium has released the preliminary 2021 report card results predicting a NARW population of 340 (Pettis et al. 2022). However, the consortium "alters" the methods of Pace et al. (2017) to subtract additional mortality. This method is used in order to estimate all mortality, not just the observed mortality, therefore the Hayes et al. (2022) SAR will be used to report an unaltered output of the Pace et al. (2017) model (DoC and NOAA 2020).

[d] Bottlenose dolphins occurring in the RWF likely belong to the Western North Atlantic Offshore stock (Hayes et al. 2022).

[e] This estimate includes all undifferentiated Mesoplodon spp. beaked whales in the Atlantic. Sources: Kenney and Vigness-Raposa (2009), Rhode Island Ocean Special Area Management Plan (2011), Waring et al. (2011, 2013, 2015), Hayes et al. (2022).

[f] This estimate includes both dwarf and pygmy sperm whales. Source: Hayes et al. (2022).

[g] Estimate of gray seal population in US waters. Data are derived from pup production estimates; Hayes et al. (2022) notes that uncertainty about the relationship between whelping areas along with a lack of reproductive and mortality data make it difficult to reliably assess the population trend.

[h] Hayes et al. (2022) report insufficient data to estimate the population size of harp seals in US waters; the best estimate for the whole population is 7.4 million.

3.2. Mean Monthly Marine Mammal Density Estimates

Mean monthly marine mammal density estimates (animals per 100 square kilometers [animals/100 km^2]) for all modeled species are provided in Table 12. These were obtained using the Duke University Marine Geospatial Ecological Laboratory model results (Roberts et al. 2016a, 2016b, 2017, 2018, 2021, 2022), which were recently updated. The 2022 updated NARW model (v12) provides model predictions for three eras, 2003–2019, 2003–2009, and 2010–2019, to reflect the apparent shift in NARW distribution around 2010. The modeling reported herein used the 2010–2019 density predictions as recommended by Roberts et al. (2022). Similarly, the 2022 updated humpback whale model (v11) provides model predictions for three eras, 2002–2019, 2002–2008, and 2009–2019. The modeling reported herein used the 2009-2019 density predictions as recommended by Roberts et al. (2022).

Densities were calculated within a perimeter set at 10 km from the lease area (see Figure 6). The perimeter distance was based on the largest 10 dB attenuated exposure range across all species, construction scenarios, and threshold criteria (excluding Wood et al. [2012] thresholds) (i.e., 6.29 km), and rounded up to the nearest 5-km increment. This 10 km range density perimeter is applied to all species. Wood et al. (2012) exposure ranges were not considered in this estimate because they include a small subset of very long ranges for migrating mysticetes and harbor porpoise.

The mean density for each month was determined by calculating the unweighted mean of all 5 × 5 km grid cells partially or fully within the analysis polygon (Figure 6). Densities were computed for an entire year to coincide with possible planned activities. In cases where monthly densities were unavailable, annual mean densities were used instead.

Long-finned and short-finned pilot whales were modeled separately, although there is only one density model for pilot whales as a guild from Roberts et al. (2016a, 2016b, 2017, 2022). Densities were adjusted based on their relative abundances, e.g.,

$$D_{long\text{-}finned} = D_{\mathrm{overall}} \times N_{\mathrm{long\text{-}finned}} / (N_{\mathrm{long\text{-}finned}} + N_{\mathrm{short\text{-}finned}}) \quad (1)$$

where D is density and N is abundance. Similarly, densities are provided for seals as a guild consisting primarily of harbor and gray seals (Roberts et al. 2016a, 2022). Gray and harbor seal densities were scaled by relative NOAA Fisheries SARs (NOAA Fisheries 2021c) abundance.

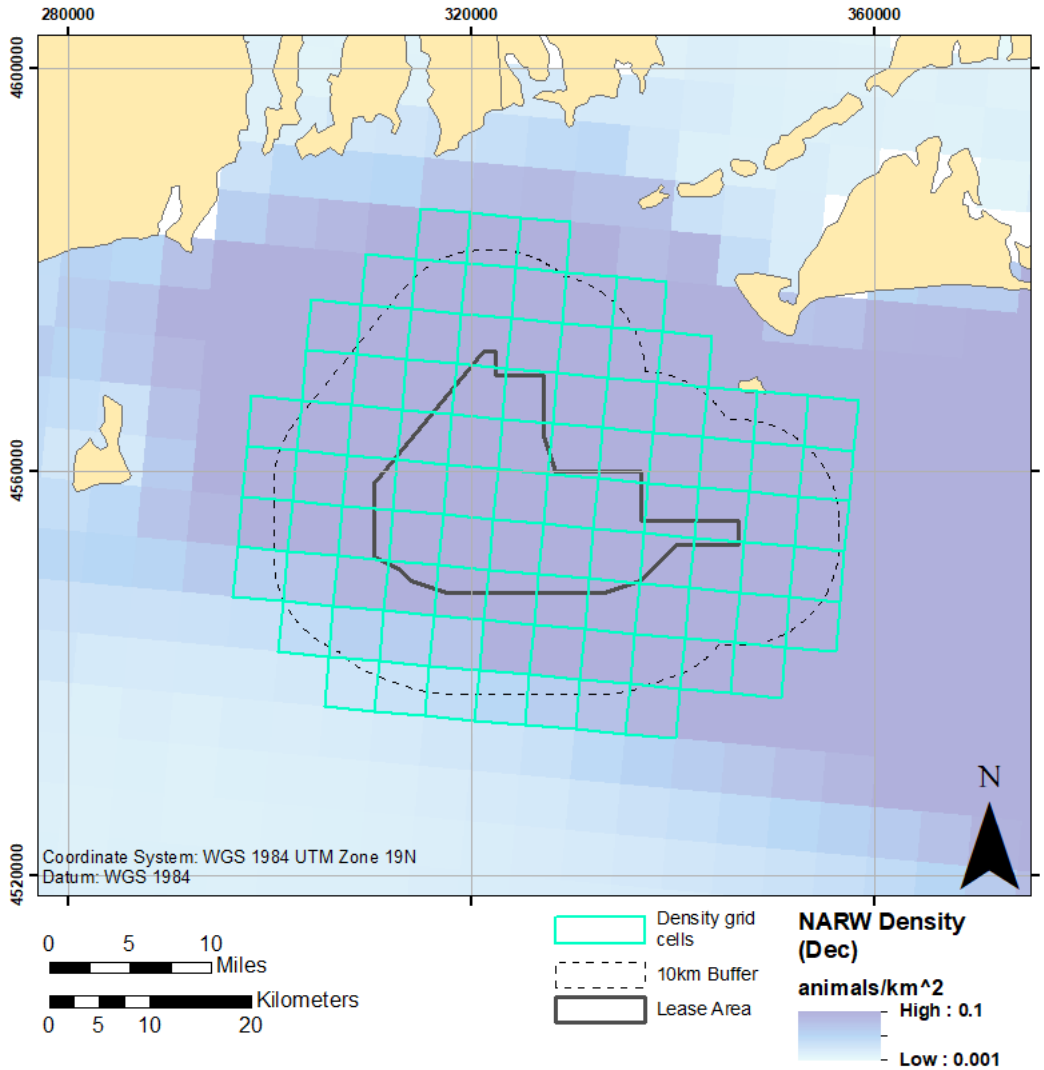

Figure 6. Marine mammal (e.g., NARW) density map showing highlighted grid cells used to calculate mean monthly species estimates within a 10 km perimeter around full OCS-A 0486 lease area (Roberts et al. 2016a, 2021, 2022).

Table 12. Mean monthly marine mammal density estimates for all modeled species within a 10 km perimeter around OCS-A 0486 lease area.

Species of interest	Monthly densities (animals/100 km^2) [a]												Annual mean
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Fin whale [b]	0.225	0.145	0.086	0.196	0.223	0.182	0.292	0.236	0.089	0.031	0.067	0.174	0.162
Minke whale	0.121	0.121	0.119	0.732	1.743	1.036	0.453	0.267	0.197	0.187	0.051	0.092	0.427
Humpback whale	0.049	0.032	0.029	0.102	0.205	0.146	0.105	0.094	0.119	0.135	0.153	0.043	0.101
North Atlantic right whale [b]	0.451	0.587	0.604	0.517	0.218	0.044	0.018	0.017	0.027	0.049	0.079	0.257	0.239
Sei whale [b]	0.035	0.019	0.031	0.093	0.126	0.020	0.006	0.007	0.013	0.020	0.065	0.068	0.042
Atlantic white sided dolphin	0.920	0.512	0.395	0.645	1.743	1.273	0.679	0.372	0.942	1.107	1.097	1.273	0.913
Atlantic spotted dolphin	<0.001	<0.001	<0.001	<0.001	0.001	0.002	0.004	0.007	0.040	0.052	0.037	0.004	0.012
Common dolphin	4.552	1.282	0.855	1.989	2.982	5.985	4.366	4.629	6.694	4.781	5.974	7.432	4.293
Bottlenose dolphin	0.222	0.048	0.027	0.079	0.431	0.699	0.897	0.906	0.740	0.637	0.644	0.638	0.497
Risso's dolphin	0.024	0.001	0.001	0.005	0.022	0.008	0.014	0.017	0.021	0.016	0.064	0.166	0.030
Long-finned pilot whale [c]	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
Short-finned pilot whale [c]	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
Sperm whale [b]	0.010	0.005	0.006	0.003	0.009	0.017	0.014	0.040	0.026	0.006	0.018	0.009	0.014
Harbor porpoise	7.271	7.487	6.643	5.880	3.981	0.227	0.216	0.216	0.168	0.202	0.269	5.145	3.142
Gray seal [c]	6.189	5.460	4.262	2.630	5.862	3.229	0.527	0.489	0.809	1.947	2.226	4.694	3.194
Harbor seal [c]	17.300	15.261	11.914	7.352	16.385	9.024	1.474	1.368	2.260	5.443	6.221	13.120	8.927
Harp seal	6.189	5.460	4.262	2.630	5.862	3.229	0.527	0.489	0.809	1.947	2.226	4.694	3.194

[a] Density estimates are from habitat-based density modeling of the entire Atlantic Exclusive Economic Zone (EEZ) (Roberts et al. 2016a, 2016b, 2017, 2018, 2021, 2022).
[b] Listed as Endangered under the ESA.
[c] Density adjusted by relative abundance.

3.3. Sea Turtles and Fish Species of Concern that may Occur in the Area

Four species of sea turtles may occur in the Project Area (Table 13), and all are listed as threatened or endangered: loggerhead sea turtle (*Caretta caretta*), Kemp's ridley sea turtle (*Lepidochelys kempii*), green sea turtle (*Chelonia mydas*), and leatherback sea turtle (*Dermochelys coriacea*). Many species of sea turtles prefer coastal waters; however, the leatherback and loggerhead sea turtles are known to occupy deep-water habitats and are considered common during summer and fall in Southern New England waters. Kemp's ridley sea turtles are thought to be regular visitors and green sea turtles, although uncommon, may be present during those seasons when water temperatures are highest.

There are four federally listed Threatened or Endangered fish species that may occur off the northeast Atlantic coast: shortnose sturgeon (*Acipenser brevirostrum*), Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), Atlantic salmon (*Salmo salar)*, and giant manta ray (*Manta birostris*).

Atlantic sturgeon distribution varies by season, but they are primarily found in shallow coastal waters (bottom depth less than 20 m) during summer (May to September) and move to deeper waters (20–50 m) in winter and early spring (December to March) (Dunton et al. 2010). Shortnose sturgeon occur primarily in fresh and estuarine waters and occasionally enter the coastal ocean. Adults ascend rivers to spawn from February to April, and eggs are deposited over hard bottom, in shallow, fast-moving water (Dadswell et al. 1984). Because of their preference for mainland rivers and fresh and estuarine waters, shortnose sturgeon are unlikely to be found in the vicinity of the Project Area. Atlantic salmon is an anadromous species that historically ranged from northern Quebec southeast to Newfoundland and southwest to Long Island Sound. The Gulf of Maine Distinct Population Segment (DPS) of the Atlantic salmon that spawns within eight coastal watersheds within Maine is federally listed as Endangered. In 2009, the DPS was expanded to include all areas of the Gulf of Maine between the Androscoggin River and the Dennys River (NOAA Fisheries 2021a). It is possible that adult Atlantic salmon may occur off the Massachusetts coast while migrating to rivers to spawn. However, only certain Gulf of Maine populations are listed as Endangered, and Gulf of Maine salmon are unlikely to be encountered south of Cape Cod (BOEM 2014). The giant manta ray is found worldwide in tropical, subtropical, and temperate bodies of water and is commonly found offshore, in oceanic waters, and near productive coastlines. As such, giant manta rays can be found in cool water, as low as 19°C, although temperature preference appears to vary by region. For example, off the US East Coast, giant manta rays are commonly found in waters from 19 to 22°C, whereas those off the Yucatan peninsula and Indonesia are commonly found in waters between 25 to 30°C. Individuals have been observed as far north as New Jersey in the Western Atlantic basin, indicating that the Offshore Development Area is located at the northern boundary of the species' range (NOAA Fisheries 2021b).

Table 13. Sea turtle species potentially occurring within the regional waters of the Western North Atlantic Outer Continental Shelf (OCS) and Project Area.

Species [b]	Distinct population segment	Current listing status [a]	Relative occurrence in RWF
Leatherback sea turtle * (*Dermochelys coriacea*)	N/A	ESA Endangered	Common
Loggerhead sea turtle * (*Caretta caretta*)	Northwest Atlantic	ESA Threatened	Common
Kemp's ridley sea turtle * (Lepidochelys kempii)	N/A	ESA Endangered	Uncommon
Green sea turtle* (*Cheloria mydas*)	North Atlantic	ESA Threatened	Uncommon

* = modeled species

[a] Listing status as stated in NOAA Fisheries n.d., MA NHESP 2019; RI DEM 2011; NYSDEC 2020a

[b] Hawksbill sea turtle (*Eretmochelys imbricata*) is not included in this report because this species is extralimital to the Mid-Atlantic and New England waters (85 FR 3880, January 23, 2020).

3.4. Sea Turtle Density Estimates

There are limited density estimates for sea turtles in the lease area. For this analysis, sea turtle densities were obtained from the US Navy Operating Area Density Estimate (NODE) database on the Strategic Environmental Research and Development Program Spatial Decision Support System (SERDP-SDSS) portal (DoN, 2012, 2017) and from the Northeast Large Pelagic Survey Collaborative Aerial and Acoustic Surveys for Large Whales and Sea Turtles (Kraus et al. 2016). These data are summarized seasonally (winter, spring, summer, and fall). Since the results from Kraus et al. (2016) use data that were collected more recently, those were used preferentially where possible.

Sea turtles were most commonly observed in summer and fall, absent in winter, and nearly absent in spring during the Kraus et al. (2016) surveys of the Massachusetts Wind Energy Area (WEA) and Rhode Island-Massachusetts WEAs. Because of this, the more conservative winter and spring densities from SERDP-SDSS are used for all species. It should be noted that SERDP-SDSS densities are provided as a range, where the maximum density will always exceed zero, even though turtles are unlikely to be present in winter. As a result, winter and spring sea turtle densities in the lease area, while low, are likely still overestimated.

For summer and fall, the more recent leatherback and loggerhead densities extracted from Kraus et al. (2016) were used. These species were the most commonly observed sea turtle species during aerial surveys by Kraus et al. (2016) in the Massachusetts WEA and Rhode Island-Massachusetts WEAs.

However, Kraus et al. (2016) reported seasonal densities for leatherback sea turtles only, so the loggerhead densities were calculated for summer and fall by scaling the averaged leatherback densities from Kraus et al. (2016) by the ratio of the seasonal sighting rates of the two species during the surveys. The Kraus et al. (2016) estimates of loggerhead sea turtle density for summer and fall are slightly higher than the SERDP-SDSS densities, and thus more conservative.

Kraus et al. (2016) reported only six total Kemp's ridley sea turtle sightings, so the estimates from SERDP-SDSS were used for all seasons. Green sea turtles are rare in this area and there are no density data available for this species, so the Kemp's ridley sea turtle density is used as a surrogate to provide a conservative estimate.

Sea turtle densities used in exposure estimates are provided in Table 14.

Table 14. Sea turtle density estimates for all modeled species within a 10 km perimeter around OCS-A 0486 lease area.

Common name	Density (animals/100 km^2) [a]			
	Spring	Summer	Fall	Winter
Kemp's ridley sea turtle [b]	<0.001	<0.001	<0.001	<0.001
Leatherback sea turtle [b]	0.020	0.630c	0.873c	0.020
Loggerhead sea turtle	0.131	0.206d	0.633d	0.131
Green sea turtle [e]	<0.001	<0.001	<0.001	<0.001

[a] Density estimates are extracted from SERDP-SDSS NODE database within a 10 km perimeter range of the lease area, unless otherwise noted.
[b] Listed as Endangered under the ESA.
[c] Densities calculated as averaged seasonal densities from 2011 to 2015 (Kraus et al. 2016).
[d] Densities calculated as the averaged seasonal leatherback sea turtle densities scaled by the relative, seasonal sighting rates of loggerhead and leatherback sea turtles (Kraus et al. 2016).
[e] Kraus et al. (2016) did not observe any green sea turtles in the RI/MA WEA. Densities of Kemp's ridley sea turtles are used as a conservative estimate.

In addition to the sea turtle density estimates described above, exposures were also calculated using sea turtle densities from the aforementioned SERDP-SDSS NODE database, but with adjustments made by the Sea Mammal Research Unit (SMRU 2013), available in the Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP) (Halpin et al. 2009). These data are summarized seasonally (winter [December to February], spring (March to May), summer [June to August], and fall [September to November] and provided as a range of potential densities per square kilometer within each grid square. Leatherback and loggerhead sea turtles were the most commonly observed turtle species during aerial surveys by Kraus et al. (2016) in the Massachusetts WEA and Rhode Island-Massachusetts WEAs, with an additional six identified Kemp's ridley sea turtle sightings over five years. Denes et al. (2021) used averaged seasonal leatherback sea turtle densities from Kraus et al. (2016) for summer and fall, as they provide more-recent non-zero estimates of leatherback density that are more geographically specific than the information in the OBIS database. Loggerhead densities were calculated for summer and fall by scaling the averaged leatherback densities from Kraus et al. (2016) by the ratio of the seasonal sighting rates of the two species during the surveys. Comparing the sightings rate of loggerhead and leatherback sea turtles in Kraus et al. (2016), leatherbacks are 1.16 more abundant than loggerheads in autumn, 1.14 times more abundant in spring, and 3.06 times more abundant in summer. These densities are also described within the South Fork Wind Farm Biological Opinion (NMFS 2021) and are shown in Table 15.

Table 15. Sea turtle density estimates for all modeled species, corrected from Denes et al. (2021)[b].

Common name	Density (animals/100 km^2) [a]			
	Spring	Summer	Fall	Winter
Kemp's ridley sea turtle	0.93	0.93	0.93	0.93
Leatherback sea turtle	0.59	0.63 [b]	0.87 [b]	0.59
Loggerhead sea turtle	3.50	0.21 [c]	0.76 [c]	3.50
Green sea turtle	0.93	0.93	0.93	0.93

Source: (NMFS 2021)

[a] Density estimates are derived from the Strategic Environmental Research and Development Program-Spatial Decision Support System unless otherwise noted. http://seamap.env.duke.edu/serdp

[b] Densities calculated as averaged seasonal densities from 2011 to 2015 (Kraus et al. 2016).

[c] Densities calculated as the averaged seasonal leatherback sea turtle densities scaled by the relative, seasonal sighting rates of loggerhead and leatherback sea turtles (Kraus et al. 2016).

[d] Kraus et al. (2016) did not observe any green sea turtles in the Rhode Island-Massachusetts Wind Energy Area. Densities of Kemp's ridley sea turtles are used as a conservative estimate.

4. Results

Sound fields from 7/12 m WTG monopiles were modeled at two locations: L024-002 in the northwest section of the RWF area and L024-114 in the southeast (L024_002 and L024_114 in Table 3 and Figure 2). The OSS monopile foundations were modeled at three proposed installation locations within the RWF area (OSS1, OSS2, and OSS3 in Table 3 and Figure 2). This section summarizes the source modeling results (Section 4.1), the acoustic propagation modeling results (Section 4.2), exposure estimates and exposure ranges from animal movement modeling of marine mammals and sea turtles (Sections 4.3 and 4.4), and the acoustic ranges to thresholds for fish (Section 4.5).

For exposure-based range estimates ($ER_{95\%}$), animal movement modeling is used to estimate ranges to regulatory-defined acoustic thresholds for marine mammals and turtles for two pile types (Section 4.1). Results based on both summer and winter sound speed profiles are reported. NAS mitigation was considered by attenuating the sound fields in the simulations by 0, 6, 10, and 15 dB.

4.1. Modeled Source Characteristics

Forcing functions were computed for each pile type using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010). The model assumed direct contact between the hammers, helmets, and piles (i.e., no cushion material) (Figures 7–8). The forcing functions serve as the inputs to JASCO's impact pile driving source models used to estimate equivalent acoustic source characteristics detailed in Appendix F. Decidecade spectral source levels for each pile type, hammer energy, and modeled location for both summer and winter sound speed profiles are shown in Figures 9–14.

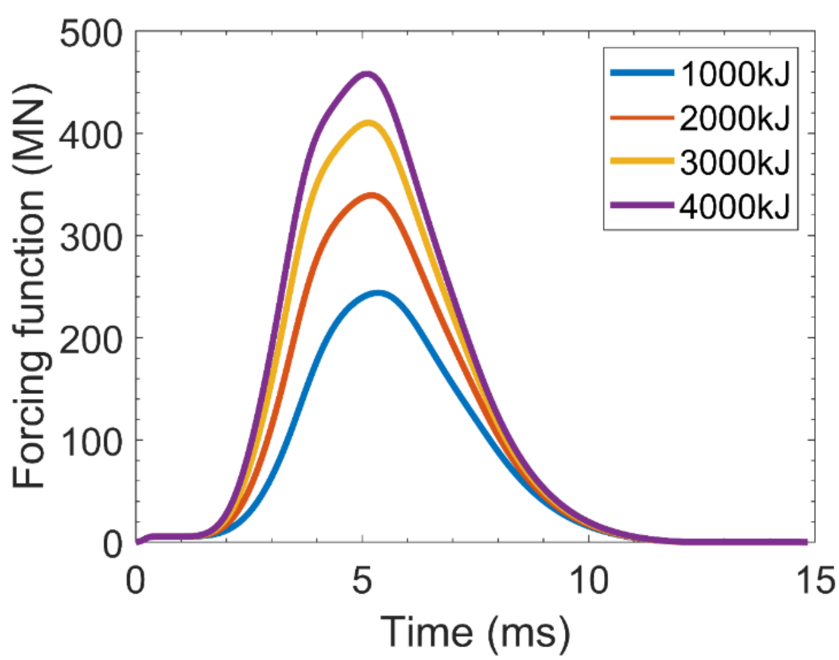

Figure 7. Modeled forcing functions versus time for the IHC S-4000 impact hammer for a 12 m monopile as a function of hammer energy.

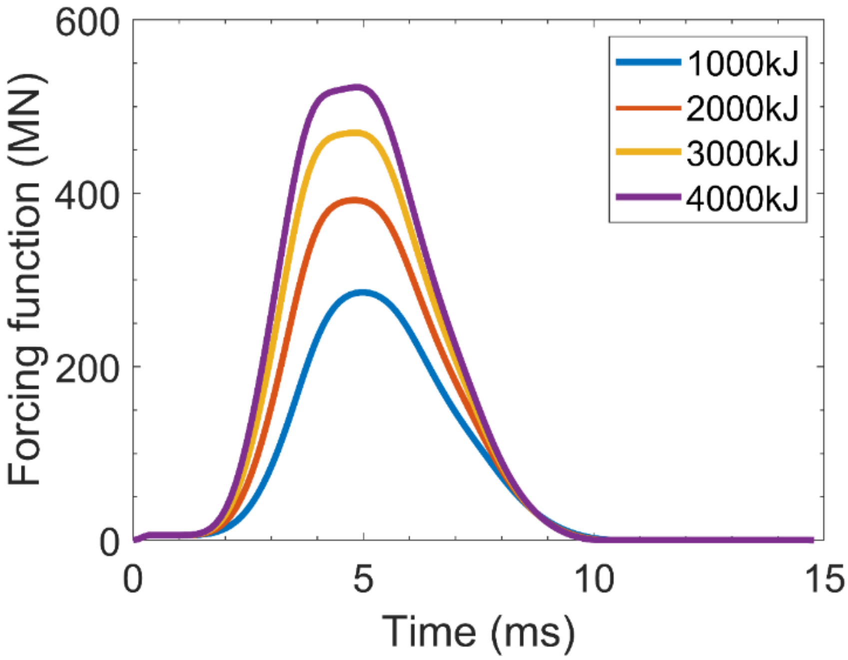

Figure 8. Modeled forcing functions versus time for the IHC S-4000 impact hammer for a 15 m monopile as a function of hammer energy.

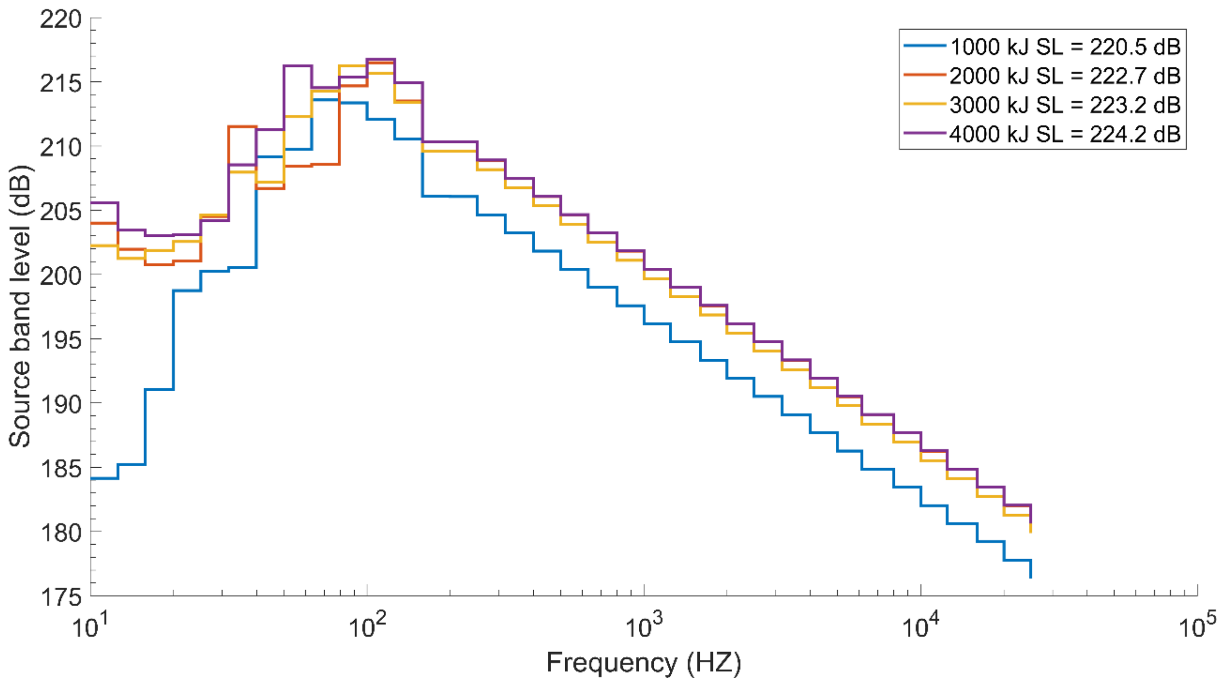

Figure 9. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-002 with a summer sound speed profile.

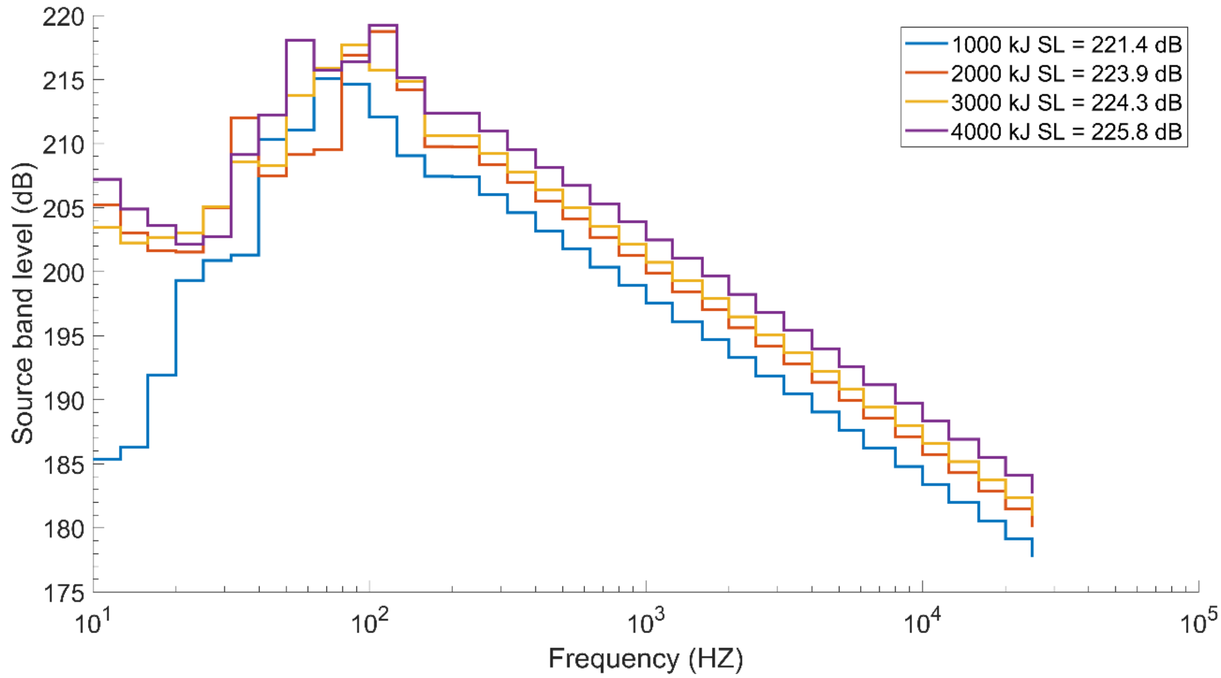

Figure 10. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-002 with a winter sound speed profile.

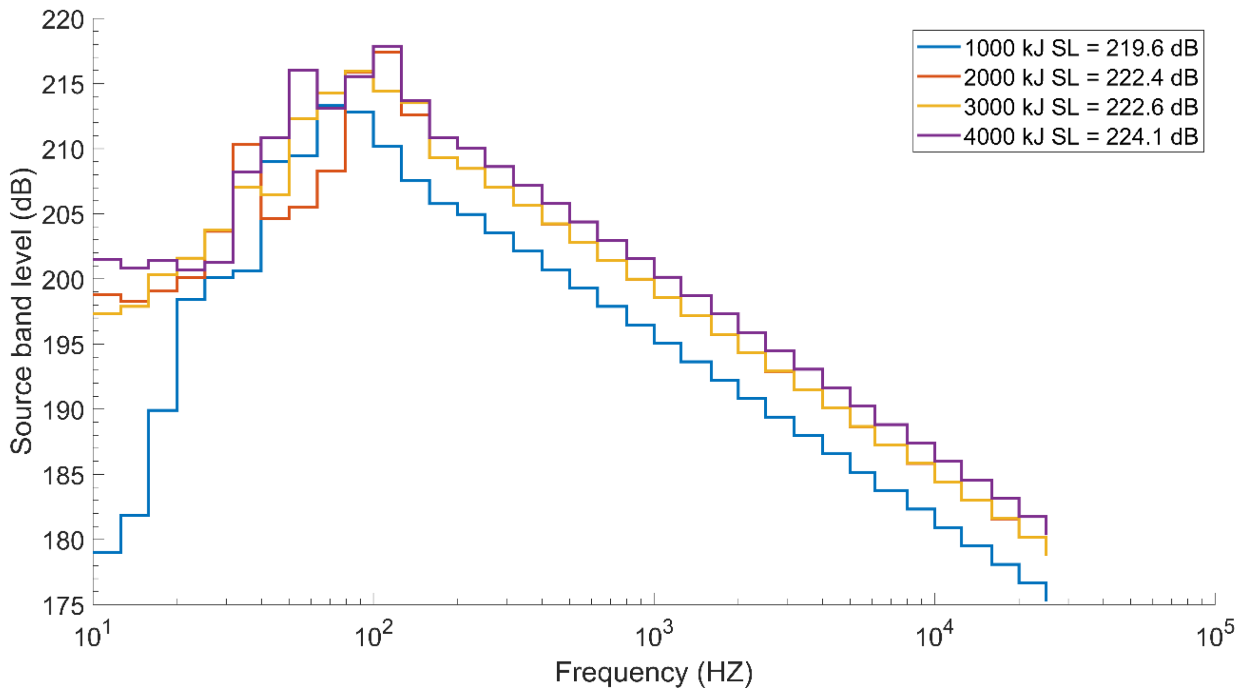

Figure 11. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-114 with a summer sound speed profile.

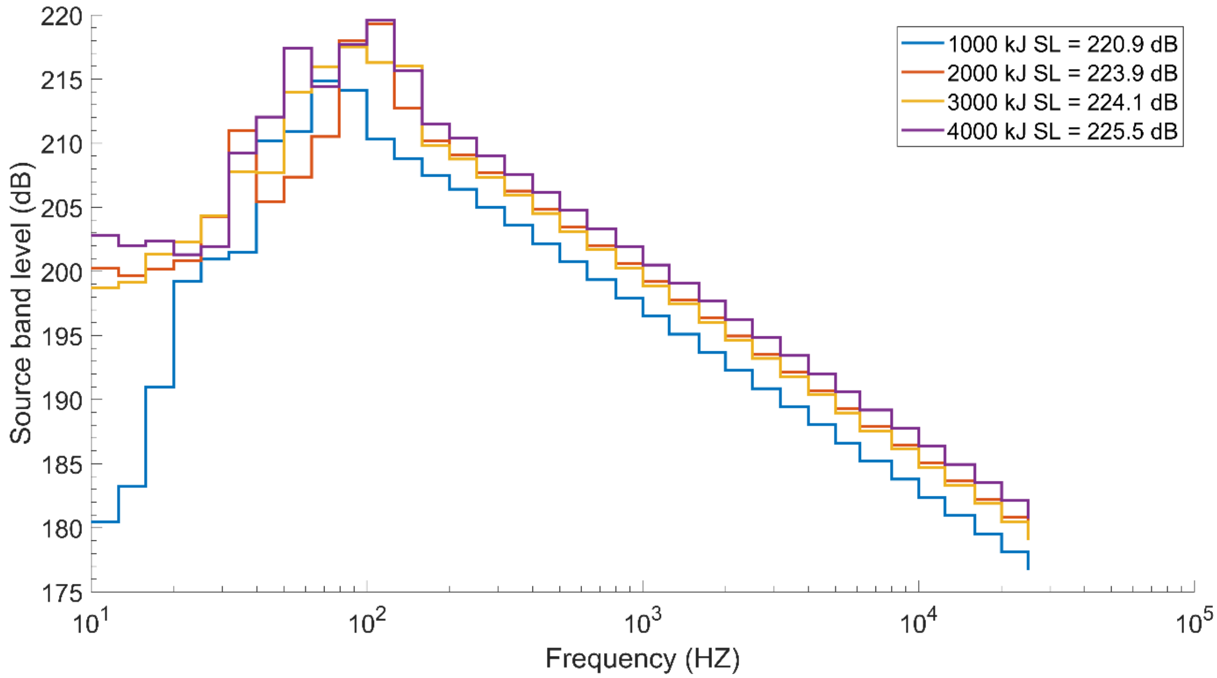

Figure 12. Decidecade band spectral source levels for monopile (12 m) installation using an IHC S-4000 hammer at site L024-114 with a winter sound speed profile.

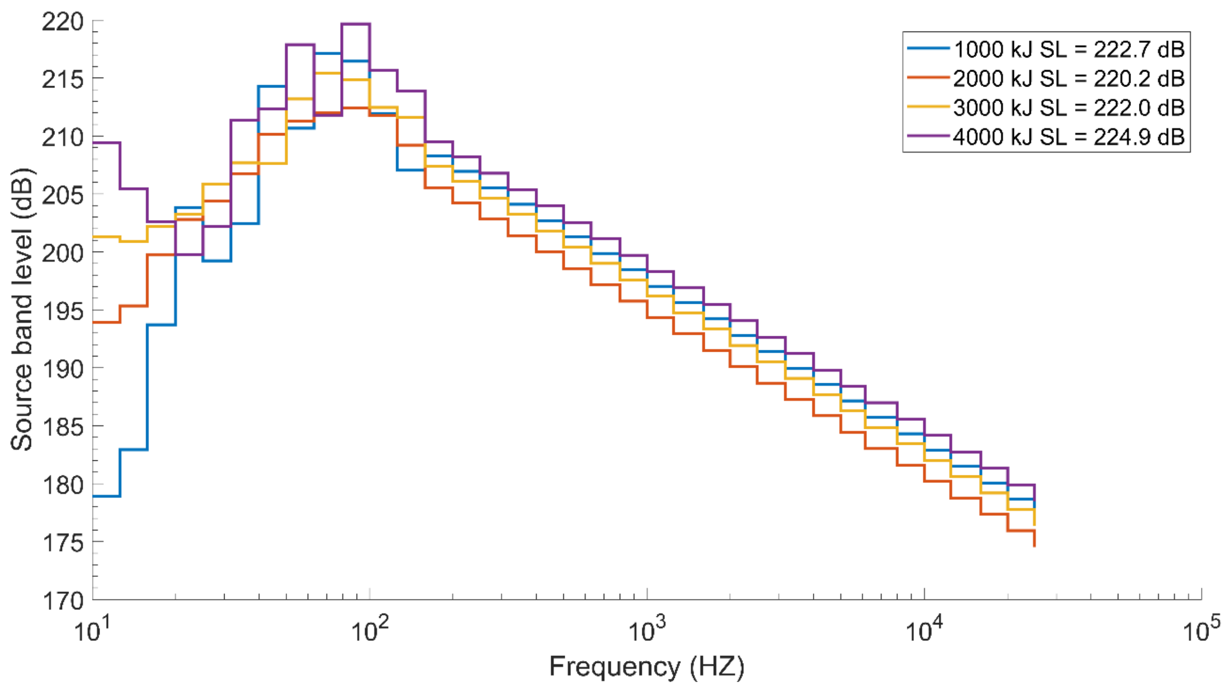

Figure 13. Decidecade band spectral source levels for monopile (15 m) installation using an IHC S-4000 hammer with a summer sound speed profile.

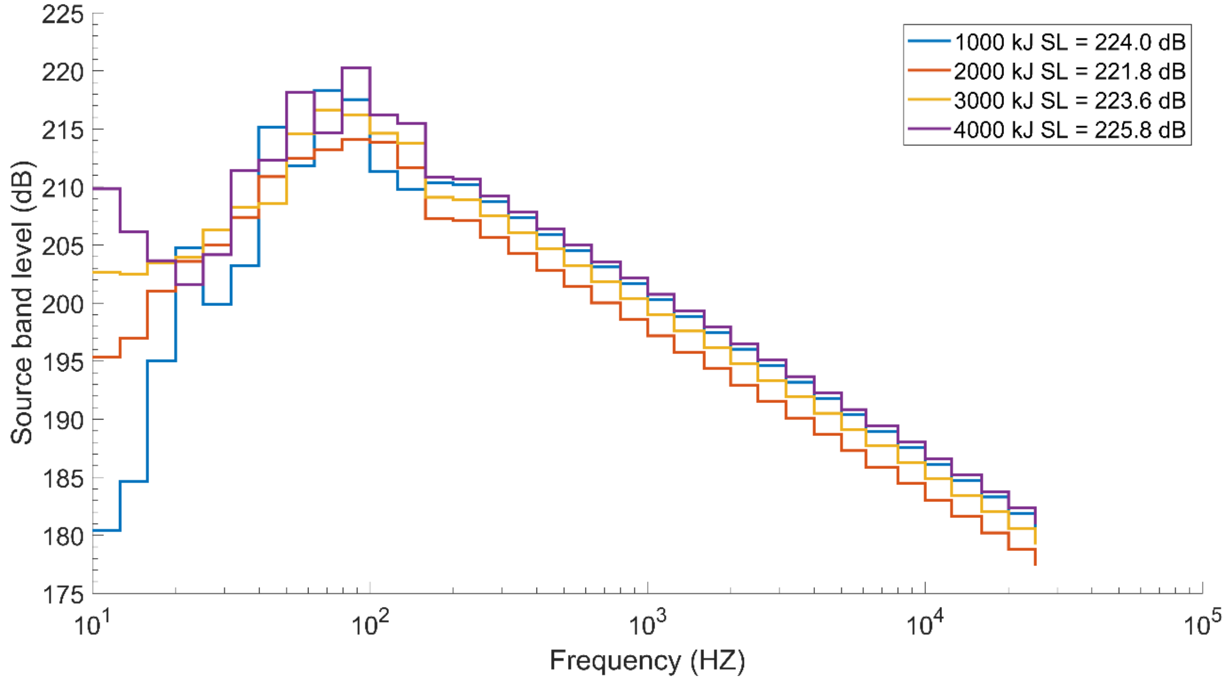

Figure 14. Decidecade band spectral source levels for monopile (15 m) installation using an IHC S-4000 hammer with a winter sound speed profile.

4.2. Modeled Sound Fields

Three dimensional (3-D) sound fields for 7/12 m monopiles and 7/15 m monopiles were calculated using the source characteristics (Section 4.1 and Appendix F) at representative locations (Table 3). Environmental parameters (bathymetry, geoacoustic information, and sound speed profiles) chosen for the propagation modeling and the modeling procedures are found in Appendix G. Subsequent ranges to various isopleths for single hammer strikes at the different hammer energy levels are shown in Appendix H. A comparison of unweighted, broadband, received levels at 750 m was made between the computed sound fields in this study and forecasted levels for 7/12 m monopiles and 7/15 m monopiles, from the ITAP empirical model (Bellmann et al. 2020) (Appendix I).

4.3. Exposure Estimates

Exposure estimates were calculated for marine mammals and sea turtles using the proposed construction schedule assumptions shown in Table 5. Sections 4.3.1 and 4.3.2 include results for each species and metric, assuming 10 dB attenuation and a summer sound speed profile. For full results, including all modeled attenuation levels, see Appendices J.2.1 and J.2.2.

4.3.1. Marine Mammals

Table 16. WTG and OSS monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 100 WTG and two OSS monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

	Species	Injury		Behavior	
		$L_{E,\,24h}$	L_{PK}	L_p [a]	L_p [b]
LF	Fin whale [c]	7.94	0	18.31	14.88
	Minke whale	73.37	0.14	228.95	530.05
	Humpback whale	7.99	0.02	14.07	11.57
	North Atlantic right whale [c]	20.46	<0.01	26.37	38.82
	Sei whale [c]	3.26	0	9.32	31.17
MF	Atlantic white sided dolphin	0.13	0	245.76	110.17
	Atlantic spotted dolphin	0	0	0	0
	Common dolphin	0	0	1632.47	1236.21
	Bottlenose dolphin	0	0	86.51	33.93
	Risso's dolphin	0.01	0	17.99	17.06
	Long-finned pilot whale	0	0	3.35	1.41
	Short-finned pilot whale	<0.01	0	3.53	1.43
	Sperm whale [c]	0	0	3.33	1.32
HF	Harbor porpoise	380.47	25.82	800.73	7207.89
PW	Gray seal	6.73	0	318.05	251.48
	Harbor seal	43.30	0	1122.27	816.12
	Harp seal	11.36	0	394.94	295.65

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.3.1.1. Effect of Aversion

The mean exposure estimates reported in Table 16 do not consider animals avoiding loud sounds (aversion) or implementation of mitigation measures other than sound attenuation using NAS. Some marine mammals are well known for their aversive responses to anthropogenic sound (e.g., harbor porpoise), although it is assumed that most species will avert from noise. The Wood et al. (2012) step function includes a probability of response that is based primarily on observed aversive behavior in field studies. Additional exposure estimates with aversion based on the Wood et al. (2012) response probabilities were calculated for NARW and harbor porpoise in this study. For comparative purposes only, the results are shown with and without aversion (Table 17).

Table 17. WTG and OSS monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 100 WTG and two OSS monopiles and with and without aversion. Construction schedule assumptions are summarized in Section 1.2.2

Species	10 dB attenuation – no aversion				10 dB attenuation – with aversion			
	Injury		Behavior		Injury		Behavior	
	$L_{E,\,24h}$	L_{pk}	L_p [a]	L_p [b]	$L_{E,\,24h}$	L_{pk}	L_p [a]	L_p [b]
North Atlantic right whale [c]	20.46	<0.01	26.37	38.82	3.82	0	9.95	25.32
Harbor porpoise	380.47	25.82	800.73	7207.89	1.46	0	29.17	4380.45

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.3.2. Sea Turtles

As was done for marine mammals (see Section 4.3.1), the numbers of individual sea turtles predicted to receive sound levels above threshold criteria were determined using animal movement modeling. The construction schedule described in Table 5 was used to calculate the total number of real-world individual turtles predicted to receive sound levels above injury and behavior thresholds (Finneran et al. 2017) in the RWF. Tables 18 and 19 include results assuming broadband attenuation of 10 dB, calculated in the same way as the marine mammal exposures. Table 18 shows exposure estimations based on density data included in Table 14, while Table 19 uses density data from Table 15.

Table 18. WTG and OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 100 WTG and two OSS monopiles, using density data from Table 14. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury		Behavior
	$L_{E,\,24h}$	L_{PK}	L_p
Kemp's ridley turtle [a]	<0.01	0	<0.01
Leatherback turtle [a]	0.69	0	7.52
Loggerhead turtle	0.13	0	3.20
Green sea turtle	<0.01	0	<0.01

[a] Listed as Endangered under the ESA.

Table 19. WTG and OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 100 WTG and two OSS monopiles, using density data from Table 15. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury		Behavior
	$L_{E,\,24h}$	L_{PK}	L_p
Kemp's ridley turtle [a]	0.56	0	8.70
Leatherback turtle [a]	0.69	0	7.49
Loggerhead turtle	0.78	0	19.01
Green sea turtle	1.35	0	9.46

[a] Listed as Endangered under the ESA.

4.4. Exposure Range Estimates

The following subsections contain tables of exposure ranges ($ER_{95\%}$) calculated for Level A sound exposure thresholds (SEL) and peak thresholds (PK), as well as Level B exposure thresholds (SPL) described in Sections 2.4 and 2.4.2. $ER_{95\%}$, values were calculated for both marine mammals and sea turtles, and these results are summarized in Figure 15 for each of the foundation types and installation schedules. Sections 4.4.1 and 4.4.2 provide additional detail for each species and metric, assuming 10 dB attenuation and a summer sound speed profile. For full results, including all modeled attenuation levels and both summer and winter sound speed profiles, see Appendices J.2.3 and J.2.4.

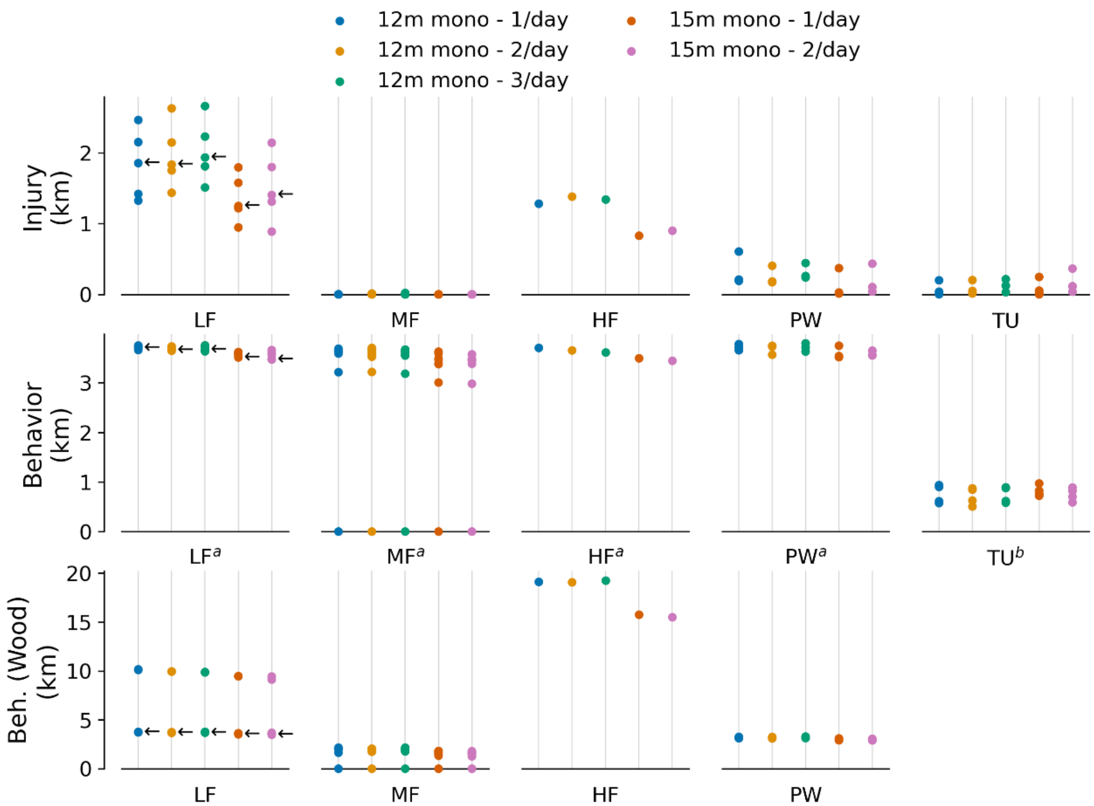

Figure 15. Maximum exposure ranges ($ER_{95\%}$) for injury and behavior thresholds, shown for each hearing group, assuming an attenuation of 10 dB and summer sound speed profile. The middle row represents ranges to Level B from unweighted SPL acoustic thresholds (NOAA 2005), and the bottom row represents ranges to Level B from m-weighted SPL acoustic thresholds (Wood et al. 2012). Each dot represents a species within the indicated hearing group (LF = low frequency, MF = mid frequency, HF = high frequency, PW = pinniped in water, TU = turtle, and arrows indicate NARW), and dot color represents a combination of foundation type and installation schedule (number of piles installed per day). Note the difference in y-axis scaling between the injury and behavior plots.

4.4.1. Marine Mammals

Exposure ranges ($ER_{95\%}$) to Level A SEL and PK acoustic thresholds are presented for WTG monopile and OSS monopile (Tables 20 and 21). Results are reported for 1, 2, and 3 piles per day for WTG monopiles, and 1 and 2 piles per day for OSS monopiles. Ranges to Level B unweighted SPL acoustic thresholds (NOAA 2005) and m-weighted SPL acoustic thresholds (Wood et al. 2012) are also included. Results are presented for summer and assume 10 dB broadband attenuation. It is noted that exposure ranges for multiple piles per day may be similar to the ranges for one pile per day because they are effectively separate events, and the differences primarily result from the statistical nature of the modeling process. Results for different seasons and at different attenuation levels can be found in Appendix J.2.3.

Table 20. WTG monopile foundation (7 to 12 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with 10 dB sound attenuation.

Species		One pile per day				Two piles per day				Three piles per day			
		Injury		Behavior		Injury		Behavior		Injury		Behavior	
		$L_{E,24h}$	L_{PK}	L_p [a]	L_p [b]	$L_{E,24h}$	L_{PK}	L_p [a]	L_p [b]	$L_{E,24h}$	L_{PK}	L_p [a]	L_p [b]
LF	Fin whale [c]	2.15	0	3.74	3.73	2.14	0	3.73	3.73	2.23	0	3.76	3.77
LF	Minke whale	1.32	<0.01	3.71	10.09	1.43	0	3.65	9.92	1.51	<0.01	3.63	9.84
LF	Humpback whale	2.46	<0.01	3.75	3.76	2.62	0	3.70	3.72	2.66	<0.01	3.72	3.73
LF	North Atlantic right whale [c]	1.85	0	3.70	3.72	1.83	<0.01	3.66	3.66	1.93	0	3.67	3.67
LF	Sei whale [c]	1.42	0	3.66	10.15	1.75	0	3.68	9.95	1.81	0	3.67	9.88
MF	Atlantic white sided dolphin	0	0	3.59	1.96	0.01	0	3.57	2.01	0.01	0	3.63	2.02
MF	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0
MF	Common dolphin	0	0	3.63	2.01	0	0	3.59	2.05	0	0	3.56	2.07
MF	Bottlenose dolphin	0	0	3.21	1.64	0	0	3.22	1.74	0	0	3.18	1.77
MF	Risso's dolphin	0	0	3.69	2.15	<0.01	0	3.70	2.01	<0.01	0	3.67	2.15
MF	Long-finned pilot whale	0	0	3.65	2.05	0.01	0	3.53	1.96	0	0	3.55	1.98
MF	Short-finned pilot whale	<0.01	0	3.62	2.06	<0.01	0	3.62	2.01	0.02	0	3.57	2.01
MF	Sperm whale [c]	0	0	3.66	2.10	0	0	3.66	2.02	0	0	3.63	2.08
HF	Harbor porpoise	1.28	0.18	3.71	19.13	1.38	0.16	3.66	19.05	1.34	0.16	3.62	19.24
PW	Gray seal	0.60	0	3.78	3.25	0.40	0	3.73	3.24	0.44	0	3.80	3.29
PW	Harbor seal	0.21	0	3.66	3.13	0.18	0	3.57	3.10	0.24	0	3.63	3.13
PW	Harp seal	0.19	0	3.72	3.12	0.17	0	3.75	3.20	0.26	0	3.71	3.17

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table 21. OSS monopile foundation (7 to 15 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with 10 dB sound attenuation.

Species		One pile per day				Two piles per day			
		Injury		Behavior		Injury		Behavior	
		$L_{E,24h}$	L_{PK}	L_p [a]	L_p [b]	$L_{E,24h}$	L_{PK}	L_p [a]	L_p [b]
LF	Fin whale [c]	1.57	0	3.62	3.62	1.80	0	3.66	3.67
	Minke whale	0.94	0	3.56	9.44	0.89	0	3.47	9.11
	Humpback whale	1.79	0	3.61	3.61	2.14	<0.01	3.57	3.57
	North Atlantic right whale [c]	1.25	<0.01	3.51	3.51	1.40	0	3.47	3.47
	Sei whale [c]	1.22	0	3.58	9.47	1.31	<0.01	3.61	9.43
MF	Atlantic white sided dolphin	0	0	3.46	1.54	0	0	3.48	1.65
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0
	Common dolphin	0	0	3.49	1.78	0	0	3.46	1.68
	Bottlenose dolphin	0	0	3.00	1.33	0	0	2.98	1.26
	Risso's dolphin	0	0	3.59	1.79	0	0	3.46	1.79
	Long-finned pilot whale	0	0	3.38	1.75	0	0	3.38	1.69
	Short-finned pilot whale	0	0	3.39	1.59	0	0	3.45	1.54
	Sperm whale [c]	0	0	3.63	1.81	0	0	3.57	1.52
HF	Harbor porpoise	0.83	0.11	3.50	15.76	0.90	0.15	3.45	15.49
PW	Gray seal	0.37	0	3.75	3.10	0.43	0	3.65	3.06
	Harbor seal	0.01	0	3.54	2.95	0.04	0	3.55	2.89
	Harp seal	0.03	0	3.52	2.91	0.10	0	3.56	2.91

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.4.2. Sea Turtles

Similar to the results presented for marine mammals (Section 4.4.1), exposure ranges ($ER_{95\%}$) for sea turtles are summarized for WTG monopile and OSS monopile foundations for the summer season and assuming 10 dB broadband attenuation in Tables 16-18. Again, it is noted that exposure ranges for multiple piles per day may be similar to, or smaller than, the ranges for one pile per day because they are effectively separate events, and the differences primarily result from the statistical nature of the modeling process. Results for different seasons and at different attenuation levels can be found in Appendix J.2.4.

Table 22. WTG monopile foundation (7 to 12 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with 10 dB sound attenuation.

Species	One pile per day			Two piles per day			Three piles per day		
	Injury		Behavior	Injury		Behavior	Injury		Behavior
	$L_{E,24h}$	L_{PK}	L_p	$L_{E,24h}$	L_{PK}	L_p	$L_{E,24h}$	L_{PK}	L_p
Kemp's ridley turtle [a]	0.04	0	0.90	0.05	0	0.84	0.12	0	0.88
Leatherback turtle [a]	<0.01	0	0.61	0.03	0	0.63	0.12	0	0.62
Loggerhead turtle	0.02	0	0.57	0.01	0	0.50	0.03	0	0.58
Green sea turtle	0.20	0	0.94	0.20	0	0.87	0.21	0	0.89

[a] Listed as Endangered under the ESA.

Table 23. OSS monopile foundation (7 to 15 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with 10 dB sound attenuation.

Species	One pile per day			Two piles per day		
	Injury		Behavior	Injury		Behavior
	$L_{E,24h}$	L_{PK}	L_p	$L_{E,24h}$	L_{PK}	L_p
Kemp's ridley turtle [a]	0.05	0	0.97	0.11	0	0.89
Leatherback turtle [a]	0	0	0.72	0.12	0	0.70
Loggerhead turtle	0.04	0	0.76	0.04	0	0.59
Green sea turtle	0.25	0	0.82	0.36	0	0.82

[a] Listed as Endangered under the ESA.

4.5. Acoustic Threshold Ranges for Impact Pile Driving: Fish

Ranges to regulatory defined acoustic thresholds (Section 2.4.2) are presented for fish for WTG monopile and OSS monopile (Table 24 to Table 31), at two locations for two seasons with 10 dB attenuation.

Table 24. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of one 12 m monopile in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	13,937				7,708				13,163				7,043			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Large fish	$L_{E,12hr}$	187	10,144				6,048				9,180				5,576			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Small fish	L_{p}	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805
Large fish	L_{p}	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805

Table 25. Ranges ($R_{95\%}$ in meters) to thresholds for fish groups (Popper et al. 2014) due to impact hammering of one 12 m monopile in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114).

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	128				102				144				113			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	662				464				668				474			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,063				744				1,102				761			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Eggs and larvae	$L_{E,24hr}$	210	662				464				668				474			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	224				179				260				179			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder	$L_{E,24hr}$	203	1,914				1,348				2,020				1,360			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	11,009				6,476				9,911				5,904			

Table 26. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of two 12 m monopile in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	17,746				9,023				18,209				8,217			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Large fish	$L_{E,12hr}$	187	12,794				7,294				11,833				6,678			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Small fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805
Large fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805

Small fish are defined as having a total mass of <2 g.
Large fish are defined as having a total mass of ≥2 g.

Table 27. Ranges ($R_{95\%}$ in meters) to thresholds for fish groups (Popper et al. 2014) due to impact hammering of two 12 m monopile in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114).

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	224				179				260				179			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	1,063				747				1,102				762			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,680				1,161				1,780				1,177			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Eggs and larvae	$L_{E,24hr}$	210	1,063				747				1,102				762			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	382				268				412				283			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder	$L_{E,24hr}$	203	2,800				1,986				2,836				1,993			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	13,945				7,711				13,178				7,048			

Table 28. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of three 12 m monopiles in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	20,832				9,795				22,506				8,986			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Large fish	$L_{E,12hr}$	187	14,821				8,022				14,164				7,318			
	L_{pk}	206	51	73	100	122	55	72	94	115	51	69	92	110	53	68	85	103
Small fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805
Large fish	L_p	150	7,085	9,862	9,562	10,664	4,916	5,829	5,952	6,301	6,063	8,755	8,992	9,758	4,390	5,413	5,343	5,805

Table 29. Ranges ($R_{95\%}$ in meters) to thresholds for fish groups (Popper et al. 2014) due to impact hammering of three 12 m monopiles in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (L024-002 and L024-114).

Group	Metric	Threshold (dB)	L024-002								L024-114							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	310				228				340				224			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	1,393				987				1,468				971			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	2,135				1,484				2,201				1,500			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Eggs and larvae	$L_{E,24hr}$	210	1,393				987				1,468				971			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	538				358				563				388			
	L_{pk}	213	4	14	11	18	4	15	11	18	4	14	12	18	4	15	12	18
Fish with swim bladder	$L_{E,24hr}$	203	3,479				2,447				3,419				2,374			
	L_{pk}	207	21	59	89	113	21	63	84	106	40	61	81	101	42	60	76	95
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	15,930				8,468				15,801				7,701			

Table 30. Ranges ($R_{95\%}$ in meters) to thresholds for fish (Popper et al. 2014) due to impact hammering of one 15 m monopile in 24 hr, using an IHC S-4000 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				*Summer*				*Winter*				*Summer*			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
Mortality and Potential Mortal Injury																		
Fish without swim bladder	$L_{E,24hr}$	219	213				171				223				171			
	L_{pk}	213	10	10	12	19	10	10	12	19	10	10	12	19	10	10	12	19
Fish with swim bladder not involved in hearing	$L_{E,24hr}$	210	953				722				979				747			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Fish with swim bladder involved in hearing	$L_{E,24hr}$	207	1,431				1,084				1,470				1,120			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Eggs and larvae	$L_{E,24hr}$	210	953				722				979				747			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Recoverable injury																		
Fish without swim bladder	$L_{E,24hr}$	216	360				268				373				273			
	L_{pk}	213	10	10	12	19	10	10	12	19	10	10	12	19	10	10	12	19
Fish with swim bladder	$L_{E,24hr}$	203	2,298				1,714				2,343				1,781			
	L_{pk}	207	38	60	74	91	41	58	72	87	38	60	74	91	41	58	72	87
Temporary Threshold Shift																		
All fish	$L_{E,24hr}$	186	9,687				5,981				11,403				6,944			

Table 31. Ranges ($R_{95\%}$ in meters) to thresholds for fish (GARFO 2016) due to impact hammering of one 15 m monopile in 12 hr, using an IHC S-4000 hammer at two selected modeling locations (OSS1 and OSS2). The duration of impact pile driving will be <12 hr per day, so 12 and 24 hr SEL are equivalent.

Group	Metric	Threshold (dB)	OSS1								OSS2							
			Winter				Summer				Winter				Summer			
			Hammer energy (kJ)								Hammer energy (kJ)							
			1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000	1000	2000	3000	4000
GARFO (2016)																		
Small fish	$L_{E,12hr}$	183	12,238				7,021				14,224				8,197			
	L_{pk}	206	47	67	84	99	47	66	78	93	47	67	84	99	47	66	78	93
Large fish	$L_{E,12hr}$	187	8,980				5,681				10,564				6,524			
	L_{pk}	206	47	67	84	99	47	66	78	93	47	67	84	99	47	66	78	93
Small fish	L_p	150	7,128	7,160	8,149	9,221	5,082	4,620	5,114	5,959	8,417	8,389	9,561	10,888	5,781	5,063	5,786	6,921
Large fish	L_p	150	7,128	7,160	8,149	9,221	5,082	4,620	5,114	5,959	8,417	8,389	9,561	10,888	5,781	5,063	5,786	6,921

Small fish are defined as having a total mass of <2 g.
Large fish are defined as having a total mass of ≥2 g.

5. Discussion

This study predicted underwater sound levels associated with the installation of piles supporting WTG and OSS foundations. Sounds fields produced during impact pile driving for installation of 7/11 m WTG monopile foundations and 7/15 OSS monopile foundations were found by modeling the vibration of the pile when struck with a hammer, determining a far-field representation of the pile as a sound source, and then propagating the sound from the apparent source into the environment. A comparison of the modeled sound fields was made with a forecasting, empirical model (ITAP) that predicts broadband pile driving sound levels at 750 m from the pile (Appendix I).

Sound fields were sampled by simulating animal movement within the sound fields and determining if simulated marine mammal and sea turtle animats (simulated animals) exceed regulatory thresholds. The mean number of individuals of each species likely to exceed the thresholds was determined by scaling the animat results using the real-world density of each species. For those animats that exceeded thresholds, the closest point of approach to the source was found and the distance accounting for 95% of exceedances was reported as the exposure range, $ER_{95\%}$. The species-specific $ER_{95\%}$ (see tables in Section 4.4) were determined with different broadband attenuation levels (0, 6, 10, 15, and 20 dB) to account for the use of noise reduction systems, such as bubble curtains. $ER_{95\%}$ can be used for mitigation purposes, like establishing monitoring or exclusion areas. Fish were considered as static receivers, so exposure ranges were not calculated. Instead, the acoustic distance to their regulatory thresholds were determined and reported, with the different broadband attenuation levels (see tables in Section 4.5).

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Appendix A. Glossary

1/3-octave

One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band

Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing center frequency.

A-weighting

Frequency-selective weighting for human hearing in air that is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies.

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

ambient noise

All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 (R2004)), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

Auditory frequency weighting (auditory weighting function, frequency-weighting function)

The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation, it is also called bearing.

bandwidth

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI and ASA S1.13-2005 (R2010)).

boxcar averaging

A signal smoothing technique that returns the averages of consecutive segments of a specified width.

broadband sound level

The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cavitation

A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean

Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period (ANSI and ASA S1.13-2005 (R2010)). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade

One-tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one-third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band

Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing center frequency.

decibel (dB)

One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 (R2004)).

delphinid

Family of oceanic dolphins, or Delphinidae, composed of approximately thirty extant species, including dolphins, porpoises, and killer whales.

ensonified

Exposed to sound.

frequency

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing group

Groups of marine mammal species with similar hearing ranges. Commonly defined functional hearing groups include low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

hertz (Hz)

A unit of frequency defined as one cycle per second.

high-frequency (HF) cetacean

The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for hearing high frequencies.

impulsive sound

Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA and US Dept of Commerce 2013, [ANSI] American National Standards Institute S12.7-1986 (R2006)). For example, seismic airguns and impact pile driving.

low-frequency (LF) cetacean

The functional cetacean hearing group that represents mysticetes (baleen whales) specialized for hearing low frequencies.

mid-frequency (MF) cetacean

The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for mid-frequency hearing.

Monte Carlo simulation

The method of investigating the distribution of a non-linear multi-variate function by random sampling of all of its input variable distributions.

mysticete

Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but they use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

non-impulsive sound

Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI and ASA S3.20-1995 (R2008)). For example, marine vessels, aircraft, machinery, construction, and vibratory pile driving (NIOSH 1998, NOAA 2015).

octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete

The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The skulls of toothed whales are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

otariid

A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

parabolic equation (PE) method

A computationally-efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is *negligible* for most ocean-acoustic propagation problems.

particle acceleration

The rate of change of particle velocity. Unit: meter per second squared (m/s^2). Symbol: *a*.

particle velocity

The physical speed of a particle in a material moving back and forth in the direction of the pressure wave. Unit: meter per second (m/s). Symbol: *v*.

peak pressure level (PK)

The maximum instantaneous sound pressure level, in a stated frequency band, within a stated period. Also called zero-to-peak sound pressure level. Unit: decibel (dB).

permanent threshold shift (PTS)

A permanent loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid

A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

pinniped

A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source

A source that radiates sound as if from a single point (ANSI S1.1-1994 (R2004)).

pressure, acoustic

The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

pressure, hydrostatic

The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

propagation loss

The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called transmission loss.

received level (RL)

The sound level measured (or that would be measured) at a defined location.

rms

root-mean-square.

shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound

A time-varying pressure disturbance generated by mechanical vibration waves traveling through a fluid medium such as air or water.

sound exposure

Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ($Pa^2 \cdot s$) (ANSI S1.1-1994 (R2004)).

sound exposure level (L_ESEL)

A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound field

Region containing sound waves (ANSI S1.1-1994 (R2004)).

sound pressure level (SPL)

The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 (R2004)).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

source level (SL)

The sound level measured in the far-field and scaled back to a standard reference distance of 1 meter from the acoustic center of the source. Unit: dB re 1 µPa·m (pressure level) or dB re 1 µPa^2·s·m (exposure level).

spectral density level

The decibel level (10·$\log_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 µPa^2/Hz and dB re 1 µPa^2·s/Hz, respectively.

spectrum

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

temporary threshold shift (TTS)

Temporary loss of hearing sensitivity caused by excessive noise exposure.

transmission loss (TL)

The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

Appendix B. Summary of Study Assumptions

Table B-1. Summary of model inputs, assumptions, and methods.

Parameter	Description
12 m WTG Monopile Impact Pile Driving Source Model	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; hammer forcing functions computed using GRLWEAP. Hammer above water.
Impact hammer model	IHC S4000
Ram weight	1977 kN (200 ton)
Helmet weight	3234 kN (330 ton)
Impact hammer energy	1000, 2000, 3000, 4000 kJ
Modeled seabed penetration for each hammer energy	6, 24, 36, 50 m
Final pile seabed penetration	50 m
Penetration rate for each hammer energy	10, 5, 6, 5 mm/bl
Pile self-settling penetration	3 m
Strike rate	50 min^{-1}
Estimated number of strikes to drive pile at each energy	1705, 3590, 2384, 3061
Total number of strikes per pile	10,740
Expected duration to drive one pile	~215 min
Number of piles per site per day	2–3
Pile length	110 m
Pile diameter	12 m
Pile thickness	16 cm
Monopile modeled locations (ID, easting, northing, water depth)	L024-002, 320793.48, 4569669.5, 41.3 L024-114, 336403.93, 4551413.22, 36.8
15 m OSS Monopile Impact Pile Driving Source Model	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; hammer forcing functions computed using GRLWEAP. Hammer above water.
Impact hammer model	IHC S4000
Ram weight	1977 kN (202 ton)
Helmet weight	3234 kN (330 ton)
Impact hammer energy	1000, 2000, 3000, 4000 kJ
Modeled seabed penetration for each hammer energy	5, 17, 36, 50 m
Final pile seabed penetration	50 m
Penetration rate for each hammer energy	18, 8, 5, 2.5 mm/bl
Pile self-settling penetration	3 m
Strike rate	50 min^{-1}
Estimated number of strikes to drive pile at each energy	954, 2944, 4899, 2766

Total number of strikes per pile	11,563
Expected duration to drive one pile	~231 min
Number of piles per site per day	0.5–1
Pile length	120 m
Pile diameter	15 m
Pile thickness	20 cm
Monopile modeled locations (ID, easting, northing, water depth)	OSS1, 327480.00, 4554999.69, 34.18 OSS2, 321190.00, 4564259.69, 34.42 OSS(Backup), 321190.00, 4558703.69, 33.49
Environmental Parameters	
Sound speed profile	Sound speed profile from GDEM data averaged over region
Bathymetry	SRTM data combined with bathymetry data provided by client
Geoacoustics	Fine sand. Elastic seabed properties based on USGS East coast sediment analysis for modeling region.
Propagation Model	
Modeling method	Parabolic-equation propagation model with 2.5° azimuthal resolution; FWRAM full-waveform parabolic equation (PE) propagation model for 4 radials.
Source representation	Vertical line array
Frequency range	10–2000 Hz extrapolated to 63000 Hz (frequency and range dependent absorption applied to propagation loss from 2000 Hz estimates for higher frequencies)
Synthetic trace length	1000 ms
Maximum modeled range	49.5 km

Appendix C. Secondary Sound Sources in the Project Area

The primary sources of underwater sound generated during the project are associated with installation of monopile foundations. These primary sound sources are the focus of the quantitative analysis presented in the main text. The objective of this Appendix is to provide a qualitative description and evaluation of other underwater sound sources associated with project construction and operation, collectively referred to as secondary sound sources. Secondary sound sources are anthropogenic sound sources that are only likely to cause behavioral responses and short-term stress in marine fauna. Secondary sound sources are expected to be of very low or low risk (Table C-1), and, because of their limited risk, a qualitative (instead of quantitative) evaluation of these sound sources was undertaken and is detailed for each source type below.

C.1. Vessels

All vessels emit sound from propulsion systems while in transit, and engines and machinery emit noise through the hull while in use. The emitted sounds are typically broadband, non-impulsive, continuous, low-frequency noise. A vessel's acoustic signature depends on the vessel type (e.g., tanker, bulk carrier, tug, container ship, recreational vessel) and vessel characteristics (e.g., engine specifications, propeller dimensions and number, length, draft, hull shape, gross tonnage, and speed). Large shipping vessels and tankers produce lower frequency sounds with primary acoustic energy ~40 Hz and apparent underwater source levels (SLs) of SPL 177 to 188 dB re 1 µPa·m (McKenna et al. 2012). Dynamically positioned (DP) vessels use thrusters to maneuver and maintain station, and generate substantial underwater noise with apparent SLs ranging from SPL 150 to 180 dB re 1 µPa·m depending on operations and thruster use (BOEM 2014). Smaller, high-speed vessels may produce higher-frequency sound (1,000 to 5,000 Hz) with apparent SLs between SPL 150 and 180 dB re 1 µPa·m (Kipple 2002, Kipple and Gabriele 2003).

Marine mammals, sea turtles, fish, and invertebrates in many locations are regularly subjected to vessel activity and may be habituated to vessel noise as a result of frequent or prolonged exposure (BOEM 2014). Non-Project vessel traffic in the vicinity of the Project may include recreational vessels, fishing vessels, cargo vessels, tankers, passenger vessels, and other vessels. Vessels associated with the project during construction and operation will not contribute considerably more vessel traffic above baseline conditions and therefore the potential risk of impact from Project vessel noise is low to very low.

C.2. Potential Impacts to Marine Fauna

C.2.1. Marine Mammals

The vessel sounds emitted by ship engines, propellers, thrusters, and hulls are within the (assumed) best hearing frequency ranges of low-frequency cetaceans and are audible by all marine mammals (NMFS 2018). Vessel activities in the Project Area will add to the existing ambient vessel sound level of regular vessel traffic in the area, which could cause behavioral impacts to marine mammals (Kraus et al. 2005, Southall 2005, Clark et al. 2009, Geo-Marine 2010). As with other anthropogenic sound, the potential effects from vessel noise depends on factors such as the marine mammal species, the marine mammal's location and activity, the novelty of the sound, habitat, and oceanographic conditions.

Marine mammals exposed to vessel sounds have reported variable behavioral responses. Analyses of observations made during the Behavioral Response of Australian Humpback whales (*Megaptera novaeangliae*) to Seismic Surveys (BRAHSS) study, Dunlop et al. (2015, 2016a, 2016b, 2017a, 2017b, 2018), found only minor and temporary changes in the migratory behavior of humpback whales in response to exposure to vessel and seismic airgun sounds. Increased proximity of vessels, however, led to aversive reactions (Dunlop et al. 2017b) and to reduced social interactions between migrating humpback whales (Dunlop et al. 2020). In other studies of humpback whales, most individuals did not respond to sonar vessels with the sonar turned off (Sivle et al. 2016, Wensveen et al. 2017), and Tsujii et al. (2018) found that humpback whales moved away from large vessels, while others noted temporary changes in respiratory behavior (Baker and Herman 1989, Frankel and Clark 2002)) or temporary cessation of foraging activities (Blair et al. 2016). Researchers have also reported a temporary change in the distribution and behavior of marine mammals in areas experiencing increased vessel traffic, particularly associated with whale watching, likely due to increases in ambient noise from concentrated vessel activity (Erbe 2002, Nowacek et al. 2004). The large number of studies on humpback whales and the resulting variety of documented responses clearly demonstrate how context affects behavior.

Marine mammals in the Project Area are regularly subjected to commercial shipping traffic and other vessel noise and could potentially be habituated to vessel noise (BOEM 2014). Hatch et al. (2012) estimated that calling North Atlantic right whales (*Eubalaena glacialis*) (NARWs) may have lost 63 to 67% of their communication "space" due to shipping noise. Although received levels of sound may, at times, be above the non-impulsive sound threshold for Level B harassment (120 dB SPL), NARWs have been known to continue to feed in Cape Cod Bay, Massachusetts despite disturbance from passing vessels (Brown et al. 2000). In another study, NARWs showed no behavioral response to ship sounds at all, or at least not to received levels of 132 to 142 dB re 1 µPa from large ships passing within 1 nm (1.9 km) distance, nor to received levels of 129 to 139 dB re 1 µPa (main energy between 50 and 500 Hz) to artificial playback of ship noise (Nowacek et al. 2004).

Studies of responses by mid-frequency cetaceans to vessel sounds, conducted in various parts of the world and with a variety of species, have also shown mixed results. Groups of Pacific humpback dolphins (*Sousa chinensis*) in eastern Australia that included mother-calf pairs, increased their rate of whistling after a vessel transited the area (Van Parijs and Corkeron 2001). The authors postulated that vessel sounds disrupted group cohesion, especially between mother-calf pairs, requiring re-establishment of vocal contact after vessel noise temporarily masked their communication. Lesage et al. (1999) revealed that beluga whales (*Delphinapterus leucas*) reduced their overall call rate in the presence of vessels but increased the emission and repetition of specific calls and shifted to higher frequency bands. In response to high levels of vessel traffic, killer whales increased the duration (Foote et al. 2004) or the amplitude (Holt et al. 2009) of their calls. Other studies of killer whales (*Orcinus orca)* showed temporary changes in behavior in response to vessel noise, including less foraging and increased surface-active behavior, respiration, swim speed, and direction, occurring at received levels above 130 dB re 1 µPa (0.01 to 50 kHz) (Williams et al. 2002, Lusseau et al. 2009, Noren et al. 2009, Williams et al. 2014). Marley et al. (2017) found that Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in Fremantle Inner Harbor, Australia significantly increased their average movement speed in the presence of high vessel densities during resting behavior. Behavioral budgets also changed in the presence of vessels, with animals spending more time traveling and less time resting or socializing.

Mid-frequency Cuvier's beaked whales (*Ziphius cavirostris*) responded to ship sounds by decreasing their vocalizations when they attempted to catch prey (Aguilar Soto et al. 2006), and foraging changes were observed in Blainville's beaked whales (*Mesoplodon densirostris*) when they were exposed to vessel noise (Pirotta et al. 2012). Harbor porpoises (*Phocoena phocoena*) tend to swim away from approaching vessels emitting high frequency noise in the Bay of Fundy, Canada (Polacheck and Thorpe 1990) and have been observed to move rapidly out of the path of a survey vessel within 1 km on the western coast of North America (Barlow 1988). Both harbor porpoises and beaked whale species are known to avoid relatively low levels of anthropogenic sound, and are generally recognized as behaviorally sensitive species (Wood et al. 2012 criteria).

In response to vessel noise, a tagged seal changed its diving behavior, switching quickly from a dive ascent to descent (Mikkelsen et al. 2019). This observation agrees with descriptions of changes in diving reported from juvenile northern elephant seals (*Mirounga angustirostris*) (Fletcher et al. 1996, Burgess et al. 1998). The tagging study also found that harbor seals (*Phoca vitulina*) and grey seals (Halichoerus grypus) are routinely exposed to vessel noise 2.2 to 20.5% of their time at sea (Mikkelsen et al. 2019).

Sound levels and the presence of vessels associated with the Project may result in behavioral responses by marine mammals, but within the context of an already highly trafficked region, the intermittent nature of vessel activity suggests that the impacts due to Project vessels are likely to be low.

C.2.2. Sea Turtles

Most of the underwater sound produced by ships is low frequency (~20–500 Hz) and overlaps with the known or assumed best hearing frequency range of all sea turtles. The broadband (20–1,000 Hz) apparent source level of a modern commercial ship (54,000 gross ton container ship traveling at 21.7 knots) is up to 188 dB re 1 µPa (McKenna et al. 2012). This source level is below the non-impulsive acoustic injury threshold of 200 dB re 1 µPa for sea turtles Finneran et al. (2017), meaning that only behavioral responses could be expected from sea turtles exposed to Project related vessel noise. Underwater noise that is detectable by sea turtles can mask signal detection and influence behavior, but the consequences of masking and attendant behavioral changes on the survival of sea turtles are not known (Popper et al. 2014).

Many of the proposed Project-related vessels are significantly smaller than cargo ships and most will transit at slower speeds than cargo ships. The apparent source levels of smaller, slower vessels may be below the behavioral response thresholds of sea turtles or limited to the area immediately adjacent to the vessel. As with marine mammals, sea turtles are regularly subjected to commercial shipping traffic and other vessel noise and may be habituated to vessel noise as a result of this exposure (BOEM 2014). Given the lower sound levels associated with vessel transit and operation and the limited ensonified area produced by this source, the risk of impact to sea turtles is expected to be very low to low.

C.2.3. Fish

Vessel noise may interfere with feeding and breeding, alter schooling behaviors and migration patterns (Buerkle 1973, Olsen et al. 1983, Schwarz and Greer 1984, Soria et al. 1996, Vabø et al. 2002, Mitson and Knudsen 2003, Ona et al. 2007, Sarà et al. 2007), mask important environmental auditory cues (CBD 2012, Barber 2017), and induce endocrine stress response (Wysocki et al. 2006). Fish communication is mainly in the low-frequency (<1000 Hz) range (Ladich and Myrberg 2006, Myrberg and Lugli 2006). Thus masking is a particular concern because many fish species have unique vocalizations that allow for inter- and intra-species identification, as well as because fish vocalizations are generally not loud, usually ~120 dB SPL with the loudest sounds reaching 160 dB SPL (Normandeau Associates 2012). Behavioral responses in fishes differ depending on species and life stage, with younger, less mobile age classes being the most vulnerable to vessel noise impacts (Popper and Hastings 2009, Gedamke et al. 2016).

Underwater sound from vessels can cause avoidance behavior, which has been observed for Atlantic herring (*Clupea harengus*) and Atlantic cod (*Gadus morhua*), and is a likely behavior of other species as well (Vabø et al. 2002, Handegard et al. 2003). Fish may respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fish (Ona et al. 2007, Berthe and Lecchini 2016). The avoidance of vessels by fish has been linked to high levels of infrasonic and low-frequency sound (~10 to 1,000 Hz) emitted by vessels. Accordingly, it was thought that quieter vessels would result in less avoidance (and consequently quieter vessels would have a higher chance of encountering fish) (De Robertis et al. 2010). By comparing the effects of a quieted and conventional research vessel on schooling herring, it was found that the avoidance reaction initiated by the quieter vessel was stronger and more prolonged than the one initiated by the conventional vessel (Ona et al. 2007). In a comment to this publication, Sand et al. (2008) pointed out that fish are sensitive to particle acceleration and that the cue in this case may have been low-frequency particle acceleration caused by displacement of water by the moving hull. This could explain the stronger response to the larger, noise-reduced vessel in the study by Ona et al. (2007), which would have displaced more water as it approached.

Nedelec et al. (2016) investigated the response of reef-associated fish by exposing them in their natural environment to playback of vessel engine sounds. They found that juvenile fish increased hiding and ventilation rate after a short-term vessel sound playback, but responses diminished after long-term playback, indicating habituation to sound exposure over longer durations. These results were corroborated by Holmes et al. (2017) who also observed short-term behavioral changes in juvenile reef fish after exposure to vessel noise as well as desensitization over longer exposure periods.

While sounds emitted by vessel activity are unlikely to injure fish, vessel sound has been documented to cause temporary behavioral responses (Holmes et al. 2017). Fish in the area are already exposed to vessels sounds in this high-traffic area. Project-related vessel noise will be intermittent and of short duration, so the overall impacts to fish are expected to be low.

C.2.4. Invertebrates

Although the study of effects of sound on invertebrates (e.g., crustaceans, cephalopods, and bivalves) is in its nascency, it is evident that invertebrates are sensitive to particle motion (as opposed to pressure) (Popper and Hawkins 2018) and that they can detect vibrations in the sea bed (Roberts et al. 2015, Roberts and Breithaupt 2016, Roberts and Elliott 2017). While there are currently no agreed upon metrics or clearly defined levels (in terms of sound pressure or particle motion) for assessing the effects or impacts of sound on invertebrates (Hawkins and Popper 2017), recent experiments have measured sound pressure levels and particle motion associated with trauma in cuttlefish (*Sepia officinalis*) (Solé et al. 2017) and longfin squid (*Doryteuthis pealeii*) (Mooney et al. 2016, Jones et al. 2020, Jones et al. 2021). Additionally, some studies have found potential behavioral effects (e.g., flight or retraction) or physiological (e.g., stress) responses in invertebrates. For example, shore crabs (*Carcinus maenas*) in the presence of vessel noise ceased feeding and were slower to retreat to shelter (Wale et al. 2013a). The common prawn (*Palaemon serratus*) had fewer intra-specific interactions and spent more time outside of their shelters where the sound pressure levels were lower (Filiciotto et al. 2016). Lobsters (*Nephrops norvegicus*) reduced locomotor activity and clams (*Ruditapes philippinarum*) exhibited behaviors that ultimately prevented feeding (Solan et al. 2016).

Shore crabs exposed to playbacks of vessel noise demonstrated an increase in oxygen consumption that was presumed to indicate a higher metabolic rate and/or stress (Wale et al. 2013b). A similar response was observed in the blue mussel (*Mytilus edulis*), which not only increased oxygen consumption but also had more fragmentation of cellular DNA (Wale et al. 2016). In Pacific oysters (*Magallana gigas*), chronic exposure to vessel noise was shown to depress activity and food uptake, ultimately limiting growth (Charifi et al. 2018). Evidence from a field experiment with sea hares (*Stylocheilus striatus*) demonstrated a significant increase in the likelihood of developmental failure at the embryonic stage and mortality at the free-swimming stage, when exposed to play-backs of vessel noise (Nedelec et al. 2014).

Overall, while there are preliminary indications of potential impacts of vessel noise on some invertebrates, most research has been conducted in a laboratory setting, where tank boundaries may affect the acoustic field and observed behavioral response (Rogers et al. 2016, Popper and Hawkins 2018). Further, nearly all studies measured sound pressure rather than particle motion (Jesus et al. (2020). Although high-intensity noise may produce high sound pressure levels and high levels of particle motion concurrently, it is impossible to determine this relationship without proper measurements (Popper and Hawkins 2018). It is unlikely, however, that these stimuli have more than short-term consequences. For example, the shore crabs that showed an increase in oxygen consumption did not respond after repeated exposures to vessel noise (Wale et al. 2013b). Thus, overall risks of impacts to invertebrates associated with vessel noise are expected to be low.

C.2.5. Monitoring and Mitigation

Sound levels associated with vessels vary with vessel class, speed, and activity. High speeds and the use of thrusters increase noise levels significantly (Richardson et al. 1995), although marine fauna are regularly subjected to commercial shipping traffic and other vessel noise and are likely habituated to vessel noise as a result (BOEM 2014). Many of the proposed Project-related vessels are much smaller than cargo ships that frequently transit the area and, for mitigation purposes, will typically transit at slower speeds.

C.3. Aircraft

Aircraft, both fixed wing and helicopter, may be used during Project construction and operation for crew transfers and biological monitoring activities. The evaluation of aircraft sound on marine fauna differs from other underwater sound sources in that sound generated by aircraft is produced within the air, transmitted through the water surface, and propagated underwater. Most sound energy from aircraft reflects off the air-water interface; only sound radiated downward within a 26-degree cone penetrates below the water surface (Urick 1972).

In general, underwater sound levels produced by fixed wing aircraft and helicopters are typically low frequency (16–500 Hz) and range between 84–159 dB re 1 µPa (Richardson et al. 1995, Patenaude et al. 2002, Erbe et al. 2018). (Patenaude et al. 2002) recorded the transmission of sound into water from two types of aircraft: a Twin Otter fixed-wing airplane and a Bell 212 helicopter. Sound levels were measured at 3 m and 18 m below the water surface while the aircraft flew at various airspeeds and four altitudes overhead. Maximum received levels in the 10 to 500 Hz frequency band at 18 m water depth were approximately 120 dB re 1 µPa for both the Twin Otter and Bell 212 (Patenaude et al. 2002). Received PK sound levels were generally higher at 3 m depth than at 18 m depth by an average of 2.5 dB, but varied considerably with both the altitude and speed of the aircraft (Patenaude et al. 2002). Because underwater sound from aircraft depends on height, angle, speed, and sound propagation in different environmental conditions (temperature, humidity in air, and salinity in water) (Hubbard 1991, Erbe et al. 2018), underwater sound levels from aircraft are highly variable.

There is limited research on the impacts of aircraft sounds to marine fauna. However, sound emitted by aircraft that propagates underwater has the potential to cause behavioral responses in marine mammals, sea turtle, and fish (McCauley et al. 2000b, Popper et al. 2014, Todd et al. 2015, Finneran et al. 2017, [NMFS] National Marine Fisheries Service (US) 2018). Further information is required to determine the potential underwater effects of aircraft on invertebrates (Hawkins et al. 2015). Given that the majority of sound emitted by aircraft is reflected off the surface of the water, impacts to marine fauna are expected to be very low to low.

C.4. Potential Impacts to Marine Fauna

C.4.1. Marine mammals

Aircraft noise is typically low- to mid-frequency, overlapping with cetacean calls and has the potential to cause temporary changes in behavior and localized displacement of marine mammals when transmitted from air through the water surface (Richardson et al. 1985a, Richardson and Würsig 1997, Nowacek et al. 2007). Marine mammals react to aircraft noise more often when the aircraft is lower in altitude, closer in lateral distance, and flying over shallow water (Richardson et al. 1985b, Patenaude et al. 2002). Temporary reactions displayed by marine mammals include short surfacing, hasty dives, aversion from the aircraft, or dispersal from the incoming aircraft (Bel'kovich 1960, Kleĭnenberg et al. 1964, Richardson et al. 1985a, Richardson et al. 1985b, Luksenburg and Parsons 2009). The response of cetaceans to aircraft noise largely depends on the species as well as the animals' behavioral state at the time of exposure (e.g., migrating, resting, foraging, socializing) (Würsig et al. 1998).

Cetaceans within the low frequency hearing group showed varied behavioral response when exposed to aircraft noise. Bowhead whales (*Balaena mysticetus*) displayed frequent behavioral reactions to fixed-wing aircraft and helicopter sounds at altitudes <305 m (Dahlheim 1981, Richardson et al. 1985b, Koski et al.

1988, Richardson and Malme 1993). However, Patenaude et al. (2002) noted that only 17% of observed bowhead whales showed behavioral response to passing helicopters, even at the lower altitudes (150 m) and lateral distances of 250 m. Behavioral changes were also seen in gray whales (*Eschrichtius robustus*) in response to the sound from a Bell 212 helicopter (Malme et al. 1984).

Variable behavioral reactions to aircraft sound were also observed in mid-frequency cetaceans. In the Gulf of Mexico, beaked whales, pygmy and dwarf sperm whales (*Kogia spp*.), and various delphinids (pantropical spotted [*Stenella attenuate*], Clymene [*Stenella clymene*], striped [*Stenella coeruleoalba*], and spinner [*Stenella longirostris*] dolphins) showed a strong behavioral response to an approaching fixed-winged aircraft by quickly diving (Würsig et al. 1998). Several studies reported defensive behavioral responses to approaching aircraft in sperm whales (Würsig et al. 1998, Richter et al. 2003, Richter et al. 2006, Smultea et al. 2008). In contrast, only 3.2% (or 24 of 760) of beluga whales responded to fixed wing aircraft at heights above the water ranging from 182 to 427 m (Patenaude et al. 2002). Given that recorded SPL at 18 m was approximately equivalent (~120 dB SPL) to the regulatory defined acoustic behavioral response threshold level for marine mammals, the lack of response is unsurprising in this study (Patenaude et al. 2002).

The sound emitted by aircraft has the potential to elicit temporary behavioral responses in marine mammals and Project-related aircraft can be at low altitude, but due to the intermittent nature and the small ensonified area of this sound source, the risks of aircraft impact to marine mammals are expected to be low.

C.4.2. Sea turtles

Although aircraft sounds can be within the hearing frequency range of turtles, very few studies have analyzed the impacts of aircraft noise on sea turtles. The only documented behavioral responses were from nesting sea turtles near (1.7 km) a military jet airfield in which the turtles exhibited postnatal behavioral reactions to in-air aircraft noise (Balazs and Ross 1974).

Given the frequency range and sound levels produced by aircraft, sea turtles may have adverse behavioral responses to this source. However, the intermittent nature and the small area of ensonification produced by aircraft is unlikely to impact sea turtles. Risk of impact are therefore expected to be very low.

C.4.3. Fish

Because documented sound levels in water from aircraft can be higher than the regulatory-defined non-impulsive behavioral acoustic thresholds for fish (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011), it can be inferred that aircraft may cause behavioral responses in fish. It is unlikely, however, that the underwater sound from aircraft associated with the Project will have much impact on fish because the sound produced by these aircraft is intermittent and has a small ensonified area. The risks of impacts to fish from aircraft sound are expected to be very low.

C.4.4. Invertebrates

Aircraft may produce low-frequency sounds within the hearing range of marine invertebrates but there are currently no data available on the potential impacts of this underwater sound on marine invertebrates. As with fish, the risks of impacts to invertebrates from aircraft sound propagated underwater are expected to be very low due to the small ensonified area and intermittent nature of the source.

C.4.5. Monitoring and Mitigation

To mitigate potential impacts to marine fauna from aircraft noise during aerial surveys, uncrewed aerial systems (drones) equipped with a camera system may be used for real time monitoring of marine mammals. With uncrewed aerial systems, Protected Species Observers (PSOs) monitor high-definition drone camera footage in real time from shore or a vessel. This monitoring approach minimizes traditional, more intrusive methods to detect marine mammals and limits sound from fixed-wing aircraft that is typically used in marine mammal and sea turtle aerial surveys. The underwater sound levels recorded from drones (<100 dB re 1 µPa) is well below underwater noise regulatory thresholds (Erbe et al. 2017). Helicopter and fixed-wing aircraft used during the Project construction and operation phase will be in operation intermittently and primarily maintain safe altitudes (150 to 300 m) above sea level. At these heights, and with the use of drones for aerial surveys, overall aircraft noise may elicit only short-term behavioral response in marine mammals such that the impact risk is very low.

C.5. High Resolution Geophysical (HRG) Surveys

High resolution geophysical (HRG) surveys are required to characterize the seafloor and inform the Project design. Seafloor mapping and bottom-penetrating imaging systems differ primarily in the frequency range that the various sources produce. Higher frequencies resolve smaller features so seafloor mapping is conducted using high-frequency sources, while lower frequencies are used to characterize conditions below the seabed.

Acoustic signals produced by HRG sources are impulsive, tonal, or frequency-modulated (FM) chirp pulses (short duration signals that sweep through a band of frequencies) (Halvorsen and Heaney 2018). Impulsive signals are produced by a variety of sources such as airguns, boomers, and sparkers using a variety of mechanisms (e.g., release of compressed air and electrostatic discharge) (Crocker and Fratantonio 2016). Tonal and FM chirp signals are produced by electromechanical sonars. Sub-bottom profilers are electromechanical sources that (typically) produce FM chirp signals at low frequencies able to penetrate the seafloor. Other electromechanical HRG sources, such as side-scan and multibeam sonars, as well as echosounders, produce tonal or FM chirp signals at higher frequencies for seafloor mapping. The source level, beamwidth, pulse duration, and pulse repetition rate of such sources are typically adjustable and are selected for the needs of each survey. For regulatory purposes, sound signals are classified as either impulsive or non-impulsive with accompanying thresholds for assessing potential impacts on animals. Airguns, boomers, sub-bottom profilers, and sparkers are classified by NMFS as impulsive sound sources, while all electromechanical HRG sources are classified as non-impulsive.

Penetrating HRG systems produce low frequency sounds with high source levels. Mini-airguns emit sounds <5 kHz with source levels of 217–228 re 1 µPa·m (Crocker and Fratantonio 2016). Sub-bottom profilers produce sounds with primary acoustic energy in frequency bands 2–115 kHz at levels from 178 to 241 dB re 1 µPa·m and penetrating seismic profilers produce sound at lower frequencies (0.25–15 kHz) with source levels 205–206 dB re 1 µPa·m range (Crocker and Fratantonio 2016). Many seafloor mapping systems are operated at frequencies >200 kHz, which is above the hearing range of all marine animals and not expected to have any impacts. Some electromechanical systems, however, operate at lower frequencies and are audible to marine mammals. These systems produce sounds within the 0.4–170 kHz frequency range and sound levels from 177–247 dB re 1 µPa·m (Crocker and Fratantonio 2016). For example, multibeam echosounders (MBES) produced sounds ~30 to 70 kHz at source levels up to ~230 dB re 1 µPa. And, though not used for imaging, underwater positioning equipment (e.g., ultra-short baseline, USBL, systems) used during HRG surveys emit sound in the 20–50 kHz band with source levels up to 188–191 dB re 1 µPa·m.

There is an overall paucity of information on the effects of HRG sounds on marine fauna. Impulsive sources used for imaging below the seabed such as sub-bottom profilers and airguns are likely audible to all marine fauna and their use may result in injury and behavioral disruption. If such sources are used, a quantitative impact analysis following established guidelines should be conducted. Electromechanical HRG sources operating within the established hearing range of marine fauna are classified as non-impulsive by NMFS, eliminating the potential for injury, but do have the potential to cause behavioral disturbance. These sources tend to be highly directive with narrow beams and small ensonified areas, so animals are likely to receive only short-duration exposures. Impacts to marine fauna from HRG sounds are expected to be low.

C.6. Potential Impacts to Marine Fauna

C.6.1. Marine Mammals

Many HRG sources operate at frequencies (>200 kHz) above the hearing range of marine mammals, so are not expected to result in impacts. Research suggests that sound levels produced by HRG sources operating within the hearing range of marine mammals are unlikely to cause injury but could result in temporary behavioral responses.

While Varghese et al. (2020) found no consistent changes in Cuvier's beaked whale foraging behavior during multibeam echosounder surveys, analogous studies assessing mid-frequency active sonar on beaked whale foraging found that individuals would stop echolocating and leave the area. Other studies have focused on the responses of marine mammals exposed to sonar. For example, minke whales (*Balaenoptera acutorostrata*) demonstrated strong avoidance to mid-frequency sonar at 146 dB re 1 µPa (Sivle et al. 2015, Kvadsheim et al. 2017), and Wensveen et al. (2019) showed that northern bottlenose whales (*Hyperoodon ampullatus*) had a greater response to (military) sonar signals. Surface-feeding blue whales showed no changes in behavior to mid-frequency sonar, but blue whales (*Balaenoptera musculus*) feeding at deeper depths and non-feeding whales displayed temporary reactions to the source; including cessation of feeding, reduced initiation of deep foraging dives, generalized avoidance responses, and changes to dive behavior (DeRuiter et al. 2013, Goldbogen et al. 2013, Sivle et al. 2015). Several behavioral reactions were seen in beaked whale species in response to mid-frequency sonar sounds (12–400 kHz and 230 dB re 1 µPa) including cessation of clicking, termination of foraging dives, changes in direction to avoid the sound source, slower ascent rates to the surface, longer deep and shallow dive durations, and other atypical dive behavior (Tyack et al. 2011, DeRuiter et al. 2013, Stimpert et al. 2014, Miller et al. 2015, Cholewiak et al. 2017). Exposure to mid-frequency sonar at various sound levels (125–185 dB re 1 µPa) caused behavioral responses in California sea lions (*Zalophus californianus*), including a refusal to participate in trials, hauling out, an increase in respiration rate, and an increase in the time spent submerged (Houser et al. 2013, Houser et al. 2016). Hooded seals (*Cystophora cristata*) showed initial avoidance behavior to 1–7 kHz sonar signals at levels between 160 and 170 dB re 1 µPa, but these animals did adapt to the sound and stopped avoiding the source (Kvadsheim et al. 2010).

Non-impulsive, sonar-type HRG sources operating within the hearing range of marine mammals are unlikely to produce injury but could cause behavioral responses. These sources typically have narrow beams that would expose marine mammals for short time periods and only negligible effects on marine mammal species could be expected. A previous analysis by BOEM (2014) on the potential effects of sound associated with HRG surveys on marine mammals in the Mid- and South-Atlantic wind planning areas concluded that impacts are expected to be minimal with the implementation of mitigation measures for sources operating at or below 200 kHz. With mitigation and monitoring practices, impacts to marine mammals from HRG sound sources are expected to be low.

C.6.2. Sea Turtles

HRG surveys that use non-impulsive sources are not expected to impact sea turtles because they operate at frequencies above the sea turtle hearing range (<1 kHz). Low-frequency impulsive HRG equipment may produce sounds within the hearing ranges of sea turtles and impacts should be evaluated using a quantitative approach.

C.6.3. Fish

Non-impulsive sounds produced by HRG survey operations are outside of fish hearing range and are not expected to produce injury or behavioral responses in fish (BOEM 2014, Popper et al. 2014, Popper and Hawkins 2019). Potential impacts of low frequency impulsive HRG sources on fish may include behavioral responses, masking of biologically important sounds, temporary hearing loss, and physiological effects (BOEM 2014, Popper et al. 2014, Popper and Hawkins 2019). Given the mobile and therefore intermittent nature of HRG surveys, the short-duration and infrequent surveying of small areas of the seafloor relative to the overall area, and the likelihood that fish will move away from the sound source, the impacts of underwater noise from impulsive HRG source surveys are expected to be low.

C.6.4. Invertebrates

As with sea turtles and fish, non-impulsive HRG sound sources are above the hearing range of invertebrates and are not expected to cause impacts, but impulsive sources may be within the hearing range of some invertebrates. For most marine invertebrate species sensitivity to underwater sound and susceptibility to noise-induced effects has not been investigated. Anatomical and experimental evidence suggests that particle motion (not sound pressure) is the primary mode for marine invertebrates perceiving acoustic stimuli. Nearly all studies on noise-induced effects on marine invertebrates, however, have measured sound pressure rather than particle motion reducing the relevance of their findings. There are currently no appropriate metrics or clearly defined levels (sound pressure or particle motion) for assessing the effect of underwater sound on marine invertebrates (Hawkins and Popper 2017). Even though criteria and thresholds are not available for invertebrates, the short-term and infrequent nature of impulsive HRG surveys are expected to be of low risk of impact to invertebrates.

C.6.5. Monitoring and Mitigation

Monitoring and mitigation during HRG surveys can decrease the potential impacts to marine mammals from HRG sound exposure by reducing the zone of influence (ZOI) and therefore the likelihood of sound exposures exceeding regulatory thresholds. The National Oceanic and Atmospheric Administration (NOAA) and BOEM have advised that HRG sources that operate at and below 200 kilohertz (kHz) have the potential to cause acoustic harassment to marine species, including marine mammals, and therefore require the establishment and monitoring of exclusion zones (BOEM 2014). Standard mitigation employed during HRG surveys includes the use of PSOs, time of year restrictions, protective zones, ramp-up of active sound sources and shut down of sources should marine mammals or sea turtles enter the established exclusion zones.

C.7. Drilling

Project construction activities will likely include drilling for geotechnical surveys and horizontal directional drilling (HDD). Geotechnical studies are conducted using drill rigs or other excavating tools to characterize the subsurface conditions in locations where foundational structures are expected to be installed (Shell Gulf of Mexico Inc. 2015). In some areas, such as the export cable landfall location, an HDD rig may be needed to create a conduit for the cable to be pulled through.

For both activities, a drill head produces vibrations that propagate as sound through the sediment and water column (Hall and Francine 1991, Nguyen 1996, Willis et al. 2010). Geotechnical drilling operations can emit sound both from the drill at the seabed and from the machinery on the barge (Gales 1982). HDD emits sound at the mouth of the borehole and the drill head. Unlike offshore drill rigs used for geotechnical drilling that are acoustically connected to the water column via drill ships (floating rigs) or drill rigs (bottomed rigs), HDD rigs are installed on shore and the sound they produce that enters the water is often negligible (Hall and Francine 1991, Nguyen 1996, Willis et al. 2010).

Most measurements of offshore drilling sounds have been made for oil exploration and production drilling. The sound levels associated with those drilling operations have been documented to be within the hearing range of many marine species and above the recommended marine mammal, sea turtle, and fish injury and behavioral thresholds (Greene 1987, NOAA 2005, Popper et al. 2014, Finneran et al. 2017, NMFS 2018). The underwater sounds from those drilling activities are non-impulsive, low frequency (20 −1000 Hz), and of varying levels ranging from an SPL of 117 to 184 dB re 1 µPa·m (Greene 1987, Blackwell et al. 2004a, Dow Piniak et al. 2012). However, the types of drilling likely to be used during project construction are of a smaller scale and are unlikely to produce the maximum sounds reported for oil drilling. Schlesinger et al. (2016) estimated a broadband source level of 170.7 dB re 1 µPa·m for offshore rock socket drilling in British Columbia. The modeled maximum distance to an SPL of 120 dB re 1 µPa was 5.8 km for that drilling activity. Only two papers have measured sounds from geotechnical drilling. Erbe and McPherson (2017) measured broadband (30 Hz to 2 kHz) sound source levels of 142 and 145 dB re 1 µPa·m for small-core drilling from a jack-up rig at two locations off western Australia. The sound levels were up to 35 dB above ambient sound levels at some frequencies, and thus audible to marine fauna, but much less than oil production drilling sounds, and were below levels used in marine noise regulations. Willis et al. (2010) recorded a peak sound level of 107 dB re 1 $\mu Pa_{0\text{-}pk}$ at 7.5 m from hard-rock drilling.

Underwater sound emitted by project construction drilling activities is not expected to produce injury to marine fauna but is likely to be audible and could elicit temporary behavioral responses. Impacts associated with this activity are expected to be low.

C.8. Potential Impacts to Marine Fauna

C.8.1. Marine Mammals

Impacts to marine mammals from underwater sound from drilling depend on the species, distance from the source, and type of drilling activity (Awbrey and Stewart 1983, Richardson et al. 1990a, Richardson et al. 1990b, Miller et al. 2005, Blackwell et al. 2017). Observed responses can include changes in migratory pathways, avoidance, changes in calling behavior, and altered diving and feeding patterns . For prolonged, large, drilling activities, acoustic masking may be a concern for marine mammals if the sounds interfere with their ability to detect or recognize important biological acoustic signals (Richardson et al. 1999, Houser and Cross 2014).

While underwater drilling sounds can have a negative effect on some marine mammals (bowhead and beluga whales), others (ringed seals and harbor porpoises) have been documented to be far more tolerant to drilling activities (Moulton et al. 2003, Todd et al. 2009). Received sound levels of drilling from construction operations were within the hearing range of phocid seals (<100 Hz); however, no aversion to sound was observed for ringed seals (Blackwell et al. 2004b). In the North Sea, high frequency odontocete species, such as harbor porpoises, have been found feeding around offshore drilling rigs and platforms during routine drilling and production operations at relatively low sound pressure levels (120 dB re 1 μPa) (Todd et al. 2009). The lack of behavioral response from harbor porpoises to drilling sounds could cause acoustic masking; however, this impact was not discussed within this study (Todd et al. 2009).

The potential impacts on marine mammals from underwater sound exposure produced by drilling operations may be behavioral disruption, acoustic masking, and physiological responses (i.e., stress) (Richardson et al. 1999, Miller et al. 2005, Blackwell et al. 2017). These responses are expected when underwater sounds associated with drilling activities are above marine mammal behavioral thresholds (NOAA 2005). However, past research suggests not all marine mammals respond negatively to drilling operations and any reactions to this source are short-term (Blackwell et al. 2004b, Todd et al. 2009). In addition, most behavioral reactions have been reported in response to oil production drilling, whereas drilling operations associated with wind farm construction activities would be of a much smaller magnitude. Sounds emitted by offshore drilling activities for wind farm development are non-impulsive and intermittent, which makes this activity unlikely to cause prolonged behavioral responses or acoustic masking. Given the short-duration and non-impulsive nature of this source, behavioral responses to underwater marine drilling sounds during the construction phase are expected to be minor.

C.8.2. Sea Turtles

There is insufficient information on the impacts of underwater drilling sounds to sea turtles. Sea turtle hearing sensitivity is within the frequency range (100–1000 Hz) of sound produced by low-frequency sources such as marine drilling (for a summary, see Popper et al. 2014). Sound levels emitted by construction drilling operations are likely to be audible to sea turtles. However, it is unlikely that the sound from construction drilling operations will reach behavioral thresholds, and even more unlikely that the sound will reach injury thresholds, unless the sea turtle is within close proximity to the drilling activity (McCauley et al. 2000a, Dow Piniak et al. 2012, Finneran et al. 2017). Risks of impact are expected to be low, but further research is required to understand the potential effects of marine drilling noise during wind turbine installation to sea turtles.

C.8.3. Fish

It is unclear whether or not the sound emitted by marine drilling activities impact fish. The available literature suggests that noise effects on fish produced by continuous drilling operations may mask acoustic signals conveying important environmental information (McCauley 1994, Popper et al. 2014). Masking may arise when sounds exceed the hearing thresholds of fish and it is probable that, within close proximity to drilling operations, sounds would reach above the recommend thresholds. McCauley (1998) determined that any noise effects to fish from marine drilling activity would likely be temporary behavioral changes within a few hundred meters of the source. For instance, measured levels during drilling operations reached 120 dB re 1 µPa at 3–5 km, which may have caused fish avoidance (McCauley 1998). Recordings show that planktivorous fish choruses persisted during drilling operations off the coast of the Timor Sea; however, it is likely that partial masking of their calls would have occurred (McCauley 1998). The sounds emitted by marine drilling operations for wind farm construction are expected to be short-term and intermittent. It is therefore unlikely that the acoustic characteristics of this source will cause prolonged acoustic masking to fish and the risk of impact from this activity is expected to be low.

C.8.4. Invertebrates

There are no data on the effect of sound from drilling on marine invertebrates. However, evidence from research on the levels of particle motion associated with behavioral responses in blue mussels indicates that the threshold of sensitivity in this species falls within vibration levels measured near blasting, pile driving, and impact drilling (Roberts et al. 2015). Only a small number of studies have indicated reception of vibration in bivalves and an associated behavioral response, which included closing syphons and, in more active mollusks, moving away from the substrate (Mosher 1972, Ellers 1995, Kastelein 2008). Anticipated drilling for the Project is typically short duration and intermittent, so it is unlikely that drilling has more than short-term consequences. Risk of impact to invertebrates from sounds emitted by marine drilling are expected to be low.

C.8.5. Monitoring and Mitigation

Recorded drilling operation source levels were highly variable, ranging from SPL 123 dB to 184 dB re 1 µPa·m for oil production drilling (Greene 1987, Blackwell et al. 2004a, Dow Piniak et al. 2012). While received sound levels could exceed behavioral response thresholds for some marine fauna, the limited area of ensonification and intermittent nature of drilling operations mean the noise impacts from this activity are expected to be very low to low. Currently, no monitoring or mitigation practices are used for sound produced by underwater drilling.

C.9. Dredging

Dredging is most often used to create or maintain depth in channels or harbors by removing materials from the seafloor, but other uses for dredging include contaminated sediment removal, flood/storm protection, extraction of mineral resources, and fishing benthic species. As it pertains to offshore wind, dredging may be used to remove materials from the seafloor in preparation of offshore foundation and export cable locations.

There are two fundamental types of dredging that could be used by the Project – mechanical and hydraulic. Mechanical dredging refers to crane-operated buckets, grabs (clamshell), or backhoes used to remove seafloor material. Hydraulic (suction) dredging and controlled flow excavation (CFE) dredging involve the use of a suction to either remove sediment from the seabed or relocate sediment from a particular location on the seafloor. There are a variety of hydraulic and CFE dredge types including trailing suction, cutter-suction, auger suction, jet-lift, and air-lift. The sound produced by hydraulic dredging results from the combination of sounds generated by the impact and abrasion of the sediment passing through the draghead, suction pipe, and pump. The frequency of the sounds produced range from ~1 to 2 kHz, with reported sound levels from 172 to 190 dB re 1 µPa·m for suction dredges (Robinson et al. 2011, Todd et al. 2015, McQueen 2019).

There is limited research on the impacts of underwater noise related to dredging activity on marine fauna. It is unlikely that dredging operations will exceed the marine mammal, sea turtle, and fish injury thresholds unless animals are within the immediate vicinity of the operating equipment (McCauley et al. 2000b, Popper et al. 2014, Todd et al. 2015, Finneran et al. 2017, NMFS 2018). Further information is required to determine the effects of dredging activity to underwater invertebrates (Hawkins et al. 2015). Overall, the impacts of dredging are expected to be expected to be very low to low.

C.9.1. Potential Impacts to Marine Fauna

C.9.1.1. Marine Mammals

Few studies have investigated the direct effects of sound of dredging on marine mammals. The topic is further confounded by the difficulty of separating the effects of dredging from other anthropogenic activity (such as vessel noise). Most marine mammals would not be expected to exceed PTS (injury) thresholds, but as dredging occurs in one area for relatively long periods, they may experience TTS and behavioral responses (Todd et al. 2015, NMFS 2018). A case study by McQueen et al. (2020) on the expected effects of underwater dredging noise concluded that although harbor porpoises may experience TTS within 74 m from the sound source there was no evidence of significant behavioral avoidance. However, while the modeling scenario was based on relatively simple sound exposure estimates, there was uncertainty about sound propagation in the environment and uncertainty in the exposure-response relationship in the behavior of the animals, leading the authors to conclude that the impacts may be underestimated (McQueen et al. 2020).

Although most research cannot isolate the acoustic impacts of dredging from other anthropogenic activity, there is evidence to suggest that it at least contributes to the negative effects observed on some marine mammals, including displacement in bowhead whales(Richardson et al. (1990b), grey whales Bryant et al. (1984), minke whales, Anderwald et al. (2013), and grey seals (*Halichoerus grypus*, Anderwald et al. (2013)). Diederichs et al. (2010) found short-term avoidance in harbor porpoises at ranges of 600 m from a dredger operating in the North Sea. However, the most compelling evidence for potential impacts of dredging is from research that used models to differentiate the observed impacts of dredging from the vessel traffic in a busy Scotland harbor (Pirotta et al. 2013). Despite a documented tolerance of high vessel presence, bottlenose dolphins spent less time in the area during periods of high-intensity dredging (Pirotta et al. 2013).

The few existing studies suggest that acoustic exposure from dredging operations may elicit behavioral responses or cause TTS to marine mammals close to the source. With the short-duration and intermittent sounds produced by dredging activities, risks to marine mammals are expected to be low.

C.9.1.2. Sea Turtles

While the acoustic impacts of dredging to sea turtles are expected to be similar to other secondary sound sources, the response thresholds for sea turtles are not well researched and are poorly understood relative to marine mammals. There are no thresholds suggested for sea turtles exposed to non-impulsive noise, but suction dredging may produce sounds up to 190 dB re 1 μPa (Robinson et al. 2011, Todd et al. 2015), which exceeds the impulsive threshold of 175 dB re 1 μPa for behavioral disruption suggested by Finneran et al. (2017) (based on impulsive sounds studied by (McCauley et al. 2000a). Accumulated sound energy will not exceed the recommended sea turtle cumulative sound exposure threshold for TTS or PTS (SEL: 189 and 204 dB re 1 μPa, respectively) (Popper et al. 2014, Finneran et al. 2017).

There is currently no information on the direct effects of dredging noise on sea turtles (Popper et al. 2014). There is evidence, however, of potentially positive impacts of dredging to breeding flatback turtles (*Natator depressus*), which increased their use of a dredging area and made longer and deeper resting dives during dredging operations (Whittock et al. 2017). The most likely driver for the observed behavioral response was speculated to be the absence of predators which were displaced by the noise from dredging operations. In general, sound emitted by dredging operations is intermittent and typically short-term. The impacts of noise from dredging operations are likely to be very low to low.

C.9.1.3. Fish

Sound generated by dredging operations is assumed to be primarily relevant to fish that are sensitive to sound pressure (i.e., have swim bladders) (McQueen et al. 2020). However, underwater sound from activities such as dredging can cause avoidance behavior, which has been observed in Atlantic herring and Atlantic cod (Vabø et al. 2002, Handegard et al. 2003). It is unlikely that fish would be exposed to noise levels from dredging that would result in impairment or injury, but behavioral effects, such as auditory masking, could result from exposure to dredging noise (Popper et al. 2014, McQueen et al. 2020). Given that dredging operations are short-term and localized, the impacts from underwater noise to fish from are expected to be low.

C.9.1.4. Invertebrates

There is no available research on the effect of sound from dredging on invertebrates. Contact of the draghead with the seabed may result in substrate-borne vibration, which is likely to be of greater concern to benthic invertebrates than sound pressure (Roberts et al. 2015, Roberts and Breithaupt 2016, Roberts and Elliott 2017). Only a small number of studies have indicated reception of vibration in bivalves and an associated behavioral response, which included closing syphons and, in more active mollusks, moving away from the substrate (Mosher 1972, Ellers 1995, Kastelein 2008). Nevertheless, to date, there is no convincing evidence for any significant effects induced by non-impulsive noise in benthic invertebrates. It is unlikely that these stimuli have more than short-term consequences so the potential impacts of dredging sounds to invertebrates are expected to be very low.

C.10. Wind Turbine Generator Operations

Sound is generated by operating wind turbine generators (WTGs) due to pressure differentials across the airfoils of moving turbine blades and from mechanical noise of bearings and the generator converting kinetic energy to electricity. Sound generated by the airfoils, like aircraft, is produced in air and may enter the water through the air water interface. Mechanical noise associated with the operating WTG is transmitted into the water as vibration through the foundation and subsea cable. There is also a known particle motion component to noise from wind turbines (Sigray and Andersson 2012). Both airfoil sound and mechanical vibration may result in continuous underwater noise.

Underwater sound radiated from operating WTGs is low-frequency and low level (Nedwell and Edwards 2004). At distances of 14 to 20 m from operational WTGs in Europe, underwater sound pressure levels ranged from 109 dB to 127 dB re 1µPa (Tougaard et al. 2009). Pangerc et al. (2016) recorded sound levels at ~50 m from two individual 3.6 megawatt (MW) WTGs monopile foundations over a 21-day operating period. The sound pressure level increased with wind speed up to an average value of 128 dB re 1 µPa at a wind speed of ~10 m/s, and then showed a general decrease in sound levels with increasing wind speed as the turbine blades were feathered. Miller and Potty (2017) measured an SPL of 100 dB re 1 µPa within 50 m of five General Electric Haliade 150–6 MW wind turbines with a peak signal frequency of 72 Hz. At the Block Island Wind Farm off of Rhode Island, sound levels were found to be 112−120 dB re 1 µPa near the WTG when wind speeds were 2 to 12 m/s, and the WTG sound levels declined to ambient within 1 km from the WTG (Elliott et al. 2019). Tougaard et al. (2009) found that sound level from three different WTG types in European waters was only measurable above ambient sound levels at frequencies below 500 Hz, and Thomsen et al. (2016) suggest that at approximately 500 m from operating WTGs, sound levels are expected to approach ambient levels.

WTG foundation design was found to influence sound levels in the water as a function of distance. Sound levels measured at 150 m from a steel monopile WTG foundation were 133 dB re 1 µPa with peak frequencies between 50–140 Hz, while measurements at 150 m from a jacket WTG foundation were 122 dB re 1 µPa with a peak frequency of 50 Hz and secondary peaks at 150, 400, 500, and 1,200 Hz. However, at 40 m the sound pressure levels were comparable between the steel monopile (135 dB) and jacket foundation types (137 dB) (Thomsen et al. 2016).

Two recent meta-papers (Tougaard et al. 2020, Stöber and Thomsen 2021) assessed WTG operational sounds by extracting sound levels measured at various distances from operating WTGs from currently available reports. Tougaard et al. (2020) used a linear model to fit sound levels as a function of turbine size, wind speed, and distance. Their model suggested that sound from multiple WTGs would be detectable out to a few km in areas with very low ambient noise levels but would be below ambient unless "very close" to individual WTGs in areas with high ambient noise from shipping or wind. Notably, the available data were from lower-power WTGs than are currently being planned for the US east coast, and primarily from geared, rather than direct drive, WTGs. Stöber and Thomsen (2021) attempted to fill this knowledge gap by extracting a strictly defined subset of the data used by Tougaard et al. (2020) to extrapolate sound levels to larger turbine sizes and to direct drive turbines. However, the small size of their data subset greatly increases the already considerable uncertainty of the modeling results. Additionally, their model assumed that SPL increases linearly with WTG capacity, which contrasts with what is known of typical mechanical systems. Both studies found sounds to generally be higher for higher powered WTGs, and thus distances to a given sound threshold are likely to be greater for higher powered WTGs. However, as Stöber and Thomsen (2021) point out, direct drive technology could reduce these distances substantially. Importantly, no measurements exist for these larger turbine sizes and few measurements have been made for direct drive turbines so the uncertainty in these estimates is large.

The frequency and sound level generated from operating WTGs depend on WTG size, wind speed and rotation, foundation type, water depth, seafloor characteristics, and wave conditions (Cheesman 2016, Elliott et al. 2019). Operational noise from WTGs is low frequency (60 to 300 Hz) and at relatively low sound pressure levels near the foundation (100 to 151 dB re 1 μPa) and decreases to ambient within 1 km (Tougaard et al. 2009, Lindeboom et al. 2011, Dow Piniak et al. 2012). Underwater sounds emitted by WTGs are audible to marine mammals, sea turtles, fish, and invertebrates but are lower than the regulatory injury thresholds and typically lower than the behavioral thresholds for marine fauna, and often are lower than the ambient sound levels that these animals typically experience. It is unlikely that WTG operations will cause injury or behavioral responses to marine fauna, so the risk is of impact is expected to be low.

C.10.1. Potential Impacts to Marine Fauna

C.10.1.1. Marine Mammals

While underwater noise from WTGs has been measured within the hearing frequency range of marine mammals, impacts at the anticipated noise levels are limited to behavioral response and auditory masking (Bergström et al. 2014) (MMS 2007). Behavioral responses may include changes in foraging, socialization, or movement, including avoidance of the area. For example, there is evidence that harbor porpoises avoided WTGs during construction and initial operation (Teilmann and Carstensen 2012). However, they appeared to slowly increase their use of the WTG area during continued operation, demonstrating potential long-term habituation. This result also suggests that noise impacts are greater during construction than operation (Madsen et al. 2006). Harbor seals also show avoidance behavior when exposed to simulated sound from WTGs. However this response was limited to distances of less than 500 m to the source (Hastie et al. 2018). Finally, research into both harbor porpoises and harbor seals demonstrated fewer surfacings when exposed to playbacks of noise from WTGs, but this response was limited to 200 m from the source (Koschinski et al. 2003)

Auditory masking could also impact marine mammals, potentially affecting foraging, social interactions, and predator avoidance (Weilgart 2007, Erbe et al. 2016b). The potential for masking is highly dependent on the species in question, and those with low-frequency hearing will be more susceptible due to the overlap with the frequency range of WTG underwater noise.

Research with captive harbor porpoises indicated the potential for auditory masking from simulated WTG underwater noise. As with behavioral responses, the area of impact was predicted to be relatively close to the source (10–20 m) (Lucke et al. 2007).Therefore, the potential for auditory masking is likely limited to short ranges from the WTG.

Tougaard et al. (2020) estimated that WTG sounds would drop below the 120-dB re 1 μPa US regulatory threshold for marine mammal behavioral impacts from continuous sounds (NMFS 2005) within approximately 50–100 m of the WTG, using currently available sound measurements taken at various distances from operational WTGs. These WTGs all had a lower capacity than those planned for installation off the US east coast, and most were from geared-drive WTGs. Thus, Stöber and Thomsen (2021) extrapolated sound levels to larger WTG sizes and found the distance to the behavioral threshold could extend out to several kilometers. However, both the small size of their dataset and choice of modeling methods make these predicted distances unreliable. Additionally, those authors suggest that this distance could be reduced substantially (almost fivefold) for newer direct drive WTGs. The authors also noted that larger sized wind farms, for which data are nonexistent, might only have limited impacts related to behavioral response in marine mammals.

Overall, noise generated from WTG operation is minor and does not cause injury or lead to permanent avoidance at distances greater than 0.5 nm (1 km) for the species studied (e.g., harbor porpoise, seals, and fish) (Wahlberg and Westerberg 2005, Stenberg et al. 2015), with potential to have minimal effects at much closer distances up to within a few meters of the WTG (Bergström et al. 2013). Underwater noise impact to marine mammals associated with WTG operation is expected to be very low to low.

C.10.1.2. Sea Turtles

Low-frequency sound emitted by WTG is of concern for sea turtles. Their most sensitive hearing range is confined to low frequencies (Ridgway et al. 1969, Bartol et al. 1999), and sea turtles have shown behavioral avoidance to low frequency sound (O'Hara and Wilcox 1990, Dow Piniak et al. 2012). Operational WTG underwater noise may be slightly higher than ambient sound however, WTG sound levels decline to ambient levels within 1 km from the turbine (Kraus et al. 2016, Elliott et al. 2019). Because of these lower sound levels, sea turtles are unlikely to detect sounds generated by WTGs at large distances away from the Project in the presences of ambient sound. Therefore, sea turtles are at very low risk from exposure due to WTG noise. Any behavioral changes caused by exposure to WTG underwater sounds are expected to be short-term and localized to areas near the WTGs.

C.10.1.3. Fish

Underwater sound generated by operating WTGs is in the best hearing frequency range of fish but is of low intensity (Madsen et al. 2006). The measured sound levels are well below existing non-impulsive acoustic thresholds for injury or behavioral response in fish (McCauley et al. 2000b, Popper et al. 2014, Finneran et al. 2017). While the underwater sound levels are related to WTG power and wind speed, with increased wind speeds creating increased underwater sound levels, even at high wind speeds Wahlberg and Westerberg (2005) estimated permanent avoidance by fish would only occur within four meters of a WTG foundation. Stöber and Thomsen (2021) extrapolated measured sound levels to larger WTG sizes and found larger distances to a given sound threshold but noted that impacts might be limited to behavioral responses in fishes that could be offset by benefits from lower fishing effort and the creation of artificial reefs at wind farm sites.

In a study on fish near the Svante wind farm in Sweden, Atlantic cod, and roach (*Rutilus rutilus*) catch rates were significantly higher near turbines when the rotors were stopped, which could indicate fish attraction to turbine structure and avoidance to noise when operational (Westerberg 2000 as cited in Thomsen et al. 2006). In another study, no avoidance behavior was observed as fish densities increased around turbine foundations of the Lillgrund offshore wind farm in Sweden (Bergström et al. 2014). It is important to note that ambient sound levels can influence how fish detect other sounds and a change in background noise could alter how fish perceive and react to biological stimuli (Popper and Fay 1993). Current understanding is that underwater noise generated by WTG operation is of minor significance for fish (Wahlberg and Westerberg 2005, Stenberg et al. 2015). Underwater noise risks to fish associated with WTG operation is expected to be low.

C.10.1.4. Invertebrates

There is limited data on the effects of underwater sound from operating WTGs on invertebrates. Pine et al. (2012) found potential impacts on the median time to metamorphosis of estuarine crabs (*Austrohelice crassa* and *Hemigrapsus crenulatus*), although this experiment only measured the sound pressure level, not particle motion. Invertebrates may be susceptible to detecting particle motion produced by operational WTGs at the seabed, which could cause a behavioral response (Roberts et al. 2015, Roberts and Breithaupt 2016, Roberts and Elliott 2017). However, there is a paucity of data regarding responses of invertebrates to acoustic exposure, and no studies of noise-induced hearing effects. Overall, risks are expected to be very low.

C.10.1.5. Monitoring and Mitigation

Noise generated by operating WTGs is typically below regulatory thresholds for injury and behavioral disruption, and does not lead to permanent avoidance at distances >1 km for the species studied (e.g., harbor porpoise, seals, and fish) (Wahlberg and Westerberg 2005, Stenberg et al. 2015). Although there are potential behavioral impacts within a few meters of an operational WTG (Bergström et al. 2013), the risks are very low to low and no mitigation or monitoring is used for underwater sound produced by WTG operations.

C.11. Impact Risk Definitions

Risk rankings of secondary sound sources are very low, low, moderate, or high based on the probability of marine fauna exposure and the vulnerability of the marine species to a particular development stressor (Table C-1). Marine species occurrence and their relationships to the established criteria were evaluated using: 1) existing literature on marine mammal, sea turtle, fish distribution and presence/use of Lease Area OCS-A 0487, 2) information on the potential impacts of offshore wind farm construction and operations in both the U.S and globally, 3) studies that provide a general understanding of hearing, response to anthropogenic sound, and 4) other factors that influence the potential underwater noise impacts of offshore wind construction, operations, and decommissioning activities on marine fauna.

Table C-1. Definitions of Impact Risk, Exposure, and Vulnerability used in Impact Assessment

Risk level	Exposure	Individual vulnerability
Very low	• No or limited observations of the species in or near the proposed Project infrastructure and acoustic exposure zones (low expected occurrence), and/or • Species tends to occur mainly in other habitat (e.g., deeper water or at lower/higher latitudes), and/or • No indication that the Lease Area has regional importance as it pertains to a particular species life history characteristics.	• Literature and/or research suggest the affected species and timing of the stressor are not likely to overlap, and/or • Literature suggests limited sensitivity to the stressor, and/or • Little or no evidence of impacts from the stressor in the literature.
Low	• Few observations of the species in or near the proposed Project infrastructure and noise exposure zones (occasional occurrence), and/or • Seasonal pattern of occurrence in or near the proposed Project infrastructure and acoustic exposure zones.	• Literature and/or research suggest the affected species and timing of the stressor may overlap and/or • Literature suggests some low sensitivity to the stressor and/or • Literature suggests impacts are typically short-term (end within days or weeks of exposure) and/or • Literature describes mitigation/best management practices (BMPs) that reduce risk
Moderate	• Moderate year-round use of the areas associated with proposed Project infrastructure and acoustic exposure zones	• Literature and/or research suggest the affected species and timing of the stressor are likely to overlap, and/or • Literature and/or research suggest a moderate susceptibility to the stressor exists in the region and/or from similar activities elsewhere, and • Literature does not describe mitigation/BMPs that reduce risk.
High	• Significant year-round use of the areas associated with proposed Project infrastructure and acoustic exposure zones	• Literature and/or research suggest the affected species and timing of the stressor will overlap, and • Literature suggests significant use of WTA and ECC and acoustic exposure zones for feeding, breeding, or migration, and • Literature does not describe mitigation/BMPs that reduce risk.

Appendix D. Underwater Acoustics

D.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa in water and p_0 = 20 μPa in air. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, impact pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

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

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \quad \text{(D-1)}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{p,pk\text{-}pk}$; dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{p,\mathrm{pk\text{-}pk}} = 10\log_{10}\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2} \quad \text{(D-2)}$$

The sound pressure level (SPL or L_p; dB re 1 µPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt \Big/ p_0^2\right)\,\mathrm{dB} \quad \text{(D-3)}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying L_p function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted SPL ($L_{p,\mathrm{fast}}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,\mathrm{boxcar\ 125ms}}$. Another approach, historically used to evaluate L_p of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

The sound exposure level (SEL or L_E; dB re 1 µPa²·s) is the time-integral of the squared acoustic pressure over a duration (*T*):

$$L_E = 10 \log_{10}\left(\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right) \text{ dB} \quad \text{(D-4)}$$

where T_0 is a reference time interval of 1 s. SEL continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the *N* individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the *N* individual events:

$$L_{E,N} = 10 \log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) \text{ dB} \quad \text{(D-5)}$$

Because the SPL(T_{90}) and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T) \quad \text{(D-6)}$$

$$L_{p90} = L_\mathrm{E} - 10\log_{10}(T_{90}) - 0.458 \quad \text{(D-7)}$$

where the 0.458 dB factor accounts for the 10% of pulse SEL missing from the SPL(T_{90}) integration time window.

Energy equivalent SPL (L_{eq}; dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same time period, T:

$$L_\mathrm{eq} = 10 \log_{10}\left(\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right) \quad \text{(D-8)}$$

The equations for SPL and the energy-equivalent SPL are numerically identical. Conceptually, the difference between the two metrics is that the SPL is typically computed over short periods (typically of 1 s or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the L_{eq} reflects the average SPL of an acoustic signal over time periods typically of 1 min to several hours.

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LF,24h}$; see Appendix E) or auditory-weighted SPL ($L_{p,\mathrm{ht}}$). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should also be specified.

D.2. Decidecade Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are approximately one-tenth of a decade wide and often referred to as 1/3-octave-bands. Each octave represents a doubling in sound frequency. The center frequency of the *i*th band, $f_{\mathrm{c}}(i)$, is defined as

$$f_{\mathrm{c}}(i) = 10^{\frac{i}{10}}\,\mathrm{kHz} \tag{D-9}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the *i*th decade band are defined as:

$$f_{\mathrm{lo},i} = 10^{\frac{-1}{20}} f_{\mathrm{c}}(i) \quad \text{and} \quad f_{\mathrm{hi},i} = 10^{\frac{1}{20}} f_{\mathrm{c}}(i) \tag{D-10}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure D-1). The acoustic modeling spans from band 1 (f_c (1) = 10 Hz) to band 44 (f_c (44) = 25 kHz).

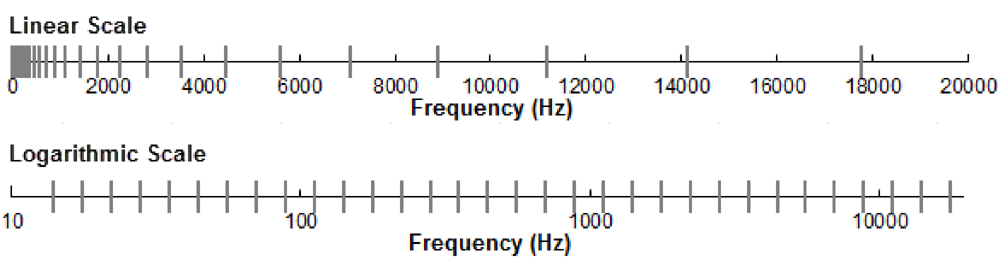

Figure D-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the *i*th band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{\mathrm{lo},i}$ and $f_{\mathrm{hi},i}$:

$$L_{p,i} = 10 \log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\, df \tag{D-11}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}}\,. \tag{D-12}$$

Figure D-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the spectral levels, at higher frequencies. Acoustic modeling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

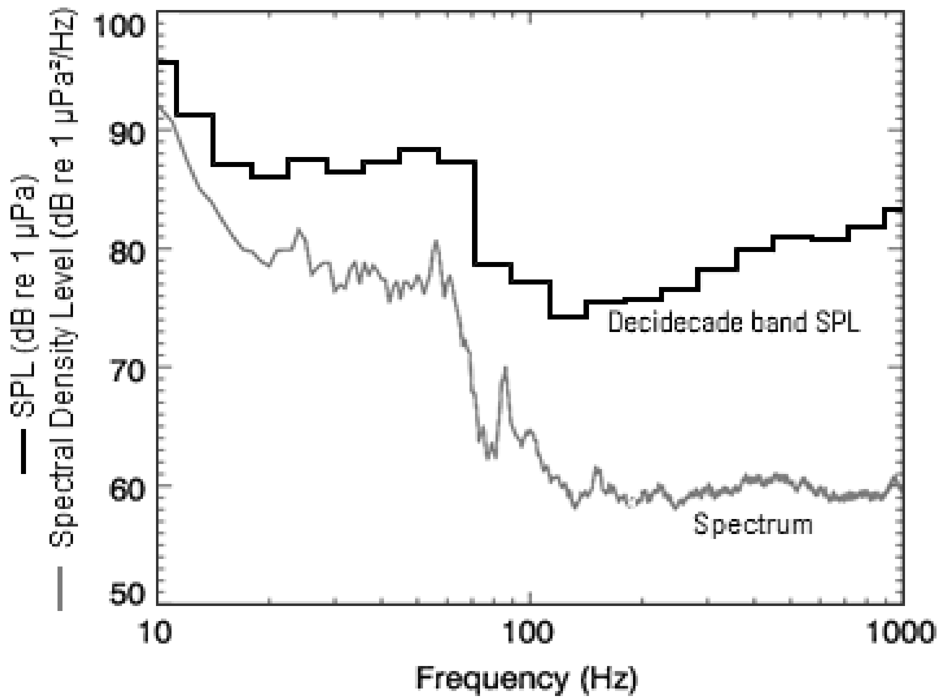

Figure D-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.

Appendix E. Auditory (Frequency) Weighting Functions

The potential for noise to affect animals of a certain species depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

E.1. Frequency Weighting Functions-Technical Guidance (NMFS 2018)

In 2015, a US Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. This frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right]. \quad \text{(E-1)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS, 2018). Table E-1 lists the frequency-weighting parameters for each hearing group. Figure E-1 shows the resulting frequency-weighting curves.

In 2017, the Criteria and Thresholds for US Navy Acoustic and Explosive Effects Analysis (Finneran et al. 2017) updated the auditory weighting functions to include sea turtles. The sea turtle weighting curve uses the same equation used for marine mammal auditory weighting functions (Equation E-1). Parameters are provided in Table E-1.

Table E-1. Parameters for the auditory weighting functions recommended by NMFS (2018).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	1.6	2	8,800	110,000	1.20
High-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid pinnipeds in water	1.0	2	1,900	30,000	0.75
Otariid pinnipeds in water	2.0	2	940	25,000	0.64
Sea turtles	1.4	2	77	440	2.35

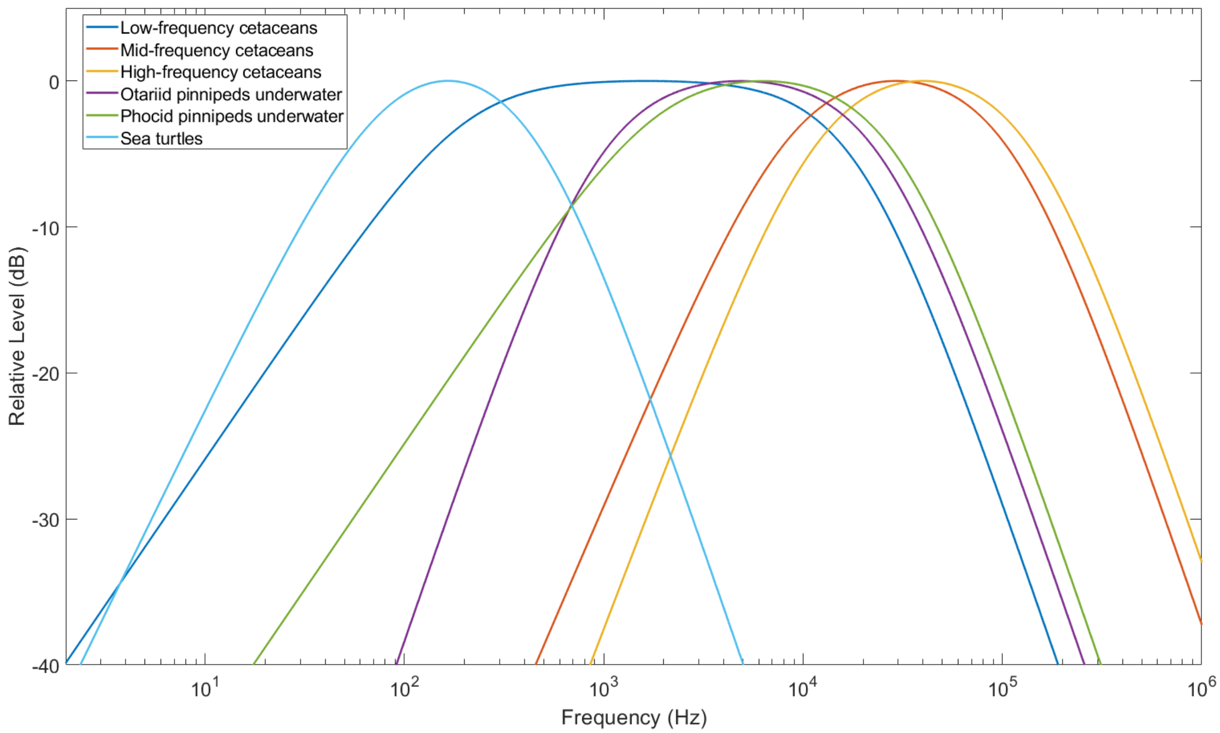

Figure E-1. Auditory weighting functions for the functional marine mammal hearing groups as recommended by NMFS (2018) and sea turtles as recommended by Finneran et al. (2017).

E.2. Southall et al. (2007) Frequency Weighting Functions

Auditory weighting functions for marine mammals—called M-weighting functions—were proposed by Southall et al. (2007). These M-weighting functions are applied in a similar way as A-weighting for noise level assessments for humans. Functions were defined for five hearing groups of marine mammals:

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

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

$$G(f) = -20\log_{10}\left[\left(1+\frac{a^2}{f^2}\right)\left(1+\frac{f^2}{b^2}\right)\right] \quad \text{(E-2)}$$

where $G(f)$ is the weighting function amplitude (in dB) at the frequency f (in Hz), and a and b are the estimated lower and upper hearing limits respectively, which control the roll-off and passband of the weighting function. The parameters a and b are defined uniquely for each hearing group (Table E-2). Figure E-2 shows the auditory weighting functions.

Table E-2. Parameters for the auditory weighting functions recommended by Southall et al. (2007).

Functional hearing group	a (Hz)	b (Hz)
Low-frequency cetaceans	7	22,000
Mid-frequency cetaceans	150	160,000
High-frequency cetaceans	200	180,000
Pinnipeds in water	75	75,000

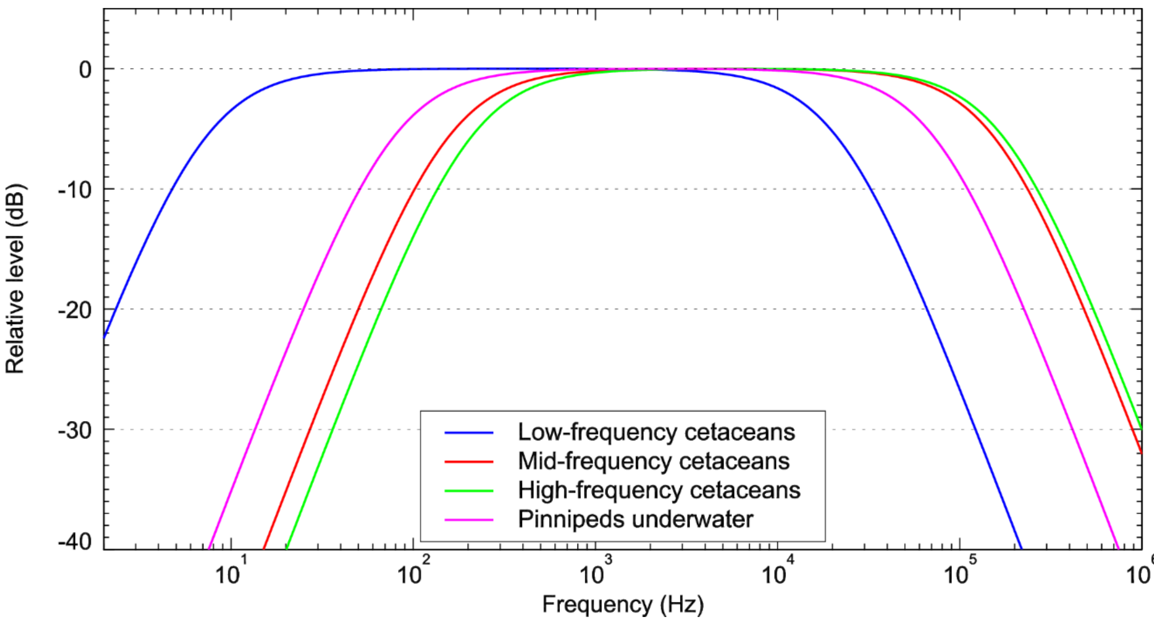

Figure E-2. Auditory weighting functions for the functional marine mammal hearing groups as recommended by Southall et al. (2007).

Appendix F. Pile Driving Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile (Figure F-1). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the pile driving hammers also had to be modeled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer's specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centered on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity, calculated using a near-field wave-number integration model, matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (see Appendix G). MacGillivray (2014) describes the theory behind the physical model in more detail.

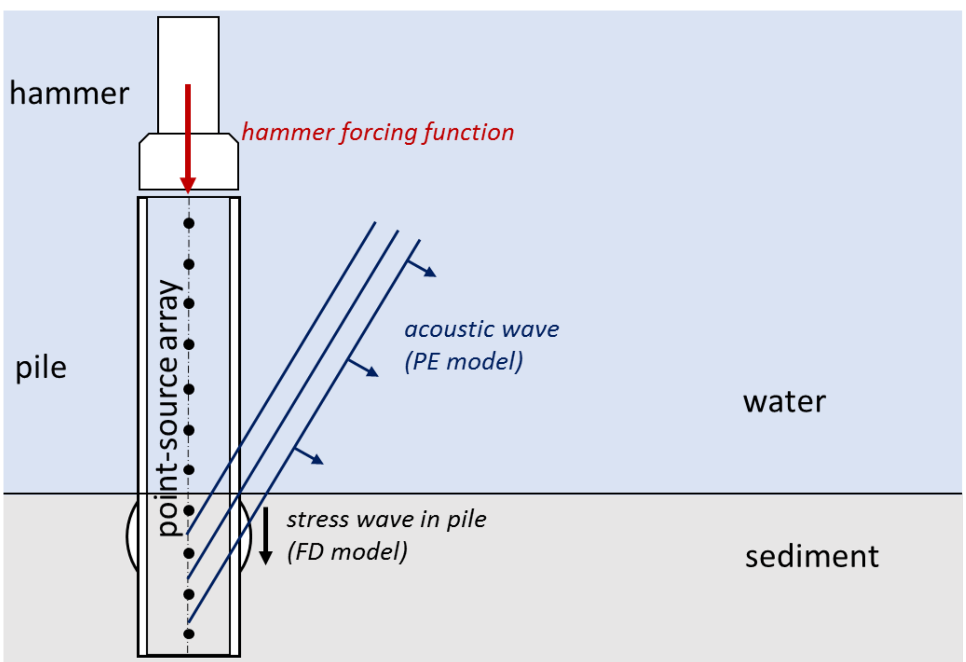

Figure F-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

Appendix G. Sound Propagation Modeling

G.1. Environmental Parameters

G.1.1. Bathymetry

A bathymetry grid for the acoustic propagation model was compiled based on data provided by Deepwater Wind South Fork, LLC (DWSF, Denes et al. 2018) and Shuttle Radar Topography Mission (SRTM) referred to as SRTM-TOPO15+ (Becker et al. 2009).

G.1.2. Geoacoustics

In shallow water environments where there is increased interaction with the seafloor, the properties of the substrate have a large influence over the sound propagation. Compositional data of the surficial sediments were provided by DWSF (Denes et al. 2018). The dominant soil type is expected to be sand. Table G-1 shows the sediment layer geoacoustic property profile based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005).

Table G-1. Estimated geoacoustic properties used for modeling, as a function of depth. Within an indicated depth range, the parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm^3)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–5	Sand	1.99–2.04	1,488–1,662	0–1.0	275	3.65
5–10		2.2	1,662–1,950	1.0–1.2		
10–100			1,950–2,040	1.2–2.1		
>100			2,604	2.1		

G.1.3. Sound Speed Profile

The speed of sound in sea-water is a function of temperature, salinity and pressure (depth) (Coppens 1981). Sound velocity profiles were obtained from the US Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003). The sound speed profiles change little with depth near the proposed construction area (Figure G-1). The months of April through October are weakly downwardly refracting (Figure G-1), leading to more interaction with the seabed and (somewhat) greater attenuation with propagation distance. The months of November through March are nearly isovelocity (same velocity with depth), though with slower sound speed, and will interact (somewhat) less with the seabed. The absolute velocity of November and December is greater than January, February, and March. For this study, a representative sound speed profile for summer and winter are both used to produce results for comparison.

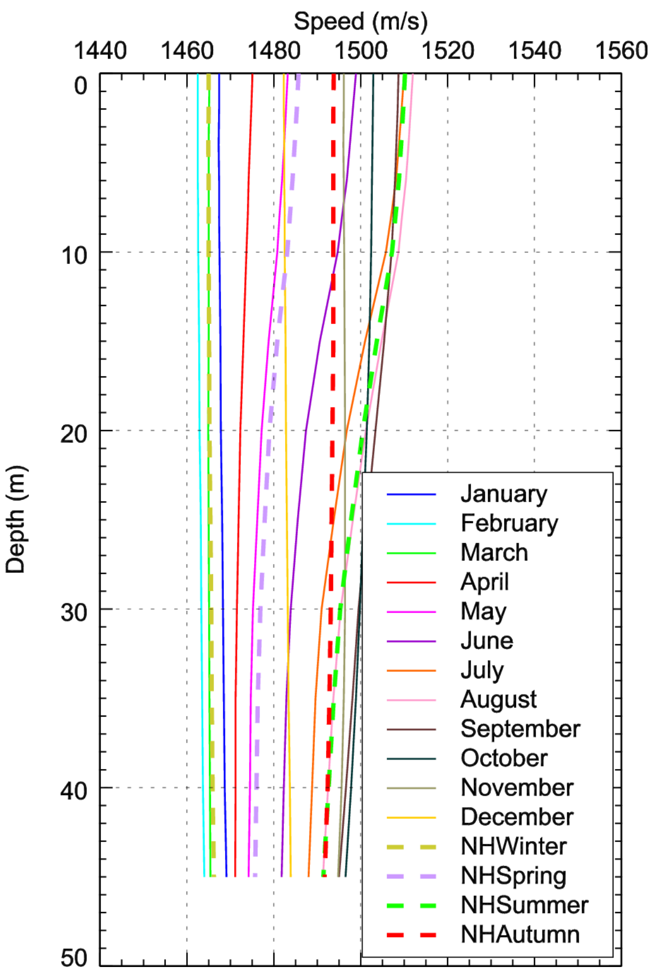

Figure G-1. Month and seasonal average sound velocity profiles in proposed construction area.

G.2. Propagation Loss

The propagation of sound through the environment can be modeled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed, scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level ($L_{\mathrm{S},E}$), expressed in dB re 1 µPa²m²s, and energy propagation loss ($N_{\mathrm{PL},E}$), in units of dB, at a given frequency are known, then the received level ($L_{E,p}$) at a receiver location can be calculated in dB re 1 µPa²s by:

$$L_{E,p}(\theta,r) = L_{\mathrm{S},E}(\theta) - N_{\mathrm{PL},E}(\theta,r), \quad \text{(G-1)}$$

where θ defines the specific direction, and r is the range of the receiver from the source.

G.3. Sound Propagation with MONM

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 2 kHz was predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received per-pulse SEL for directional impulsive sources, and SEL over 1 s for non-impulsive sources, at a specified source depth. MONM computes acoustic propagation via a wide-angle parabolic equation (PE) solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The PE method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modeled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

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

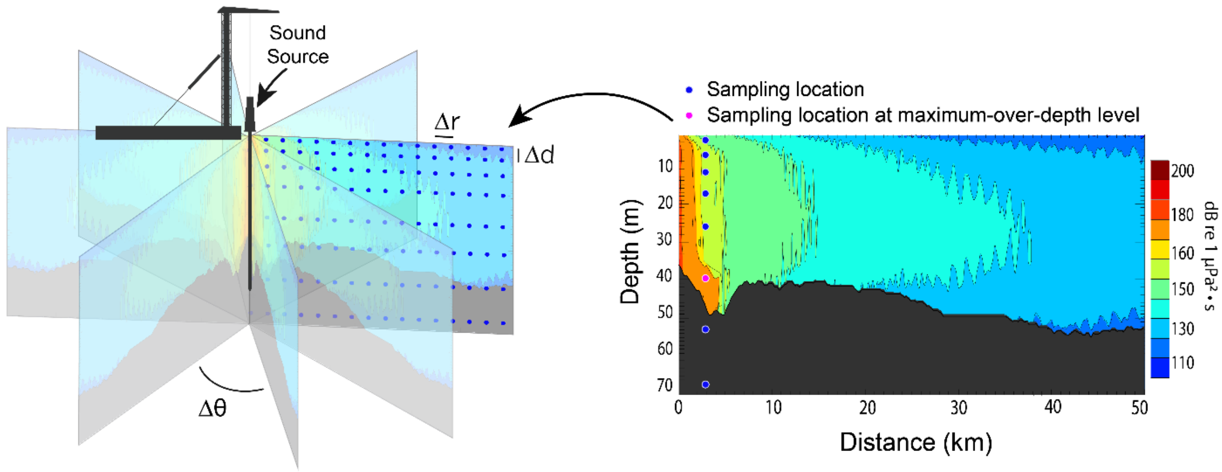

Figure G-2. Modeled three-dimensional sound field (N×2-D method) and maximum-over-depth modeling approach. Sampling locations are shown as blue dots on both figures. On the right panel, the pink dot represents the sampling location where the sound level is maximum over the water column. This maximum-over-depth level is used in calculating distances to sound level thresholds for some marine animals.

G.4. Sound Propagation with FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterize vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using FWRAM, which is a time-domain acoustic model based on the same wide-angle PE algorithm as MONM. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes the same environmental inputs as MONM (bathymetry, water sound speed profile, and seabed geoacoustic profile). Unlike MONM, FWRAM computes pressure waveforms via Fourier synthesis of the modeled acoustic transfer function in closely spaced frequency bands. FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012).

Synthetic pressure waveforms were modeled over the frequency range 10–2048 Hz, inside a 1 s window (e.g., Figure G-3). The synthetic pressure waveforms were post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

Besides providing direct calculations of the peak pressure level and SPL, the synthetic waveforms from FWRAM can also be used to convert the SEL values from MONM to SPL.

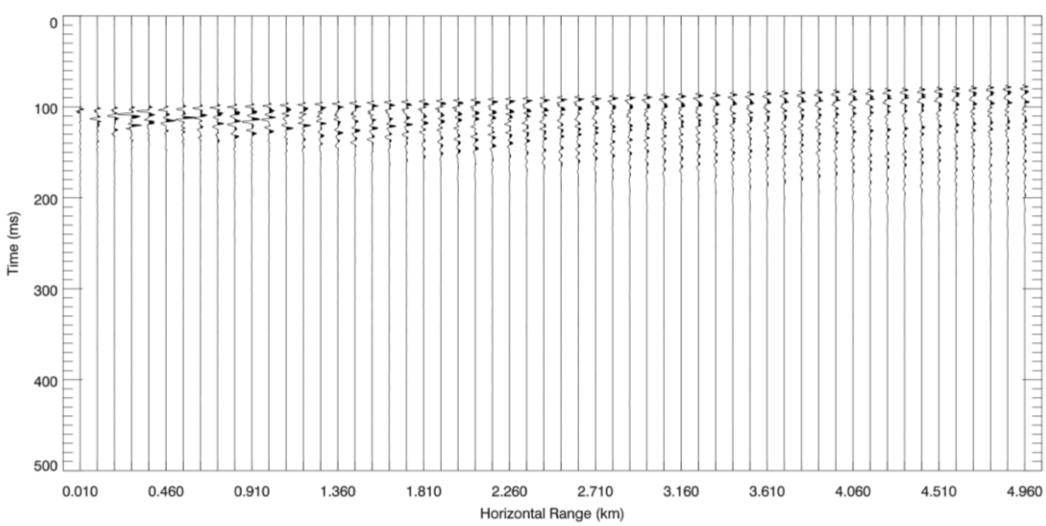

Figure G-3. Example of synthetic pressure waveforms computed by FWRAM for at multiple range offsets. Receiver depth is 35 m and the amplitudes of the pressure traces have been normalised for display purposes.

G.5. Estimating Range to Acoustic Thresholds

A maximum-over depth approach is used to determine ranges to the defined thresholds (ranges to isopleths). That is, at each horizontal sampling range, the maximum received level that occurs within the water column is used as the value at that range. The ranges to a threshold typically differ along different radii and may not be continuous because sound levels may drop below threshold at some ranges and exceed threshold at farther ranges. Figure G-4 shows an example of an area with sound levels above threshold and two methods of reporting the injury or behavioral disruption range: (1) R_{max}, the maximum range at which the sound level was encountered in the modeled maximum-over-depth sound field, and (2) $R_{95\%}$, the maximum range at which the sound level was encountered after the 5% farthest such points were excluded. $R_{95\%}$ is used because, regardless of the shape of the maximum-over-depth footprint, the predicted range encompasses at least 95% of the horizontal area that is considered to be exposed to sound at or above the specified level. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the heterogeneity of the acoustic environment. $R_{95\%}$ excludes the ends of protruding areas or small, isolated acoustic foci not representative of the nominal ensonification zone.

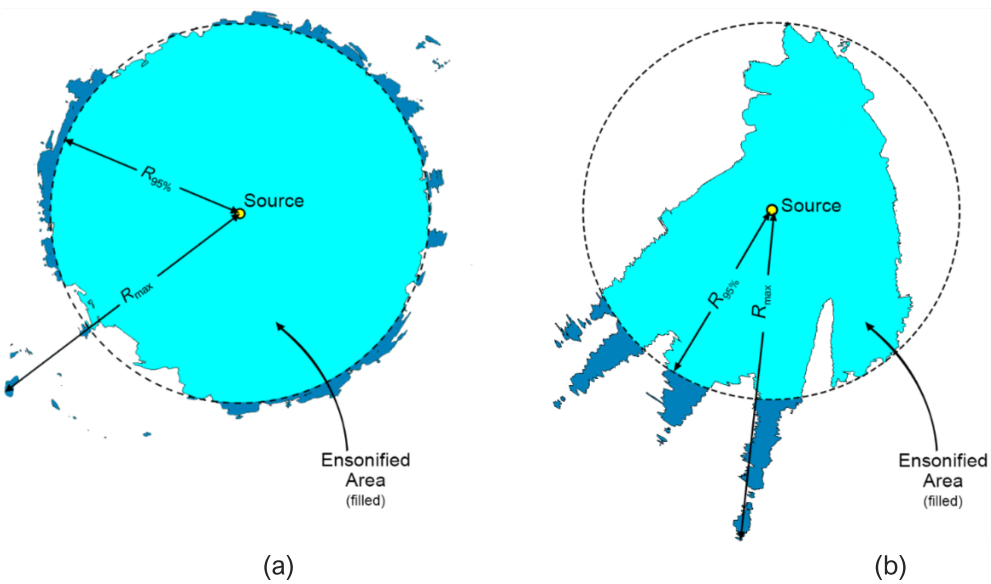

Figure G-4. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

G.6. Model Validation Information

Predictions from JASCO's propagation models (MONM and FWRAM) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Arctic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modeling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016).

Appendix H. Acoustic Ranges for Impact Pile Driving

H.1. Single-strike SPL Acoustic Ranges

Table H-1. Distance (in km) to per-strike SPL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ with 10 dB broadband attenuation for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-
190	0.089	0.089	0.089	0.089	-	-	-	-	0.028	0.028
180	0.5	0.481	0.495	0.472	0.108	0.108	0.072	0.072	0.221	0.215
170	2.184	1.967	2.18	1.945	0.616	0.58	0.393	0.362	1.16	1.075
160	4.107	3.833	4.098	3.825	2.548	2.235	2.125	1.771	3.569	3.282
150	6.433	5.805	6.43	5.794	4.274	4.098	4.108	3.869	5.196	4.696
140	11.851	9.842	11.832	9.828	7.941	7.1	7.357	6.311	9.803	8.685
130	19.551	16.34	19.546	16.31	15.587	12.5	14.156	11.333	18.229	14.776
120	30.35	25.66	30.349	25.635	26.49	21.389	25.177	19.884	28.975	24.007

Dashes indicate that thresholds were not reached

Table H-2. Distance (in km) to per-strike SPL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ with 10 dB broadband attenuation for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.02	0.02	0.02	0.02	-	-	-	-	-	-
190	0.122	0.122	0.12	0.117	0.02	0.02	-	-	0.045	0.045
180	0.728	0.671	0.723	0.662	0.134	0.128	0.082	0.082	0.344	0.328
170	2.96	2.741	2.937	2.724	0.901	0.82	0.625	0.563	1.968	1.713
160	4.601	4.271	4.586	4.26	3.453	3.24	3.046	2.772	3.978	3.785
150	11.732	9.758	11.732	9.741	6.964	6.007	5.38	4.776	9.713	8.222
140	34.632	29.234	34.612	29.177	25.809	20.302	21.022	17.282	31.13	25.93
130	>49.469	41.18	>49.469	41.18	>49.469	41.178	>49.469	41.178	>49.469	41.18
120	>49.469	41.257	>49.469	41.257	>49.469	41.256	>49.469	41.255	>49.469	41.257

Dashes indicate that thresholds were not reached

Table H-3. Distance (in km) to per-strike SPL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ with 10 dB broadband attenuation, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
190	0.122	0.119	0.117	0.116	<0.001	<0.001	<0.001	<0.001	0.045	0.045
180	0.599	0.566	0.593	0.558	0.09	0.09	0.06	0.06	0.213	0.205
170	2.135	1.977	2.125	1.966	0.502	0.469	0.288	0.28	1.133	1.059
160	4.07	3.875	4.052	3.863	2.11	1.935	1.567	1.386	3.358	3.16
150	6.647	6.092	6.626	6.067	4.124	3.968	3.801	3.648	4.998	4.677
140	11.46	10.223	11.44	10.205	7.442	6.879	6.328	5.823	9.891	8.86
130	17.392	14.883	17.378	14.869	13.398	11.802	12.168	10.766	15.84	13.666
120	25.206	19.869	25.189	19.858	21.362	17.393	20.101	16.446	23.468	18.919

Table H-4. Distance (in km) to per-strike SPL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ with 10 dB broadband attenuation, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting (m-weighting) applied (Southall et al. 2007); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water.

SPL (dB re 1 µPa)	Unweighted		LF		MF		HF		PPW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.021	0.021	0.021	0.021	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
190	0.135	0.128	0.128	0.128	<0.001	<0.001	<0.001	<0.001	0.045	0.045
180	0.738	0.695	0.725	0.68	0.108	0.108	0.064	0.063	0.288	0.279
170	2.703	2.502	2.676	2.475	0.655	0.612	0.408	0.392	1.524	1.42
160	4.292	4.122	4.284	4.111	2.953	2.712	2.221	1.942	3.78	3.606
150	10.459	9.423	10.441	9.401	5.103	4.706	4.226	4.002	8.234	7.483
140	25.539	19.455	25.068	19.433	17.88	14.772	15.294	12.842	22.512	18.067
130	>49.47	39.967	>49.47	39.967	>49.47	38.452	47.363	36.668	>49.47	39.894
120	>49.47	39.992	>49.47	39.991	>49.47	39.987	49.47	39.989	>49.47	39.989

H.2. Single-strike SEL Acoustic Ranges

Table H-5. Distance (in km) to per-strike SEL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ with 10 dB broadband attenuation for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (Southall et al. 2007, NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water, TUW: turtles underwater.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-	-	-
190	-	-	-	-	-	-	-	-	-	-	-	-
180	0.117	0.117	0.028	0.028	-	-	-	-	-	-	0.063	0.063
170	0.597	0.555	0.189	0.184	-	-	-	-	-	-	0.408	0.385
160	2.472	2.185	0.956	0.882	-	-	-	-	0.108	0.108	2.131	1.824
150	5.437	4.851	3.369	3.069	0.06	0.06	0.028	0.028	0.668	0.621	4.871	4.456
140	9.801	8.618	7.383	6.62	0.316	0.297	0.156	0.152	2.797	2.357	9.569	8.164
130	16.745	14.26	13.534	11.422	2.003	1.547	1.172	1.066	6.586	5.646	16.645	13.618
120	26.686	22.726	23.849	19.574	4.852	3.827	3.619	2.827	13.132	10.295	25.922	21.804

Dashes indicate that thresholds were not reached.

Table H-6. Distance (in km) to per-strike SEL isopleths for WTG monopile foundation at Site L024-114 at a hammer energy of 4000 kJ with 10 dB broadband attenuation for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water, TUW: turtles underwater.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	-	-	-	-	-	-	-	-	-	-	-	-
190	0.028	0.028	-	-	-	-	-	-	-	-	-	-
180	0.146	0.144	0.04	0.04	-	-	-	-	-	-	0.102	0.102
170	0.852	0.8	0.272	0.268	-	-	-	-	0.02	0.02	0.628	0.591
160	3.507	3.15	1.636	1.409	-	-	-	-	0.134	0.128	2.875	2.669
150	9.612	7.81	5.723	5.154	0.1	0.1	0.028	0.028	1	0.773	7.908	7.181
140	25.799	20.453	18.279	15.137	0.481	0.418	0.242	0.206	4.566	3.997	21.223	17.836
130	>49.469	40.87	>49.469	40.487	2.478	2.167	1.434	1.124	19.779	14.549	>49.469	40.109
120	>49.469	41.239	>49.469	41.239	9.091	6.975	5.603	4.326	>49.469	41.17	>49.469	41.168

Dashes indicate that thresholds were not reached.

Table H-7. Distance (in km) to per-strike SEL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ with 10 dB broadband attenuation, computed for a summer sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water, TUW: turtles underwater.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	<0.001	<0.001	<0.001	<0.001	-	-	-	-	-	-	<0.001	<0.001
190	0.021	0.021	<0.001	<0.001	-	-	-	-	-	-	<0.001	<0.001
180	0.142	0.135	0.029	0.029	-	-	-	-	<0.001	<0.001	0.09	0.09
170	0.695	0.654	0.182	0.172	<0.001	<0.001	-	-	<0.001	<0.001	0.452	0.433
160	2.363	2.184	0.922	0.872	<0.001	<0.001	<0.001	<0.001	0.083	0.08	1.958	1.782
150	5.605	5.052	3.048	2.847	0.029	0.029	0.021	0.021	0.454	0.405	4.882	4.493
140	10.1	9.07	7.104	6.541	0.2	0.189	0.09	0.09	2.125	1.995	9.569	8.58
130	15.741	13.53	12.774	11.203	1.112	1.031	0.744	0.66	5.917	5.088	15.183	13.106
120	22.895	18.459	20.12	16.525	3.845	3.29	2.612	2.169	11.12	9.78	22.302	18.08

Dashes indicate that thresholds were not reached.

Table H-8. Distance (in km) to per-strike SEL isopleths for OSS monopile foundations at Site OSS2 at a hammer energy of 4000 kJ with 10 dB broadband attenuation, computed for a winter sound propagation environment. Ranges are reported as maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances from the source to modeled broadband (1–25,000 Hz) maximum over depth sound level thresholds, unweighted and with frequency weighting applied (NMFS 2018); LF: low-frequency cetaceans, MF: mid-frequency cetaceans, HF: high-frequency cetaceans, PPW: phocid pinnipeds in water, TUW: turtles underwater.

SEL (dB re 1 µPa²·s)	Unweighted		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	<0.001	<0.001	<0.001	<0.001	-	-	-	-	-	-	<0.001	<0.001
190	0.029	0.029	<0.001	<0.001	-	-	-	-	-	-	<0.001	<0.001
180	0.153	0.146	0.04	0.04	0	-	-	-	<0.001	<0.001	0.102	0.101
170	0.85	0.807	0.223	0.209	<0.001	<0.001	-	-	<0.001	<0.001	0.593	0.56
160	3.114	2.862	1.228	1.153	<0.001	<0.001	<0.001	<0.001	0.09	0.085	2.484	2.293
150	8.297	7.592	4.635	4.3	0.029	0.029	0.021	0.021	0.541	0.504	7.485	6.802
140	18.721	15.889	14.934	12.276	0.243	0.22	0.12	0.113	2.818	2.384	17.357	14.634
130	43.947	35.072	41.679	32.659	1.422	1.16	0.817	0.703	13.705	10.493	35.314	28.082
120	>49.47	39.812	>49.47	39.791	5.767	5.007	3.82	3.379	42.332	34.227	>49.47	39.929

Dashes indicate that thresholds were not reached.

H.3. Single-strike Peak Acoustic Ranges

Table H-9. Distance (in km) to peak pressure level (PK) isopleths at the highest hammer energy for each of the pile types using a summer sound speed profile. All ranges are reported assuming a 10 dB broadband attenuation.

PK (dB)	Ranges (km)	
	WTG Monopile Foundation	OSS Monopile Foundation
230	-	-
219	0.005	0.006
218	0.006	0.007
216	0.010	0.011
213	0.018	0.019
210	0.072	0.071
207	0.095	0.090
202	0.178	0.260

Dashes indicate that thresholds were not reached

Table H-10. Distance (in km) to peak pressure level (PK) isopleths at the highest hammer energy for each of the pile types using a winter sound speed profile. All ranges are reported assuming a 10 dB broadband attenuation.

PK (dB)	Ranges (km)	
	WTG Monopile Foundation	OSS Monopile Foundation
230	-	-
219	0.005	0.006
218	0.006	0.007
216	0.010	0.010
213	0.018	0.019
210	0.074	0.072
207	0.101	0.095
202	0.200	0.260

Dashes indicate that thresholds were not reached

H.4. Impact Pile Driving per Pile SEL Ranges

H.4.1. Summer

Table H-11. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one WTG 12 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (L024-002 and L024-114).

Hearing group	Threshold (dB)	L024-002				L024-114			
		Attenuation level (dB)				Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	9.978	7.087	5.358	3.544	9.304	6.655	5.061	3.377
Mid-frequency cetaceans	185	0.636	0.146	0.085	0.06	0.599	0.189	0.102	0.028
High-frequency cetaceans	155	7.374	5.200	3.918	2.687	7.128	5.049	3.780	2.600
Phocid pinnipeds	185	3.548	1.805	1.174	0.612	3.516	1.966	1.163	0.580
Sea turtles	204	3.104	1.523	0.860	0.372	2.979	1.594	0.868	0.394

Table H-12. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one OSS 15 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1				OSS2			
		Attenuation level (dB)				Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	7.925	5.569	4.258	2.857	9.116	6.329	4.702	2.933
Mid-frequency cetaceans	185	0.526	0.122	0.063	0.029	0.372	0.127	0.063	0.029
High-frequency cetaceans	155	6.010	4.114	3.044	1.978	6.458	4.38	3.238	2.013
Phocid pinnipeds	185	2.668	1.319	0.763	0.310	2.990	1.513	0.762	0.313
Sea turtles	204	2.604	1.362	0.835	0.388	2.741	1.440	0.856	0.389

H.4.2. Winter

Table H-13. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one WTG 12 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (L024-002 and L024-114).

Hearing group	Threshold (dB)	L024-002 Attenuation level (dB)				L024-114 Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	28.963	15.602	10.433	6.035	35.059	15.024	9.550	5.760
Mid-frequency cetaceans	185	0.767	0.281	0.108	0.063	0.762	0.261	0.122	0.063
High-frequency cetaceans	155	16.282	9.311	6.499	3.711	16.658	9.376	6.456	3.701
Phocid pinnipeds	185	6.828	2.634	1.451	0.591	6.672	2.648	1.480	0.617
Sea turtles	204	4.756	2.275	1.274	0.552	4.585	2.404	1.344	0.592

Table H-14. Ranges ($R_{95\%}$ in km) to injury thresholds (NMFS 2018) for marine mammal functional hearing groups due to impact hammering of one OSS 15 m monopile in 24 hours, using an IHC S-4000 hammer with attenuation at two selected modeling locations (OSS1 and OSS2).

Hearing group	Threshold (dB)	OSS1 Attenuation level (dB)				OSS2 Attenuation level (dB)			
		0	6	10	15	0	6	10	15
Low-frequency cetaceans	183	21.052	10.681	7.287	4.369	22.189	12.349	8.442	4.786
Mid-frequency cetaceans	185	0.525	0.161	0.100	0.029	0.482	0.145	0.083	0.029
High-frequency cetaceans	155	12.152	6.717	4.422	2.356	12.774	7.317	4.750	2.381
Phocid pinnipeds	185	4.385	1.831	0.996	0.401	4.554	1.921	0.95	0.424
Sea turtles	204	3.766	1.944	1.140	0.536	4.014	1.974	1.171	0.544

Appendix I. ITAP Comparison

ITAP GmbH is a German agency accredited for measuring and forecasting sound levels produced during impact pile driving for installations such as wind farms (see below/attachment). Sound level predictions were made using ITAP's empirical model to forecast single-strike SEL at 750 m from the pile (results supplied by Ørsted). ITAP's empirical forecasting model was created by compiling and fitting numerous measurements at 750 m for a variety of pile dimensions, hammer types, hammer energy levels, and at several locations (though primarily in the North Sea). The ITAP model is based on the 95th percentile of the single-strike SEL measurement. That is, the SEL value used to generate the model was the level inclusive of 95% of the single-strike measurements at a given hammer energy level (the highest 5% of single-strike SEL measurements were discarded). Because the ITAP model forecasts mean values from aggregated measurements, application to specific pile driving scenarios may be expected to differ to some degree from the forecast.

As a way of validating the acoustic modeling for this study, single-strike SEL received levels at 750 m from the driven pile were determined from the calculated 3-D sound fields (see Appendices F, G, and H) and compared to the ITAP forecast (Tables I-1 and I-2). ITAP's model forecasts the 95th percentile of SEL values while the acoustic modeling in this study results in an estimate of a median value (50th percentile), so the levels calculated for this study at 750 m are expected to be lower than the forecasted levels. All values were rounded to the nearest dB.

Table I-1 shows that the single- strike SEL levels at 750 m predicted in this study compare well with the ITAP forecast. At lower hammer energy levels, this study's predicted received levels are lower than the ITAP forecast, and at higher hammer energy levels, the predicted received levels are greater than the forecast levels. It is likely that the pile penetration depth accounts for this trend. When more of the pile has penetrated into the seabed, the pile as a sound source has a larger radiating area in the water and substrate and produces more sound energy. In this study, lower hammer energy levels were measured at the start of pile driving when little of the pile has penetrated into the substrate. Within the ITAP model, measurements from all hammer energy levels represent a range of pile penetration depths such that measurements of lower hammer energy strikes include piles near full penetration and driven with smaller hammers, which may produce louder sounds.

Table I-1. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of WTG monopile foundation modeled sound field with itap (Bellmann et al. 2020) at 750 m.

Source location/Season	Hammer energy (kJ)			
	1000 kJ	2000 kJ	3000 kJ	4000 kJ
itap (12 m)	*179*	*181*	*183*	*184*
L024-002, Summer	179	181	182	183
L024-114, Summer	181	184	184	185
L024-002, Winter	179	181	182	183
L024-114, Winter	180	184	184	185

Table I-2. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of OSS monopile modeled sound field with itap (Bellmann et al. 2020) at 750 m.

Source location/Season	Hammer energy (kJ)			
	1000 kJ	2000 kJ	3000 kJ	4000 kJ
itap (15 m)	*180*	*182*	*184*	*185*
OSS1, Summer	181	179	181	184
OSS2, Summer	183	181	183	185
OSS1, Winter	181	179	181	184
OSS2, Winter	183	181	183	185

I.1. itap Description and Qualifications

ITAP GmbH ▪ Marie-Curie-Straße 8▪ 26129 Oldenburg
Ørsted Wind Power

INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Messstelle nach §29b BImSchG für Geräusche

Oldenburg, August 10th 2020

Dr. Michael A. Bellmann

Qualification and References of the *itap GmbH*

Dear Mr. Matej Simurda,

as requested, please find below a short description / biography of the *itap GmbH*. In case you need more detailed information, please feel free to contact me.

Short description of the *itap GmbH*

Graduates from the Carl von Ossietzky University of Oldenburg founded the Institute of Technical and Applied Physics (itap) in 1992 (https://www.itap.de/en/). As the demand for technical-scientific services rose, the institute was transferred into an independent limited liability company in 1995.

Meanwhile, the company can look on 25 years business experience, during which new areas of activity opened up constantly. Over time, different physical problems were dealt with; the focus however always was in the field of technical acoustics. To be named hereby in particular: our sustainable activities in the field of immission (pollution) control onshore as well as our pioneering role in the investigation of underwater noise with the aim to protect marine life.

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Akkreditiertes Prüflaboratorium nach ISO/IEC 17025:
Ermittlung von Geräuschen und Erschütterungen; Lärm am Arbeitsplatz;
ausgewählte Verfahren zu Geräuschmessungen an Windenergieanlagen; Unterwasserschall; Modul Immissionsschutz

Qualification and certification

The *itap GmbH* is a notified measuring agency in Germany according to §29b BImSchG (Federal Control of Pollution Act) and has an accredited quality management system (QMS) according to the ISO/IEC 17025 for emission and immission (pollution) measurements of sounds and vibrations (accreditation in accordance with the DAkkS – German accreditation body – for measurements and forecasts of underwater noise (impulse and continuous noise), the immission (pollution) protection module sounds and vibrations, as well as noise in the workplace).

Technical references: underwater noise

The itap GmbH was involved in all German Offshore Windfarm (OWF) construction projects since 2008, by predicting the estimated pile-driving noise during construction, consultancy services regarding noise measurements and noise mitigation strategies, as well as measuring ambient and pile-driving noise during the construction phase and operational noise of Offshore Wind Turbine Generators after completion of construction works.

Within a Research and Development (R&D) project the technical information system for underwater noise MarinEARS (Marine Explorer and Registry of Sound https://marinears.bsh.de) was designed in cooperation with the German regulatory authority BSH (Bundesamt für Seeschifffahrt und Hydrographie). All quality checked and post-processed underwater noise measurement data from 2012 till 2020 for German OWF projects within MarinEARS were provided by the *itap GmbH*. The technical field report regarding the experiences with impact pile-driving noise as well as the application of noise mitigation measures of this R&D project is available in German and English version at our homepage: https://www.itap.de/en/news/field-report-pile-driving-noise-published/.

Furthermore, the *itap GmbH* was also involved in OWF construction projects in Belgium, The Netherlands, Denmark, Sweden, United Kingdom and Taiwan, providing underwater noise predictions and consultancy services as well as performing underwater noise measurements.

The *Itap GmbH* has measured underwater noise during use of all available noise mitigation measures (noise mitigation systems as well as noise abatement systems) for offshore constructions worldwide under offshore conditions (offshore reliable and state-of-the-art noise mitigation measures as well as prototypes in accordance to DIN SPEK 45653 (2017)).

Besides the main task domain of underwater noise in connection with OWF construction projects (pile-driving noise), the *itap GmbH* predicts and measures underwater noise of all kinds of maritime activities. Such as for offshore projects like cable or pipe laying activities, cable fault detection, any acoustical surveys (e. g. sonar operations), clearance of unexploded ordnances (UXO), detonations or decommissioning of any offshore constructions, vessel based noise as well as for costal projects (e. g. within harbor facilities).

Services: underwater noise

Consultancy: The *itap GmbH* provides consultancy services related to the full scope of underwater noise predictions and measurements (especially related to Offshore Wind Farms). In recent years, our experience in Europe has expanded and extended beyond Europe to the United States of America, Taiwan and Australia. Due to our pioneering role in this field and the associated 20 years of experience in Europe, we can offer a wide range of consulting services. Such as preparation of noise mitigation concepts, selection of suitable noise mitigation measures, support within approval procedures and contact to local authorities.

Underwater noise prognosis: In recent years, our portfolio of underwater noise prediction services regarding pile driving noise has grown to meet a variety of different local regulatory requirements for various noise mitigation values throughout Europe and Taiwan and to assist the environmental impact assessment by species specific underwater noise modelling like in UK, Australia and the USA. The *itap GmbH* is able to perform underwater noise prognosis for various noise sources regarding impulsiveness and continuous noise according to national guidelines and project-specific requirements of the local approval authorities and respective local environmental conditions.

For underwater noise prognosis we are using our extensive experiences within this domain. Based on this, we have developed two models for underwater noise prediction:

1) Impulsiveness underwater noise model: Our validated pile-driving noise model based on measured values over the last 20 years within more than 35 pcs OWF and more than 30 pcs single foundation projects (empirical approach). With this pile-driving model, mitigated as well as unmitigated pile-driving noise can be predicted (broadband as well as frequency depending).
   This model also contains the empirical approach of Soloway and Dahl (2014) as well as own measured data during UXO clearance activities and detonations.
2) Continuous noise model: *Itap GmbH* also developed a model for continuous noise activities like vessel based construction projects (pipe and cable laying projects as well as operational noise from Offshore Wind Turbine Generator). However, this model will currently be extended to vibro-piling activities based on measured data as well.

Underwater noise measurements: At the beginning of the underwater noise measurements with regard to OWFs in 2000, there was no measurement device commercially available on the market, so the decision was made to develop an own system. The benefit of our own developed and constructed devices is that we can adapt our measurement devices to a variety of special requirements regarding amplitude and frequency range (from ambient noise till noise during UXO clearance from 20 Hz up to 200 kHz). Furthermore, the mooring systems for our measurement devices are self-constructed and can be adapted to the local environmental conditions easily. During the last 20 years we have been able to gain a lot of experience with different measurements under different environmental conditions.

All measurement devices of *itap GmbH* are fulfilling the requirements of national and international standards (e. g. BSH, 2011; ISO 18406) and the calibration is performed in accordance to ISO/IEC 17025 (2018).

Research and Development: Due the special expertise in the field of technical acoustics the *itap GmbH* has participated in various research projects dealing with underwater noise (https://www.itap.de/en/research-projects/). E. g. in the field of underwater sound propagation, further development of noise mitigation measures and the evaluation of the impact of underwater noise on marine mammals.

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Dr. Michael A. Bellmann

CEO

Appendix J. Animal Movement and Exposure Modeling

To assess the risk of impacts from anthropogenic sound exposure, an estimate of the received sound levels for individuals of each species known to occur in the Project Area during the assessed activities is required. Both sound sources and animals move. The sound fields may be complex, and the sound received by an animal is a function of where the animal is at any given time. To a reasonable approximation, the locations of the project sound sources are known, and acoustic modeling can be used to predict the individual and aggregate 3-D sound fields of the sources. The location and movement of animals within the sound field, however, is unknown. Realistic animal movement within the sound field can be simulated. Repeated random sampling (Monte Carlo method simulating many animals within the operations area) is used to estimate the sound exposure history of the population of simulated animals (animats) during the operation.

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more animats, the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF is scaled using the real-world density.

Several models for marine mammal movement have been developed (Ellison et al. 1999, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behavior. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth distances can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behavior model (3MB; Houser 2006) and used to predict the exposure of animats (virtual marine mammals and sea turtles) to sound arising from sound sources in simulated representative surveys. Inside JASMINE, the sound source location mimics the movement of the source vessel through the proposed survey pattern. Animats are programmed to behave like the marine animals likely to be present in the survey area. The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, surface times, etc.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modeled sound exposure levels are summed over the total simulation duration, such as 24 hours or the entire simulation, to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as the 3MB model (Houser 2006) but has been extended to be directly compatible with MONM and FWRAM acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioral states based on time and space dependent modeled variables such as received levels for aversion behavior (Ellison et al. 2016).

J.1. Animal Movement Parameters

JASMINE uses previously measured behavior to forecast behavior in new situations and locations. The parameters used for forecasting realistic behavior are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behavior of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behavior states. The probability of an animat starting out in or transitioning into a given behavior state can in turn be defined in terms of the animat's current behavioral state, depth, and the time of day. In addition, each travel parameter and behavioral state has a termination function that governs how long the parameter value or overall behavioral state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. A description of parameters relating to travel in these two planes are briefly described below. JASCO maintains species-specific choices of values for the behavioral parameters used in this study. The parameter values are available for limited distribution upon request.

Travel sub-models

- **Direction**–determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to distance from strongly biased to undirected. A random walk model can be used for behaviors with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Bottom following**–determines whether an animat returns to the surface once reaching the ocean floor, or whether it follows the contours of the bathymetry.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behavior is used to emulate the foraging behavior of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

J.1.1. Exposure Integration Time

The interval over which acoustic energy (*SEL*) should be integrated and maximal sound pressure (*SPL*) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 h baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 h can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behavior collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. Therefore, the simulation time should be limited to a few weeks, the approximate scale of the collected data (e.g., marine mammal tag data) (Houser 2006). For this study, one-week simulations (i.e., 7 days) were modeled.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that might be present in the Project Area during sound-producing activities is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited in this analysis to a maximum distance of 38 miles (70 km) from the RWF (see figures in Section J.3). In the simulation, every animat that reaches and leaves a border of the simulation area is replaced by another animat entering at an opposite border—e.g., an animat departing at the northern border of the simulation area is replaced by an animat entering the simulation area at the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition (Appendix Section J.3). The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.

J.1.2. Aversion

Aversion is a common response of animals to sound, particularly at relatively high sound exposure levels (Ellison et al. 2012). As received sound level generally decreases with distance from a source, this aspect of natural behavior can strongly influence the estimated maximum sound levels an animal is predicted to receive and significantly affects the probability of more pronounced direct or subsequent behavioral effects. Additionally, animals are less likely to respond to sound levels distant from a source, even when those same levels elicit response at closer distances; both proximity and received levels are important factors in aversive responses (Dunlop et al. 2017b). As a supplement to this modeling study for comparison purposes only, parameters determining aversion at specified sound levels were implemented for the North Atlantic right whale, in recognition of its endangered status, and harbor porpoise, a species known to have a strong aversive response to loud sounds.

Aversion is implemented in JASMINE by defining a new behavioral state that an animat may transition into when a received level is exceeded. There is very little data on which aversive behavior can be based. Because of the dearth of information and in order to be consistent within this report, aversion probability is based on the Wood et al. (2012) step function that was used to estimate potential behavioral disruption. Animats will be assumed to avert by changing their headings by a fixed amount away from the source, with greater deflections associated with higher received levels (Figures J-1 and J-2). Aversion thresholds for marine mammals are based on the Wood et al. (2012) step function. Animats remain in the aversive state for a specified amount of time, depending on the level of exposure that triggered aversion (Figures J-3 and J-4). During this time, travel parameters are recalculated periodically as with normal behaviors. At the end of the aversion interval, the animat model parameters are changed (Figures J-5 and J-6), depending on the current level of exposure, and the animat either begins another aversion interval or transitions to a non-aversive behavior. If aversion begins immediately, transition to a regular behavior occurs at the end of the next surface interval, consistent with regular behavior transitions.

Table J-1. North Atlantic right whales: Aversion parameters for the animal movement simulation based on Wood et al. (2012) behavioral response criteria.

Probability of aversion (%)	Received sound level (L_p, dB re 1 µPa)	Change in course (°)	Duration of aversion (s)
10	140	10	300
50	160	20	60
90	180	30	30

Table J-2. Harbor porpoises: Aversion parameters for the animal movement simulation based on Wood et al. (2012) behavioral response criteria.

Probability of aversion (%)	Received sound level (L_p, dB re 1 µPa)	Change in course (°)	Duration of aversion (s)
50	120	20	60
90	140	30	30

J.1.3. Simulation Area: Animat Seeding

The exposure criteria for impulsive sounds were used to determine the number of animats exceeding exposure thresholds. To generate statistically reliable probability density functions, all simulations were seeded with an animat density of 0.5 animats/km^2 over the entire simulation area. Some species have depth preference restrictions, e.g., sperm whales prefer water greater than 1000 m (Aoki et al. 2007), and the simulation location contained a relatively high portion of shallow water areas.

J.2. Animal Movement Modeling Supplemental Results

Supplemental exposure modeling results are included in Appendices J.2.1 to J.2.4 assuming 0, 6, 10, 15, and 20 dB broadband attenuation. The proposed construction schedule is described in Section 1.2.2.

J.2.1. Marine Mammal Exposure Estimates

Table J-3. WTG and OSS monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with sound attenuation for a total of 100 WTG and two OSS monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species		Injury										Behavior									
		$L_{E, 24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	29.40	14.21	7.94	3.21	0.96	0.12	0	0	0	0	32.48	20.98	18.31	12.34	6.54	28.81	18.76	14.88	10.04	5.95
	Minke whale	248.90	132.98	73.37	21.42	4.16	0.85	0.14	0.14	<0.01	0	361.36	261.26	228.95	172.23	106.81	846.74	639.20	530.05	406.12	296.24
	Humpback whale	26.90	13.62	7.99	3.36	0.94	0.08	0.02	0.02	0.02	0	25.16	16.21	14.07	9.62	5.48	22.24	14.46	11.57	7.87	4.74
	North Atlantic right whale [c]	136.93	44.64	20.46	6.95	2.09	0.11	<0.01	<0.01	<0.01	0	73.60	37.69	26.37	20.81	12.73	100.50	66.01	38.82	21.84	12.58
	Sei whale [c]	14.55	6.37	3.26	1.23	0.36	0.02	<0.01	0	0	0	17.32	10.99	9.32	6.61	3.63	53.86	40.00	31.17	22.58	15.82
MF	Atlantic white sided dolphin	0.51	0.38	0.13	0	0	0	0	0	0	0	411.15	289.88	245.76	179.67	108.89	243.72	164.26	110.17	62.94	38.42
	Common dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bottlenose dolphin, coastal	0.78	0.68	0	0	0	0	0	0	0	0	3627.72	2161.07	1632.47	1345.46	965.31	2774.06	1996.15	1236.21	640.63	324.24
	Bottlenose dolphin, offshore	<0.01	0	0	0	0	0	0	0	0	0	140.53	108.58	86.51	54.56	27.85	79.61	50.14	33.93	20.14	13.39
	Risso's dolphin	0.09	0.03	0.01	0	0	0	0	0	0	0	48.42	25.70	17.99	14.47	10.05	43.37	30.94	17.06	8.05	3.70
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.38	3.81	3.35	2.56	1.54	2.91	2.02	1.41	0.79	0.49
	Short-finned pilot whale	<0.01	<0.01	<0.01	0	0	0	0	0	0	0	5.60	4.03	3.53	2.61	1.56	2.97	2.05	1.43	0.85	0.53
	Sperm whale [c]	<0.01	0	0	0	0	<0.01	0	0	0	0	5.50	3.84	3.33	2.33	1.24	3.04	2.02	1.32	0.74	0.47
HF	Harbor porpoise	1552.23	671.80	380.47	166.37	40.90	107.60	48.30	25.82	5.72	0.94	1911.37	1089.09	800.73	652.20	452.10	10358.10	8816.52	7207.89	6374.62	5844.84
PW	Gray seal	83.89	19.11	6.73	0.69	0	0	0	0	0	0	679.14	398.30	318.05	212.10	98.84	557.54	373.03	251.48	133.95	63.45
	Harbor seal	421.89	121.55	43.30	6.63	0	6.22	0	0	0	0	2159.51	1428.01	1122.27	776.21	412.31	1757.95	1181.24	816.12	471.78	262.00
	Harp seal	128.45	40.80	11.36	0.28	0.01	2.24	0	0	0	0	765.26	480.00	394.94	279.50	151.59	617.06	424.75	295.65	165.90	88.68

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

J.2.2. Sea Turtle Exposure Estimates

Table J-4. WTG and OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with sound attenuation for a total of 100 WTG and two OSS monopiles, using density data from Table 14. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	<0.01	<0.01	<0.01	<0.01	0	0	0	0	0	0	<0.01	<0.01	<0.01	<0.01	<0.01
Leatherback turtle [a]	5.92	1.36	0.69	0.13	0	<0.01	<0.01	0	0	0	31.74	14.10	7.52	3.48	1.35
Loggerhead turtle	1.54	0.49	0.13	<0.01	0	0	0	0	0	0	16.76	6.42	3.20	1.17	0.55
Green sea turtle	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0	0	0	<0.01	<0.01	<0.01	<0.01	<0.01

[a] Listed as Endangered under the ESA.

Table J-5. WTG and OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with sound attenuation for a total of 100 WTG and two OSS monopiles, using density data from Table 15. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	9.37	2.20	0.56	0.10	0	0	0	0	0	0	39.90	17.29	8.70	3.21	1.55
Leatherback turtle [a]	5.90	1.35	0.69	0.13	0	<0.01	<0.01	0	0	0	31.63	14.05	7.49	3.47	1.35
Loggerhead turtle	9.48	2.85	0.78	0.02	0.02	0	0	0	0	0	98.82	38.66	19.01	7.07	3.08
Green sea turtle	16.90	5.23	1.35	0.10	0.09	0.09	0	0	0	0	39.34	17.86	9.46	4.03	1.61

[a] Listed as Endangered under the ESA.

J.2.3. Marine Mammal Exposure Ranges

Table J-6. WTG monopile foundation (7 to 12 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	5.21	3.19	2.15	1.08	0.39	0.02	0	0	0	0	5.81	4.06	3.74	2.98	1.87	5.87	4.08	3.73	2.98	1.86
	Minke whale	4.22	2.39	1.32	0.47	0.20	<0.01	<0.01	<0.01	<0.01	0	5.66	4.07	3.71	2.85	1.73	15.31	11.89	10.09	7.81	5.85
	Humpback whale	5.97	3.78	2.46	1.26	0.46	0.02	<0.01	<0.01	0	0	5.86	4.16	3.75	2.91	1.94	5.93	4.16	3.76	2.92	1.95
	North Atlantic right whale [c]	4.87	2.69	1.85	0.77	0.22	0.06	0	0	0	0	5.56	4.08	3.70	2.83	1.82	5.67	4.12	3.72	2.83	1.82
	Sei whale [c]	4.55	2.52	1.42	0.63	0.09	0.06	<0.01	0	0	0	5.73	4.10	3.66	2.91	1.83	15.61	11.94	10.15	7.80	5.83
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	5.49	4.07	3.59	2.81	1.71	3.85	2.95	1.96	0.97	0.49
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0	0	0	0	0	0	0	0	0	0	5.60	4.05	3.63	2.85	1.79	3.85	3.02	2.01	1.10	0.52
	Bottlenose dolphin	0.13	0	0	0	0	0	0	0	0	0	5.04	3.63	3.21	2.27	1.51	3.51	2.62	1.64	0.81	0.32
	Risso’s dolphin	0	0	0	0	0	0	0	0	0	0	5.77	4.10	3.69	2.91	1.69	4.01	3.07	2.15	0.98	0.47
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.66	4.07	3.65	2.84	1.84	3.96	3.00	2.05	0.96	0.46
	Short-finned pilot whale	<0.01	<0.01	<0.01	0	0	0	0	0	0	0	5.74	4.04	3.62	2.82	1.69	3.96	2.97	2.06	0.99	0.43
	Sperm whale [c]	0	0	0	0	0	<0.01	0	0	0	0	5.61	4.04	3.66	2.78	1.67	3.82	3.08	2.10	1.10	0.54
HF	Harbor porpoise	3.71	2.11	1.28	0.49	0.11	0.56	0.28	0.18	0.04	0	5.71	4.06	3.71	2.86	1.75	31.17	23.50	19.13	14.29	11.28
PW	Gray seal	1.76	1.11	0.60	0.13	0	0	0	0	0	0	6.04	4.17	3.78	2.92	1.88	4.60	3.83	3.25	2.01	1.01
	Harbor seal	1.77	0.40	0.21	0.03	0	0.03	0	0	0	0	5.64	4.04	3.66	2.93	1.86	4.53	3.71	3.13	1.99	0.98
	Harp seal	1.54	0.61	0.19	0.01	0.01	0.01	0	0	0	0	5.72	4.06	3.72	2.88	1.83	4.73	3.72	3.12	2.14	0.97

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-7. WTG monopile foundation (7 to 12 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	5.38	3.38	2.14	1.10	0.35	0.06	0	0	0	0	5.90	4.10	3.73	2.86	1.91	5.95	4.15	3.73	2.87	1.90
	Minke whale	4.23	2.40	1.43	0.47	0.08	0.07	0	0	0	0	5.49	4.07	3.65	2.84	1.77	15.28	11.71	9.92	7.66	5.60
	Humpback whale	6.15	3.98	2.62	1.48	0.50	0.06	<0.01	0	0	0	5.70	4.13	3.70	2.91	1.87	5.78	4.14	3.72	2.94	1.87
	North Atlantic right whale [c]	5.01	2.91	1.83	0.75	0.28	0.03	<0.01	<0.01	0	0	5.61	3.95	3.66	2.84	1.81	5.71	3.99	3.66	2.84	1.81
	Sei whale [c]	4.81	2.87	1.75	0.66	0.16	0.03	<0.01	0	0	0	5.68	4.07	3.68	2.85	1.75	15.84	11.95	9.95	7.72	5.71
MF	Atlantic white sided dolphin	0.01	0.01	0.01	0	0	0	0	0	0	0	5.50	3.97	3.57	2.83	1.65	3.86	3.00	2.01	1.06	0.44
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0	0	0	0	0	0	0	0	0	5.48	4.01	3.59	2.81	1.75	3.89	3.01	2.05	1.05	0.50
	Bottlenose dolphin	0.02	0	0	0	0	0	0	0	0	0	4.63	3.69	3.22	2.32	1.37	3.59	2.51	1.74	0.77	0.34
	Risso's dolphin	<0.01	<0.01	<0.01	0	0	0	0	0	0	0	5.68	4.10	3.70	2.82	1.80	3.97	3.04	2.01	1.13	0.48
	Long-finned pilot whale	0.01	0.01	0.01	0	0	0	0	0	0	0	5.58	4.01	3.53	2.77	1.78	3.85	2.91	1.96	1.00	0.48
	Short-finned pilot whale	0.02	<0.01	<0.01	0	0	0	0	0	0	0	5.59	4.01	3.62	2.78	1.74	3.85	3.02	2.01	1.00	0.47
	Sperm whale [c]	0	0	0	0	0	0	0	0	0	0	5.60	4.06	3.66	2.89	1.78	3.92	3.08	2.02	1.05	0.45
HF	Harbor porpoise	3.68	2.07	1.38	0.49	0.14	0.59	0.26	0.16	0.06	0.03	5.63	4.03	3.66	2.81	1.78	31.20	23.81	19.05	14.24	11.12
PW	Gray seal	1.91	0.97	0.40	0.10	0	0	0	0	0	0	5.95	4.24	3.73	3.09	1.89	4.72	3.79	3.24	2.13	1.05
	Harbor seal	1.85	0.73	0.18	0.02	0	0.06	0	0	0	0	5.44	4.01	3.57	2.97	1.82	4.60	3.67	3.10	1.91	0.94
	Harp seal	1.61	0.62	0.17	0	0	0.04	0	0	0	0	5.77	4.12	3.75	2.99	1.83	4.52	3.78	3.20	1.96	0.96

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-8. WTG monopile foundation (8 to 12 m diameter, three piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	5.53	3.37	2.23	1.03	0.52	0.07	0	0	0	0	5.68	4.11	3.76	2.92	1.86	5.75	4.11	3.77	2.90	1.86
	Minke whale	4.39	2.40	1.51	0.54	0.06	0.04	<0.01	<0.01	0	0	5.60	4.08	3.63	2.79	1.76	15.28	11.72	9.84	7.60	5.72
	Humpback whale	6.24	4.01	2.66	1.49	0.51	0.04	<0.01	<0.01	<0.01	0	5.73	4.06	3.72	2.89	1.83	5.81	4.10	3.73	2.86	1.83
	North Atlantic right whale [c]	4.88	3.02	1.93	0.84	0.24	0.05	0	0	0	0	5.54	3.98	3.67	2.87	1.80	5.62	4.00	3.67	2.84	1.79
	Sei whale [c]	4.87	2.85	1.81	0.64	0.18	0.03	0	0	0	0	5.70	4.01	3.67	2.88	1.82	15.74	11.90	9.88	7.71	5.75
MF	Atlantic white sided dolphin	0.01	0.01	0.01	0	0	0	0	0	0	0	5.47	4.02	3.63	2.83	1.74	3.88	2.99	2.02	1.09	0.49
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	<0.01	<0.01	0	0	0	0	0	0	0	0	5.42	4.03	3.56	2.77	1.77	3.89	2.97	2.07	1.06	0.51
	Bottlenose dolphin	0	0	0	0	0	0	0	0	0	0	4.70	3.68	3.18	2.21	1.42	3.57	2.53	1.77	0.74	0.37
	Risso's dolphin	<0.01	<0.01	<0.01	0	0	0	0	0	0	0	5.63	4.05	3.67	2.80	1.81	3.91	3.04	2.15	1.10	0.48
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.63	4.01	3.55	2.79	1.76	3.88	2.96	1.98	1.04	0.51
	Short-finned pilot whale	0.02	0.02	0.02	0	0	0	0	0	0	0	5.52	4.02	3.57	2.78	1.73	3.92	2.96	2.01	1.03	0.46
	Sperm whale [c]	0	0	0	0	0	<0.01	0	0	0	0	5.59	4.06	3.63	2.83	1.78	3.88	2.99	2.08	1.04	0.44
HF	Harbor porpoise	3.68	2.15	1.34	0.57	0.09	0.54	0.29	0.16	0.07	<0.01	5.58	4.03	3.62	2.84	1.82	31.27	23.61	19.24	14.15	11.04
PW	Gray seal	1.96	0.96	0.44	0.21	0	0	0	0	0	0	5.90	4.20	3.80	3.05	1.95	4.67	3.83	3.29	2.12	1.01
	Harbor seal	1.87	0.67	0.24	0.02	0	0.03	0	0	0	0	5.61	4.04	3.63	2.91	1.89	4.45	3.69	3.13	1.99	0.91
	Harp seal	1.62	0.45	0.26	0	0	0.06	0	0	0	0	5.70	4.09	3.71	2.93	1.82	4.53	3.77	3.17	2.00	0.95

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-9. WTG monopile foundation (7 to 12 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,\,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	11.25	5.64	3.53	1.82	0.58	0.08	0	0	0	0	10.17	5.89	4.05	3.50	2.49	10.21	5.90	4.05	3.51	2.47
	Minke whale	11.33	5.12	3.03	1.20	0.42	<0.01	<0.01	<0.01	<0.01	0	9.89	5.77	4.07	3.33	2.42	41.41	37.59	27.98	15.01	10.04
	Humpback whale	15.39	7.79	4.88	2.43	0.88	0.02	<0.01	<0.01	0	0	10.12	6.10	4.15	3.58	2.66	10.20	6.11	4.16	3.59	2.68
	North Atlantic right whale [c]	12.38	6.07	3.42	1.65	0.47	0.06	0	0	0	0	9.76	5.71	4.06	3.27	2.40	9.91	5.78	4.07	3.28	2.40
	Sei whale [c]	10.72	5.09	2.82	1.06	0.45	0.06	<0.01	0	0	0	10.05	5.80	4.11	3.31	2.50	41.37	39.08	28.48	15.27	10.11
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	9.54	5.59	4.01	3.37	2.36	5.74	3.57	3.00	1.71	0.68
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0	0	0	0	0	0	0	0	0	0	9.73	5.61	4.06	3.36	2.42	5.78	3.56	3.02	1.64	0.73
	Bottlenose dolphin	0.24	0	0	0	0	0	0	0	0	0	8.72	5.15	3.62	3.13	2.15	5.27	3.30	2.64	1.41	0.49
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	9.98	5.89	4.07	3.35	2.48	6.07	3.61	3.00	1.64	0.62
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	9.86	5.67	4.05	3.35	2.51	5.66	3.55	2.95	1.69	0.68
	Short-finned pilot whale	<0.01	<0.01	<0.01	0	0	0	0	0	0	0	9.61	5.76	4.02	3.43	2.60	5.82	3.51	2.98	1.66	0.74
	Sperm whale [c]	0.05	0	0	0	0	<0.01	0	0	0	0	9.81	5.72	4.03	3.48	2.43	5.73	3.64	3.01	1.54	0.60
HF	Harbor porpoise	7.27	3.72	2.29	0.92	0.28	0.62	0.28	0.18	0.04	0	9.93	5.73	4.00	3.40	2.54	45.55	44.11	42.38	41.66	40.98
PW	Gray seal	3.42	1.44	0.73	0.23	0	0	0	0	0	0	10.40	6.17	4.21	3.54	2.72	8.55	4.50	3.73	2.96	1.56
	Harbor seal	3.16	1.20	0.31	0.05	0	0.06	0	0	0	0	9.95	5.73	4.10	3.39	2.56	8.31	4.36	3.58	2.95	1.53
	Harp seal	2.65	1.06	0.21	0.01	0.01	0.01	0	0	0	0	10.01	5.85	4.07	3.35	2.57	8.45	4.48	3.50	2.88	1.55

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-10. WTG monopile foundation (7 to 12 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	14.63	6.75	4.05	1.83	0.75	0.06	0	0	0	0	9.99	6.00	4.10	3.49	2.58	10.11	6.03	4.11	3.48	2.58
	Minke whale	13.72	5.85	3.26	1.33	0.33	0.07	0	0	0	0	9.64	5.61	4.03	3.35	2.47	41.45	38.46	27.54	14.68	9.79
	Humpback whale	20.52	9.28	5.59	2.72	0.99	0.07	<0.01	0	0	0	9.81	5.85	4.13	3.45	2.59	9.94	5.88	4.14	3.44	2.58
	North Atlantic right whale [c]	15.14	6.94	3.80	1.73	0.55	0.03	<0.01	<0.01	0	0	9.58	5.69	3.93	3.40	2.55	9.70	5.71	3.95	3.40	2.50
	Sei whale [c]	13.10	5.98	3.44	1.38	0.32	0.03	<0.01	0	0	0	9.80	5.84	4.07	3.40	2.42	41.62	39.49	29.08	15.18	9.90
MF	Atlantic white sided dolphin	0.01	0.01	0.01	0.01	0	0	0	0	0	0	9.37	5.59	3.94	3.35	2.42	5.74	3.54	3.01	1.65	0.73
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0	0	0	0	0	0	0	0	0	9.44	5.56	3.99	3.37	2.51	5.66	3.54	3.01	1.69	0.74
	Bottlenose dolphin	0.20	0	0	0	0	0	0	0	0	0	8.39	4.67	3.70	3.03	2.08	4.81	3.36	2.58	1.38	0.47
	Risso's dolphin	0.04	<0.01	<0.01	0	0	0	0	0	0	0	9.77	5.71	4.10	3.42	2.51	5.87	3.62	3.03	1.78	0.76
	Long-finned pilot whale	0.01	0.01	0.01	0	0	0	0	0	0	0	9.56	5.67	3.99	3.27	2.42	5.71	3.44	2.93	1.67	0.67
	Short-finned pilot whale	0.02	<0.01	<0.01	0	0	0	0	0	0	0	9.48	5.69	4.00	3.32	2.36	5.70	3.52	2.98	1.64	0.66
	Sperm whale [c]	0.08	0	0	0	0	0	0	0	0	0	9.65	5.69	4.03	3.35	2.50	5.75	3.59	3.02	1.68	0.62
HF	Harbor porpoise	8.01	3.98	2.36	1.04	0.33	0.62	0.23	0.17	0.07	0.01	9.73	5.73	3.97	3.36	2.50	46.29	44.28	42.26	41.48	40.69
PW	Gray seal	3.61	1.53	0.82	0.27	0	0	0	0	0	0	10.10	6.09	4.26	3.58	2.75	8.47	4.57	3.67	2.99	1.65
	Harbor seal	3.69	1.25	0.45	0.10	0	0.06	0	0	0	0	9.63	5.58	4.00	3.29	2.64	8.04	4.34	3.47	2.96	1.62
	Harp seal	3.22	1.07	0.51	0	0	0.04	0	0	0	0	9.79	5.84	4.09	3.46	2.52	8.24	4.33	3.60	3.01	1.56

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-11. WTG monopile foundation (7 to 12 m diameter, three piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,\,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	16.96	7.49	4.38	2.09	0.81	0.07	0	0	0	0	9.84	5.78	4.09	3.43	2.63	9.99	5.85	4.11	3.42	2.63
	Minke whale	15.59	6.45	3.45	1.46	0.41	0.04	<0.01	<0.01	0	0	9.41	5.70	4.07	3.34	2.48	41.24	38.44	27.42	14.89	9.64
	Humpback whale	23.46	10.34	6.29	3.00	1.13	0.04	<0.01	<0.01	<0.01	0	9.69	5.86	4.11	3.50	2.54	9.80	5.90	4.11	3.49	2.53
	North Atlantic right whale [c]	17.12	7.44	3.97	1.90	0.61	0.05	0	0	0	0	9.55	5.68	3.95	3.31	2.54	9.70	5.73	3.98	3.30	2.51
	Sei whale [c]	15.03	6.62	3.67	1.65	0.54	0.05	0	0	0	0	9.69	5.78	4.02	3.42	2.53	41.24	39.82	29.09	15.09	9.80
MF	Atlantic white sided dolphin	0.01	0.01	0.01	0	0	0	0	0	0	0	9.32	5.57	3.99	3.38	2.40	5.69	3.57	3.03	1.64	0.70
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	<0.01	<0.01	0	0	0	0	0	0	0	0	9.31	5.52	4.04	3.31	2.45	5.69	3.52	2.98	1.72	0.70
	Bottlenose dolphin	0.09	0	0	0	0	0	0	0	0	0	8.33	4.85	3.65	2.98	1.99	5.01	3.30	2.54	1.25	0.57
	Risso’s dolphin	0.02	<0.01	<0.01	0	0	0	0	0	0	0	9.55	5.66	4.05	3.41	2.51	5.78	3.62	3.03	1.74	0.73
	Long-finned pilot whale	0.01	0	0	0	0	0	0	0	0	0	9.44	5.70	3.97	3.26	2.44	5.69	3.52	2.96	1.65	0.73
	Short-finned pilot whale	0.06	0.02	0.02	0	0	0	0	0	0	0	9.31	5.62	3.99	3.31	2.40	5.65	3.50	2.96	1.65	0.73
	Sperm whale [c]	0.05	0	0	0	0	<0.01	0	0	0	0	9.57	5.68	4.03	3.41	2.48	5.65	3.55	2.99	1.66	0.70
HF	Harbor porpoise	8.29	4.07	2.33	1.16	0.29	0.62	0.28	0.16	0.07	<0.01	9.54	5.70	4.03	3.39	2.51	46.73	44.59	42.41	41.52	40.76
PW	Gray seal	3.62	1.57	0.81	0.32	0	0	0	0	0	0	10.08	6.09	4.23	3.53	2.68	8.45	4.49	3.71	3.03	1.61
	Harbor seal	4.35	1.32	0.50	0.05	0	0.03	0	0	0	0	9.22	5.68	3.99	3.32	2.47	7.88	4.28	3.55	2.86	1.49
	Harp seal	3.48	1.11	0.39	0.06	0	0.06	0	0	0	0	9.78	5.86	4.13	3.44	2.65	8.18	4.35	3.67	2.95	1.58

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-12. OSS monopile foundation (7 to 15 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,\,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	4.53	2.68	1.57	0.64	0.11	0.06	0	0	0	0	5.54	4.04	3.62	2.97	1.68	5.59	4.05	3.62	2.97	1.74
	Minke whale	3.53	1.70	0.94	0.45	0.06	0	0	0	0	0	5.35	4.01	3.56	2.71	1.64	13.69	11.00	9.44	7.30	5.46
	Humpback whale	5.12	3.22	1.79	1.13	0.38	0.02	0.01	0	0	0	5.47	4.06	3.61	2.95	1.69	5.58	4.07	3.61	2.93	1.69
	North Atlantic right whale [c]	3.95	2.40	1.25	0.63	0.07	<0.01	<0.01	<0.01	<0.01	0	5.37	3.93	3.51	2.80	1.61	5.45	3.94	3.51	2.80	1.61
	Sei whale [c]	3.85	2.04	1.22	0.55	0.19	0.02	0	0	0	0	5.50	3.99	3.58	2.85	1.79	14.13	11.09	9.47	7.42	5.56
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	5.25	3.88	3.46	2.64	1.55	3.61	2.53	1.54	0.83	0.41
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0.01	0	0	0	0	0	0	0	0	5.37	3.93	3.49	2.55	1.77	3.61	2.47	1.78	0.79	0.44
	Bottlenose dolphin	0	0	0	0	0	0	0	0	0	0	4.51	3.72	3.00	1.93	1.37	3.17	1.81	1.33	0.63	0.41
	Risso's dolphin	<0.01	0	0	0	0	0	0	0	0	0	5.36	3.91	3.59	2.68	1.79	3.66	2.57	1.79	0.73	0.35
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.22	3.94	3.38	2.54	1.66	3.53	2.31	1.75	0.77	0.33
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.32	3.93	3.39	2.69	1.62	3.56	2.56	1.59	0.85	0.45
	Sperm whale [c]	0.34	0	0	0	0	<0.01	0	0	0	0	5.34	3.98	3.63	2.71	1.76	3.74	2.62	1.81	0.70	0.29
HF	Harbor porpoise	2.85	1.46	0.83	0.32	0.04	0.48	0.28	0.11	0.06	0	5.25	3.96	3.50	2.78	1.69	22.93	18.28	15.76	12.82	9.97
PW	Gray seal	1.48	0.63	0.37	0	0	0	0	0	0	0	5.96	4.18	3.75	3.03	1.92	4.41	3.71	3.10	1.93	0.83
	Harbor seal	1.20	0.22	0.01	0	0	0.01	0	0	0	0	5.59	3.94	3.54	2.88	1.64	4.31	3.46	2.95	1.65	0.91
	Harp seal	0.93	0.44	0.03	0	0	0.03	0	0	0	0	5.50	4.05	3.52	2.79	1.63	4.28	3.52	2.91	1.67	1.00

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-13. OSS monopile foundation (7 to 15 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,\ 24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	4.61	2.81	1.80	0.82	0.30	0.05	<0.01	0	0	0	5.55	4.04	3.66	2.89	1.82	5.66	4.05	3.67	2.87	1.81
	Minke whale	3.46	1.74	0.89	0.41	0.05	0.05	0	0	0	0	5.23	3.97	3.47	2.80	1.72	13.78	10.80	9.11	7.27	5.38
	Humpback whale	5.33	3.25	2.14	1.01	0.38	0.01	0.01	<0.01	0	0	5.50	4.02	3.57	2.87	1.84	5.59	4.05	3.57	2.85	1.83
	North Atlantic right whale [c]	4.18	2.35	1.40	0.67	0.15	0.04	0	0	0	0	5.29	3.96	3.47	2.75	1.74	5.43	3.99	3.47	2.75	1.73
	Sei whale [c]	3.90	2.22	1.31	0.54	0.21	0.02	<0.01	<0.01	0	0	5.39	3.91	3.61	2.79	1.73	14.02	11.16	9.43	7.46	5.45
MF	Atlantic white sided dolphin	0	0	0	0	0	<0.01	0	0	0	0	5.22	3.91	3.48	2.70	1.65	3.58	2.51	1.65	0.83	0.38
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0	0	0	0	<0.01	0	0	0	0	5.24	3.91	3.46	2.69	1.69	3.55	2.51	1.68	0.84	0.46
	Bottlenose dolphin	0.03	0	0	0	0	0	0	0	0	0	4.51	3.48	2.98	2.11	1.28	3.15	1.97	1.26	0.63	0.28
	Risso's dolphin	0.01	0	0	0	0	0	0	0	0	0	5.38	3.96	3.46	2.78	1.78	3.60	2.66	1.79	0.75	0.35
	Long-finned pilot whale	0.01	0	0	0	0	0	0	0	0	0	5.08	3.88	3.38	2.53	1.68	3.58	2.41	1.69	0.77	0.44
	Short-finned pilot whale	<0.01	0	0	0	0	0	0	0	0	0	5.23	3.89	3.45	2.65	1.56	3.51	2.53	1.54	0.87	0.42
	Sperm whale [c]	0	0	0	0	0	<0.01	0	0	0	0	5.24	3.92	3.57	2.75	1.59	3.71	2.57	1.52	0.79	0.31
HF	Harbor porpoise	2.86	1.46	0.90	0.34	0.06	0.48	0.27	0.15	0.06	0.02	5.20	3.94	3.45	2.79	1.67	22.62	18.10	15.49	12.72	9.82
PW	Gray seal	1.65	0.82	0.43	0	0	0	0	0	0	0	5.89	4.18	3.65	3.03	1.97	4.43	3.65	3.06	1.97	0.96
	Harbor seal	1.20	0.46	0.04	0	0	0	0	0	0	0	5.33	4.00	3.55	2.77	1.84	4.35	3.51	2.89	1.86	0.95
	Harp seal	0.93	0.29	0.10	0	0	0.04	0	0	0	0	5.35	4.04	3.56	2.89	1.71	4.27	3.51	2.91	1.73	0.89

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-14. OSS monopile foundation (7 to 15 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	8.53	4.48	2.68	1.16	0.41	0.06	0	0	0	0	8.60	5.20	3.88	3.26	2.39	8.63	5.21	3.89	3.28	2.41
	Minke whale	7.86	3.73	1.81	0.71	0.34	0	0	0	0	0	8.18	4.95	3.84	3.23	2.15	39.37	26.73	18.39	12.43	8.28
	Humpback whale	11.77	6.09	3.56	1.74	0.72	0.02	0.01	0	0	0	8.60	5.23	3.87	3.24	2.26	8.67	5.24	3.88	3.25	2.26
	North Atlantic right whale [c]	8.84	4.26	2.66	1.09	0.34	<0.01	<0.01	<0.01	<0.01	0	8.29	4.85	3.75	3.26	2.27	8.41	4.91	3.79	3.26	2.25
	Sei whale [c]	7.72	3.75	2.05	0.84	0.20	0.02	0	0	0	0	8.30	5.17	3.92	3.18	2.31	40.34	27.44	18.76	12.73	8.37
MF	Atlantic white sided dolphin	0.01	0	0	0	0	0	0	0	0	0	8.08	4.80	3.71	3.09	2.00	4.06	3.21	2.38	1.11	0.57
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0.01	0	0	0	0	0	0	0	0	7.99	4.92	3.74	3.20	2.08	4.13	3.28	2.40	1.18	0.57
	Bottlenose dolphin	0	0	0	0	0	0	0	0	0	0	7.47	4.23	3.54	2.63	1.61	3.91	2.75	1.75	0.85	0.42
	Risso's dolphin	<0.01	0	0	0	0	0	0	0	0	0	8.22	5.04	3.78	3.27	2.25	4.39	3.32	2.39	1.23	0.51
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	7.95	4.71	3.73	3.12	2.03	4.14	3.18	2.18	1.26	0.60
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	7.94	4.88	3.76	3.02	2.13	4.17	3.11	2.47	1.16	0.59
	Sperm whale [c]	<0.01	<0.01	0	0	0	<0.01	0	0	0	0	8.24	5.04	3.81	3.19	2.23	4.37	3.28	2.51	1.21	0.45
HF	Harbor porpoise	5.04	2.32	1.25	0.41	0.12	0.52	0.28	0.08	0.06	0	8.20	4.92	3.79	3.21	2.13	46.24	42.27	41.56	40.44	36.46
PW	Gray seal	1.96	0.78	0.37	0	0	0	0	0	0	0	8.99	5.51	4.02	3.31	2.42	7.15	4.11	3.35	2.54	1.46
	Harbor seal	1.87	0.43	0.11	0	0	0.01	0	0	0	0	8.44	5.12	3.72	3.10	2.21	6.64	3.75	3.34	2.55	1.20
	Harp seal	1.45	0.44	0.13	0.01	0	0.03	0	0	0	0	8.58	5.14	3.87	3.19	2.22	6.74	3.95	3.43	2.44	1.26

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-15. OSS monopile foundation (7 to 15 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,\,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale [c]	10.19	5.21	3.21	1.36	0.55	0.06	<0.01	0	0	0	8.58	5.15	3.87	3.31	2.33	8.64	5.17	3.90	3.33	2.33
	Minke whale	9.11	4.06	2.12	0.72	0.37	0.05	0	0	0	0	8.07	4.94	3.84	3.17	2.19	39.73	26.24	18.16	12.26	8.24
	Humpback whale	13.83	6.85	4.13	1.89	0.69	0.01	0.01	<0.01	0	0	8.49	5.21	3.84	3.30	2.27	8.57	5.24	3.87	3.30	2.27
	North Atlantic right whale [c]	10.41	4.68	2.68	1.16	0.47	0.04	0	0	0	0	8.08	4.91	3.75	3.16	2.22	8.25	4.98	3.78	3.17	2.20
	Sei whale [c]	9.10	4.21	2.33	0.94	0.26	0.02	<0.01	<0.01	0	0	8.40	5.12	3.86	3.19	2.27	40.64	27.04	18.42	12.53	8.55
MF	Atlantic white sided dolphin	0.01	0	0	0	0	<0.01	0	0	0	0	8.01	4.76	3.72	3.08	2.13	4.15	3.15	2.43	1.12	0.54
	Atlantic spotted dolphin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Common dolphin	0.01	0	0	0	0	<0.01	0	0	0	0	7.99	4.85	3.72	3.16	2.15	4.14	3.26	2.41	1.23	0.56
	Bottlenose dolphin	0.03	0	0	0	0	0	0	0	0	0	7.29	4.16	3.31	2.64	1.70	3.75	2.78	1.92	0.88	0.43
	Risso's dolphin	0.01	0.01	0	0	0	0	0	0	0	0	8.22	4.88	3.74	3.16	2.27	4.35	3.21	2.41	1.15	0.51
	Long-finned pilot whale	0.01	0.01	0	0	0	0	0	0	0	0	7.85	4.69	3.70	3.08	2.05	4.18	3.10	2.21	1.22	0.58
	Short-finned pilot whale	<0.01	0	0	0	0	0	0	0	0	0	7.92	4.88	3.74	3.09	2.06	4.18	3.21	2.37	1.16	0.54
	Sperm whale [c]	0	0	0	0	0	<0.01	0	0	0	0	8.21	4.81	3.80	3.15	2.21	4.32	3.27	2.46	1.07	0.47
HF	Harbor porpoise	5.55	2.42	1.32	0.44	0.09	0.49	0.25	0.15	0.06	0.02	8.14	4.89	3.76	3.14	2.17	46.92	42.97	42.01	41.00	36.39
PW	Gray seal	2.89	0.94	0.59	0	0	0	0	0	0	0	8.94	5.45	4.04	3.29	2.43	7.15	4.09	3.53	2.53	1.46
	Harbor seal	2.25	0.58	0.11	0	0	0	0	0	0	0	8.32	5.00	3.83	3.22	2.33	6.69	3.91	3.34	2.44	1.28
	Harp seal	1.84	0.59	0.17	0	0	0.06	0	0	0	0	8.36	5.11	3.86	3.17	2.32	6.84	3.90	3.34	2.55	1.23

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

J.2.4. Sea Turtle Exposure Ranges

Table J-16. WTG monopile foundation (7 to 12 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.01	0.23	0.04	0.02	0	0	0	0	0	0	2.79	1.47	0.90	0.42	0.08
Leatherback turtle [a]	1.10	0.07	<0.01	0	0	<0.01	<0.01	0	0	0	2.44	1.23	0.61	0.30	0.11
Loggerhead turtle	0.49	0.02	0.02	0	0	0	0	0	0	0	2.18	1.04	0.57	0.47	0.08
Green sea turtle	1.32	0.57	0.20	0	0	0	0	0	0	0	2.89	1.43	0.94	0.32	0.13

[a] Listed as Endangered under the ESA.

Table J-17. WTG monopile foundation (7 to 12 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.03	0.27	0.05	<0.01	0	<0.01	<0.01	0	0	0	2.64	1.56	0.84	0.40	0.11
Leatherback turtle [a]	1.10	0.54	0.03	<0.01	0	0	0	0	0	0	2.66	1.23	0.63	0.36	0.09
Loggerhead turtle	0.53	0.23	0.01	0	0	0	0	0	0	0	2.30	1.06	0.50	0.32	0.16
Green sea turtle	1.64	0.51	0.20	0.02	0.02	0	0	0	0	0	2.95	1.61	0.87	0.30	0.21

[a] Listed as Endangered under the ESA.

Table J-18. WTG monopile foundation (7 to 12 m diameter, three piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	0.98	0.23	0.12	0.02	0	0	0	0	0	0	2.71	1.59	0.88	0.35	0.17
Leatherback turtle [a]	0.86	0.42	0.12	0.03	0	0	0	0	0	0	2.45	1.48	0.62	0.32	0.09
Loggerhead turtle	0.51	0.06	0.03	0	0	0	0	0	0	0	2.40	1.30	0.58	0.29	0.06
Green sea turtle	1.63	0.55	0.21	<0.01	<0.01	<0.01	0	0	0	0	2.91	1.61	0.89	0.37	0.17

[a] Listed as Endangered under the ESA.

Table J-19. WTG monopile foundation (7 to 12 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.55	0.42	0.04	0.02	0	0	0	0	0	0	3.32	2.19	1.08	0.45	0.26
Leatherback turtle [a]	1.51	0.38	0.07	<0.01	0	<0.01	<0.01	0	0	0	3.20	1.90	1.13	0.48	0.22
Loggerhead turtle	0.65	0.09	0.02	0	0	0	0	0	0	0	3.17	1.55	0.82	0.52	0.09
Green sea turtle	2.43	0.91	0.36	0	0	0	0	0	0	0	3.46	2.27	1.27	0.60	0.21

[a] Listed as Endangered under the ESA.

Table J-20. WTG monopile foundation (7 to 12 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.86	0.63	0.09	<0.01	<0.01	<0.01	0	0	0	0	3.31	2.12	1.23	0.59	0.18
Leatherback turtle [a]	2.18	0.61	0.21	0.03	0	0	0	0	0	0	3.21	1.93	1.19	0.47	0.27
Loggerhead turtle	0.91	0.32	0.01	0	0	0	0	0	0	0	3.02	1.81	0.90	0.49	0.22
Green sea turtle	2.84	0.94	0.45	0.02	0.02	0	0	0	0	0	3.44	2.34	1.48	0.54	0.25

[a] Listed as Endangered under the ESA.

Table J-21. WTG monopile foundation (7 to 12 m diameter, three piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.98	0.60	0.13	0.03	0	0	0	0	0	0	3.38	2.21	1.29	0.58	0.22
Leatherback turtle [a]	2.57	0.66	0.29	0.03	0	0	0	0	0	0	3.19	1.99	1.14	0.43	0.18
Loggerhead turtle	1.10	0.12	0.03	0	0	0	0	0	0	0	3.03	1.90	1.07	0.45	0.06
Green sea turtle	3.12	1.03	0.37	0.06	<0.01	<0.01	0	0	0	0	3.43	2.31	1.41	0.64	0.18

[a] Listed as Endangered under the ESA.

Table J-22. OSS monopile foundation (7 to 15 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\ 24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.12	0.27	0.05	0.01	0	0	0	0	0	0	2.70	1.40	0.97	0.31	0.16
Leatherback turtle [a]	0.84	0.51	0	0	0	0	0	0	0	0	2.50	1.19	0.72	0.36	0.19
Loggerhead turtle	0.51	0.11	0.04	<0.01	0	0	0	0	0	0	2.18	1.23	0.76	0.12	0.04
Green sea turtle	1.72	0.77	0.25	0.06	0	0	0	0	0	0	2.74	1.51	0.82	0.49	0.08

[a] Listed as Endangered under the ESA.

Table J-23. OSS monopile foundation (7 to 15 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\ 24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	0.98	0.40	0.11	0.01	0	0	0	0	0	0	2.65	1.57	0.89	0.36	0.21
Leatherback turtle [a]	0.90	0.62	0.12	<0.01	0	0	0	0	0	0	2.57	1.43	0.70	0.47	0.12
Loggerhead turtle	0.58	0.10	0.04	0	0	0	0	0	0	0	2.13	1.16	0.59	0.22	0.04
Green sea turtle	1.79	0.75	0.36	0.06	0	0	0	0	0	0	2.79	1.67	0.82	0.43	0.18

[a] Listed as Endangered under the ESA.

Table J-24. OSS monopile foundation (7 to 15 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.67	0.63	0.23	0.01	0	0	0	0	0	0	3.23	1.84	1.14	0.42	0.21
Leatherback turtle [a]	1.96	0.57	0.26	0	0	0	0	0	0	0	2.94	1.62	0.94	0.57	0.22
Loggerhead turtle	0.87	0.39	0.11	<0.01	<0.01	0	0	0	0	0	2.74	1.70	1.10	0.42	0.11
Green sea turtle	2.48	0.83	0.28	0.06	0	0	0	0	0	0	3.22	2.19	1.33	0.64	0.09

[a] Listed as Endangered under the ESA.

Table J-25. OSS monopile foundation (7 to 15 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{PK}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle [a]	1.91	0.87	0.32	0.01	0.01	0	0	0	0	0	3.20	1.80	1.11	0.61	0.22
Leatherback turtle [a]	2.33	0.65	0.28	0.12	0	0	0	0	0	0	3.12	1.70	0.91	0.61	0.21
Loggerhead turtle	1.08	0.55	0.10	0	0	0	0	0	0	0	2.63	1.38	1.06	0.57	0.05
Green sea turtle	2.93	1.13	0.47	0.13	0	0	0	0	0	0	3.21	2.03	1.34	0.67	0.17

[a] Listed as Endangered under the ESA.

J.3. Animat Seeding Area

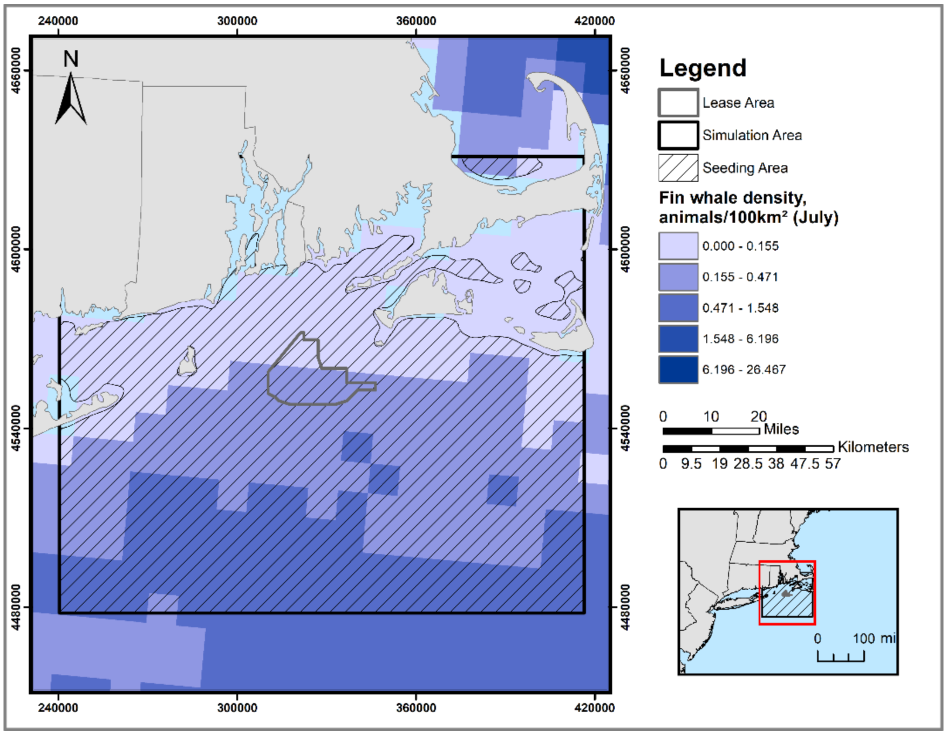

Figure J-1. Map of fin whale animat seeding range for July, the month with the highest density.

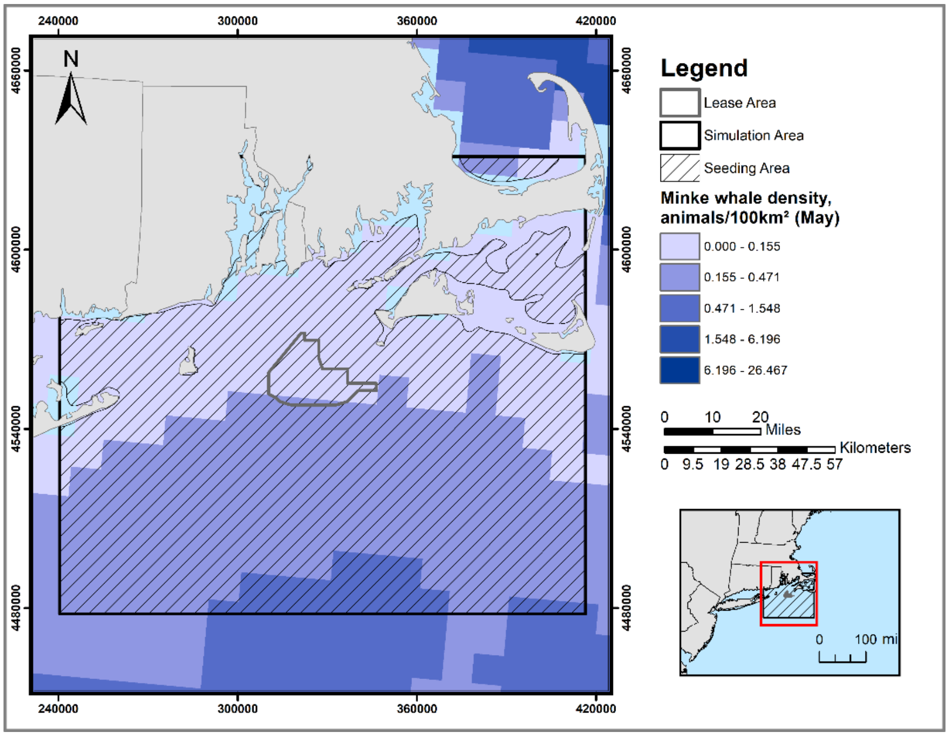

Figure J-2. Map of minke whale animat seeding range for May, the month with the highest density.

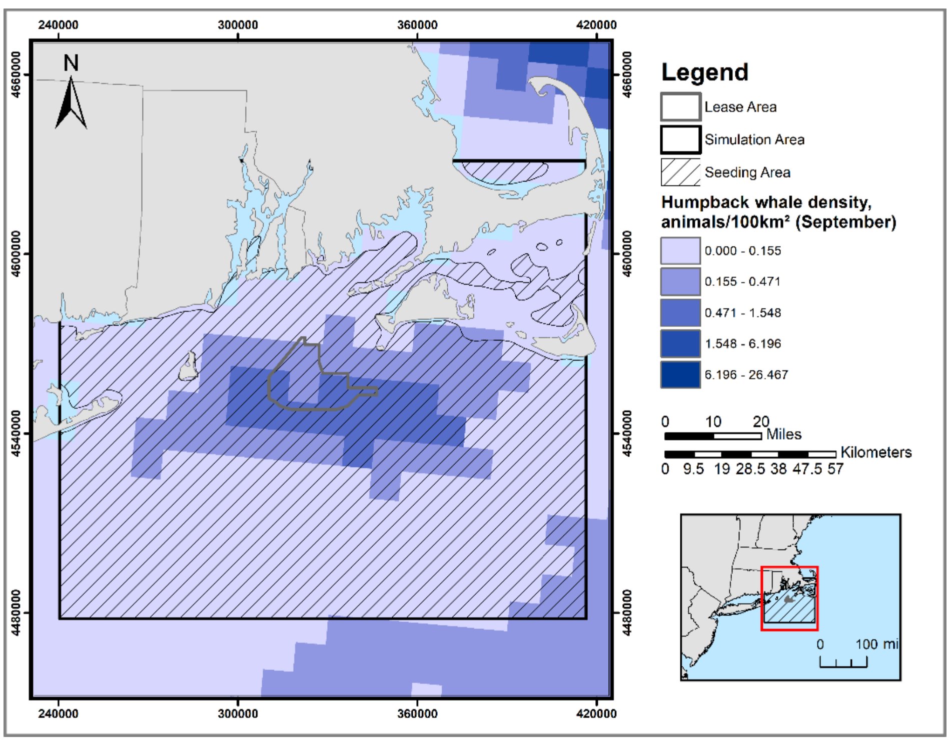

Figure J-3. Map of humpback whale animat seeding range for September, the month with the highest density.

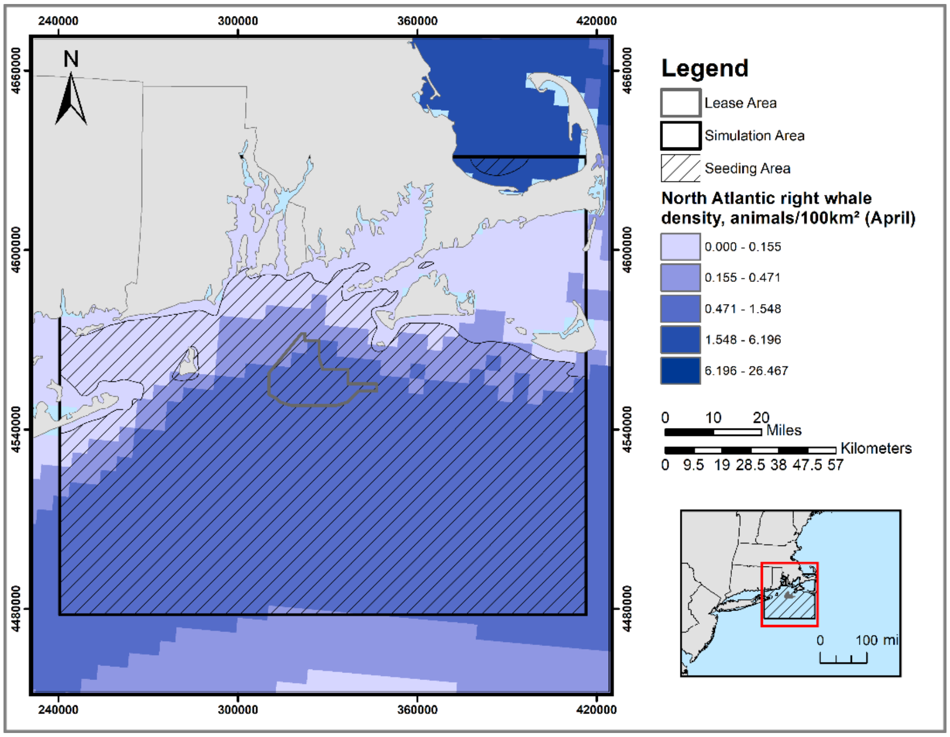

Figure J-4. Map of NARW animat seeding range for April, the month with the highest density.

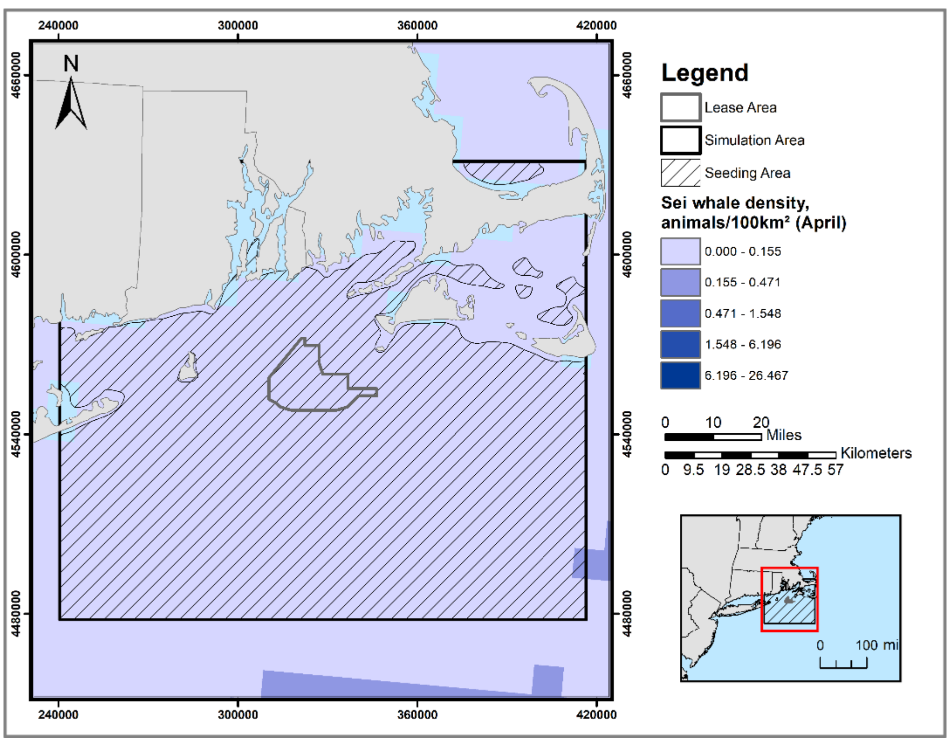

Figure J-5. Map of sei animat seeding range for April, the month with the highest density.

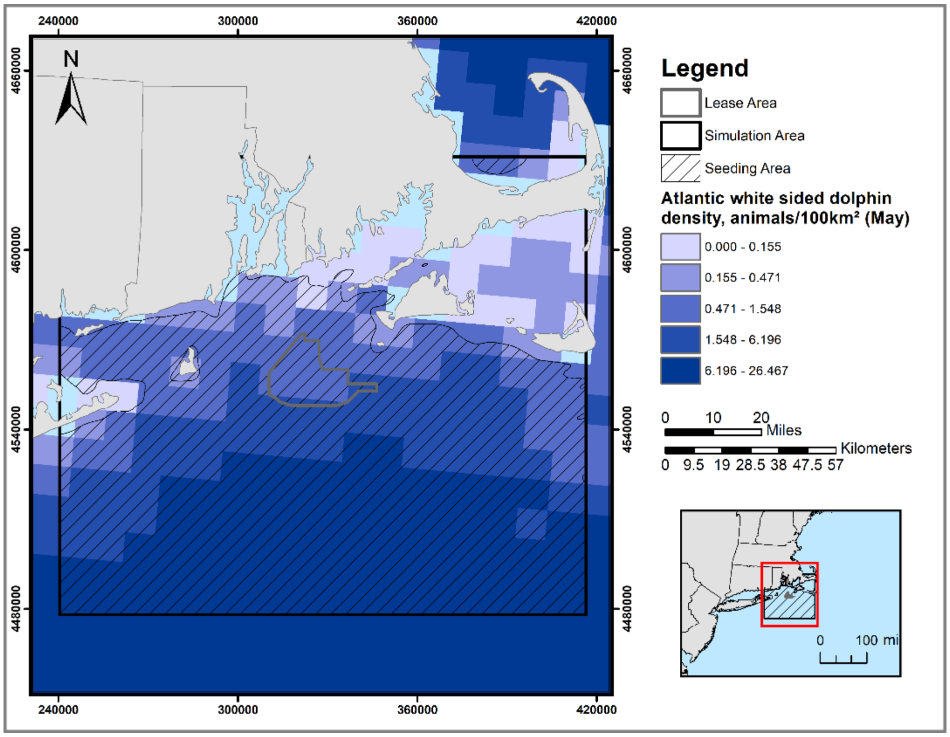

Figure J-6. Map of Atlantic white sided dolphin animat seeding range for May, the month with the highest density.

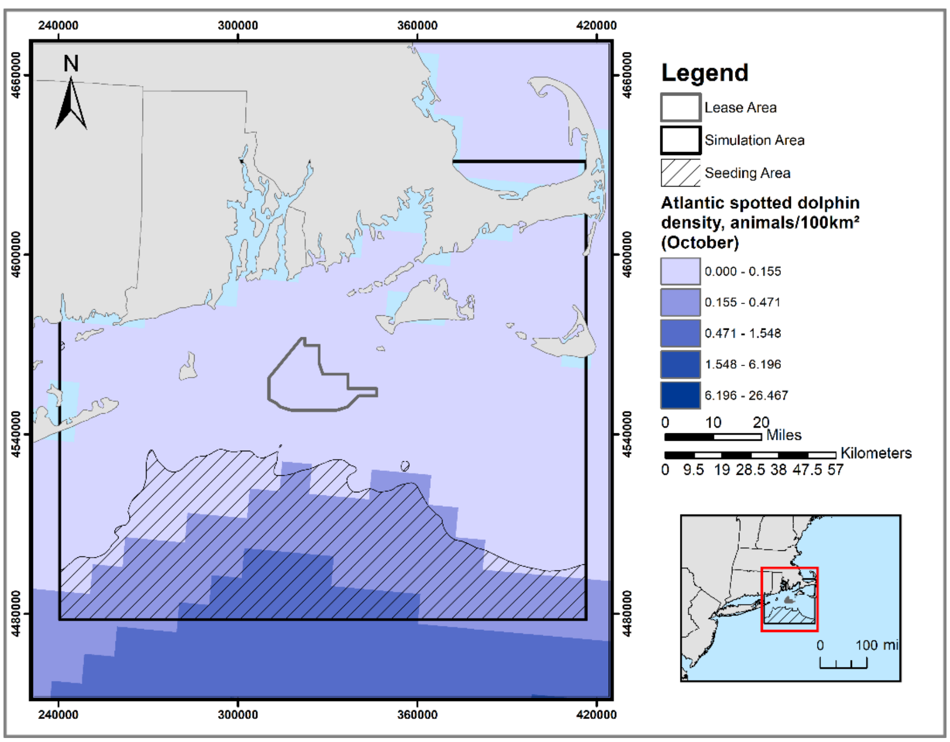

Figure J-7. Map of Atlantic spotted dolphin animat seeding range for October, the month with the highest density.

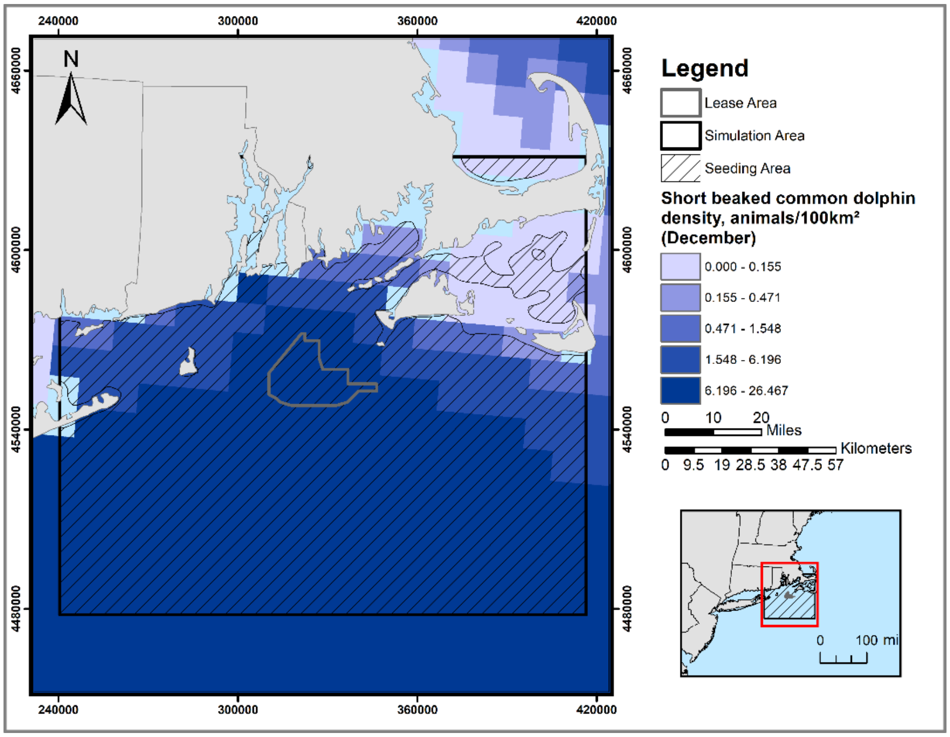

Figure J-8. Map of common dolphin animat seeding range for December, the month with the highest density.

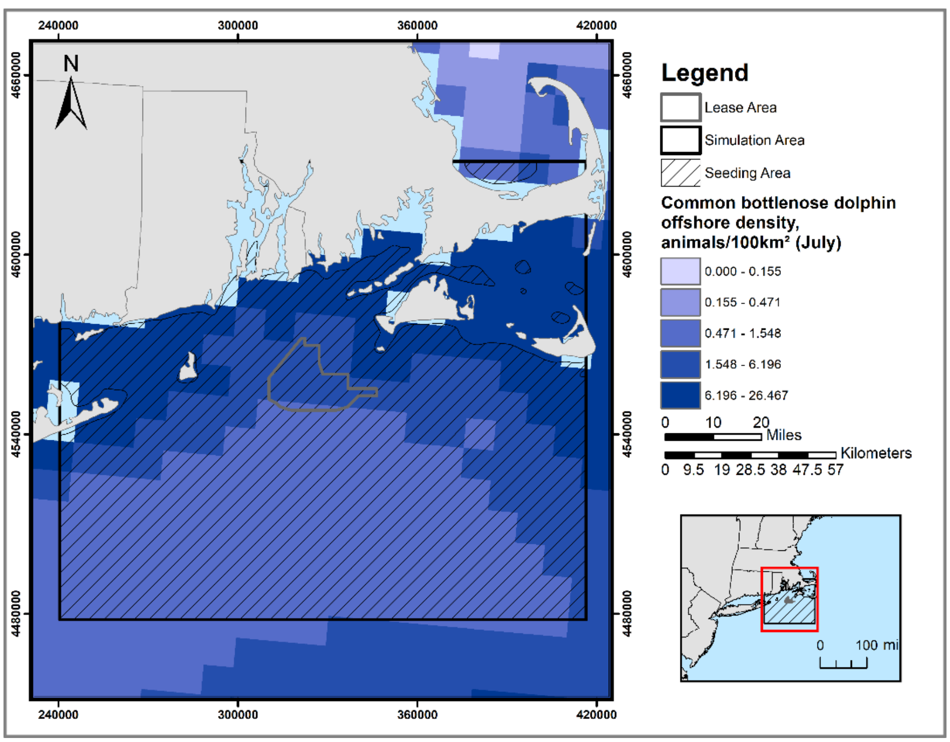

Figure J-9. Map of bottlenose dolphin animat seeding range for July, the month with the highest density.

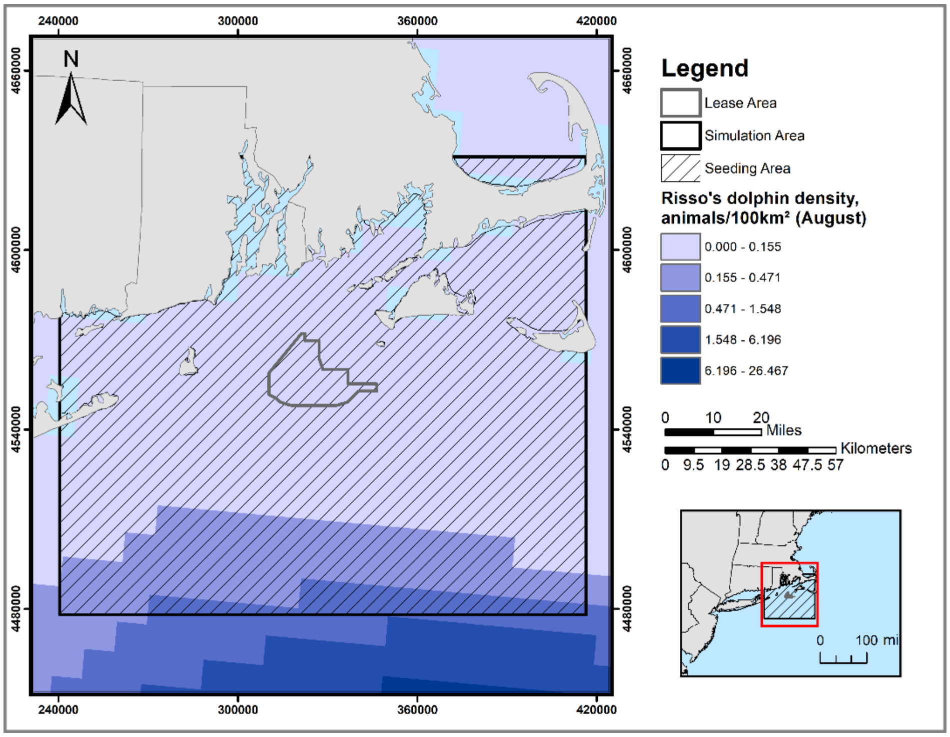

Figure J-10. Map of Risso's dolphin animat seeding range for August, the month with the highest density.

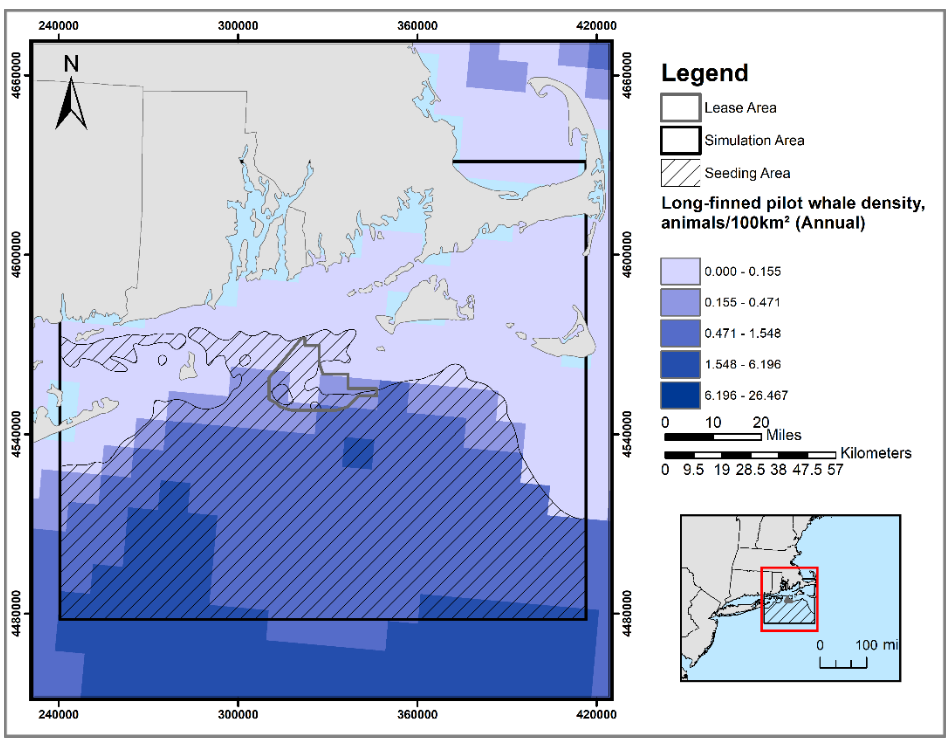

Figure J-11. Map of long-finned pilot whale animat seeding range.

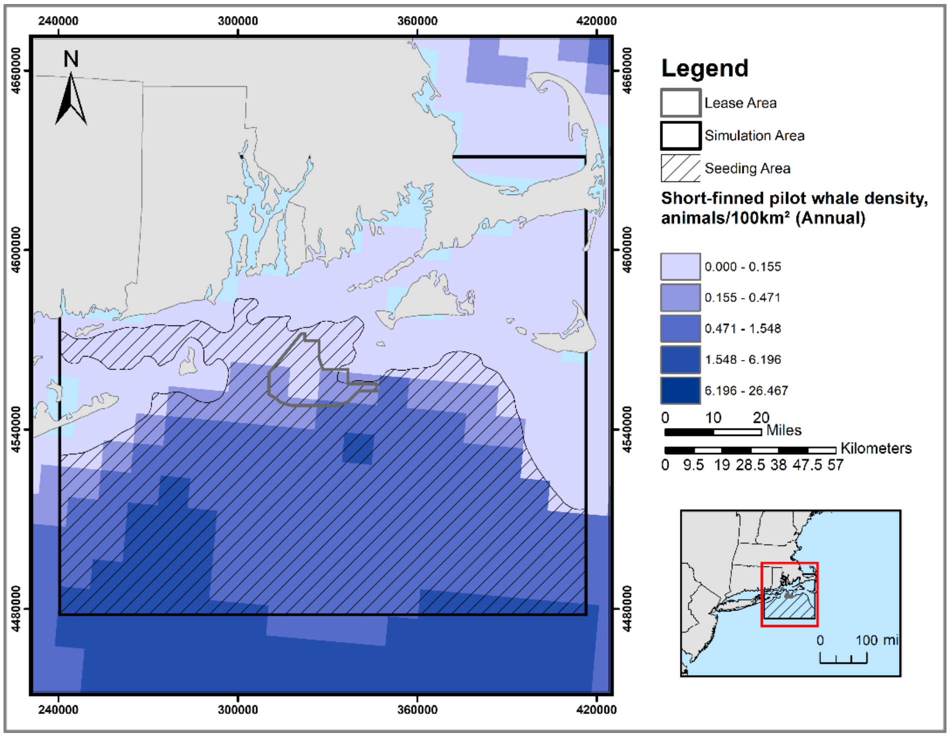

Figure J-12. Map of short-finned pilot whale animat seeding range.

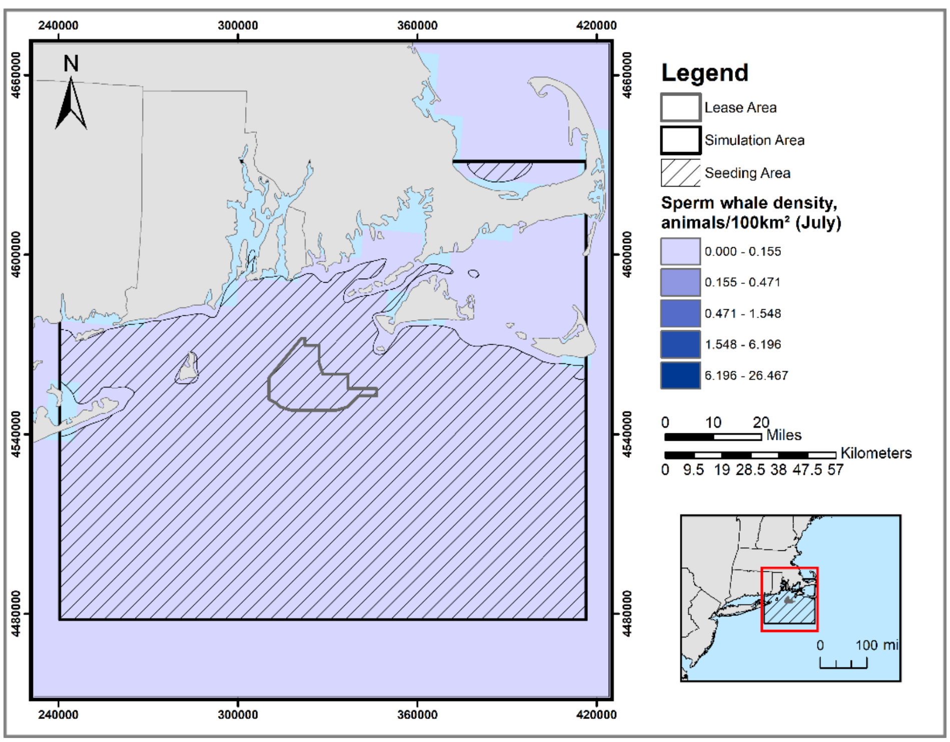

Figure J-13. Map of sperm whale animat seeding range for July, the month with the highest density.

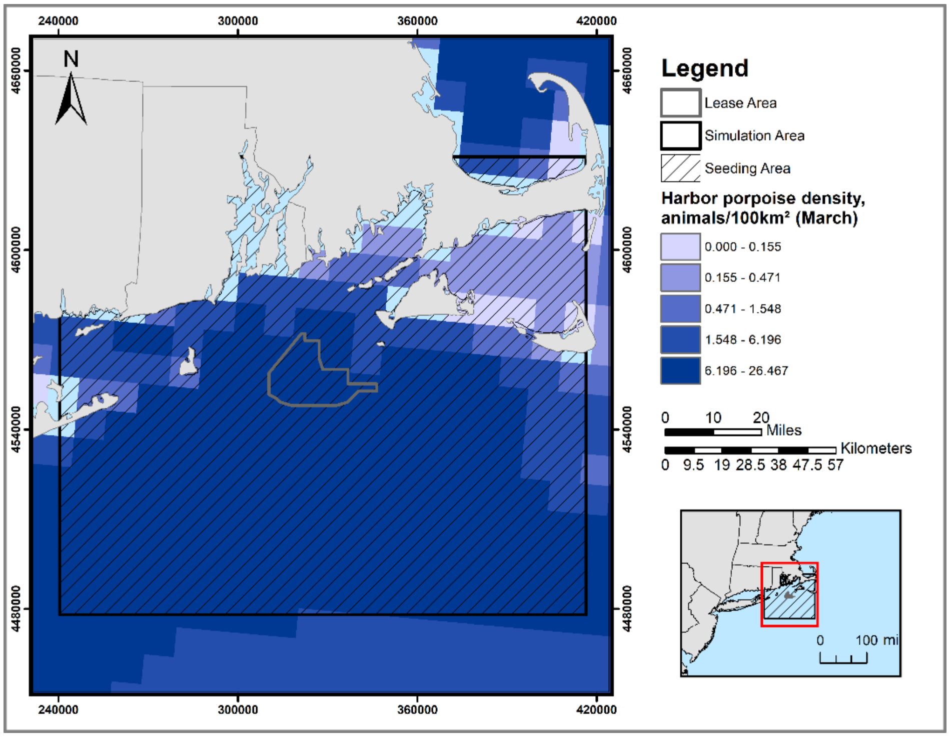

Figure J-14. Map of harbor porpoise animat seeding range for March, the month with the highest density.

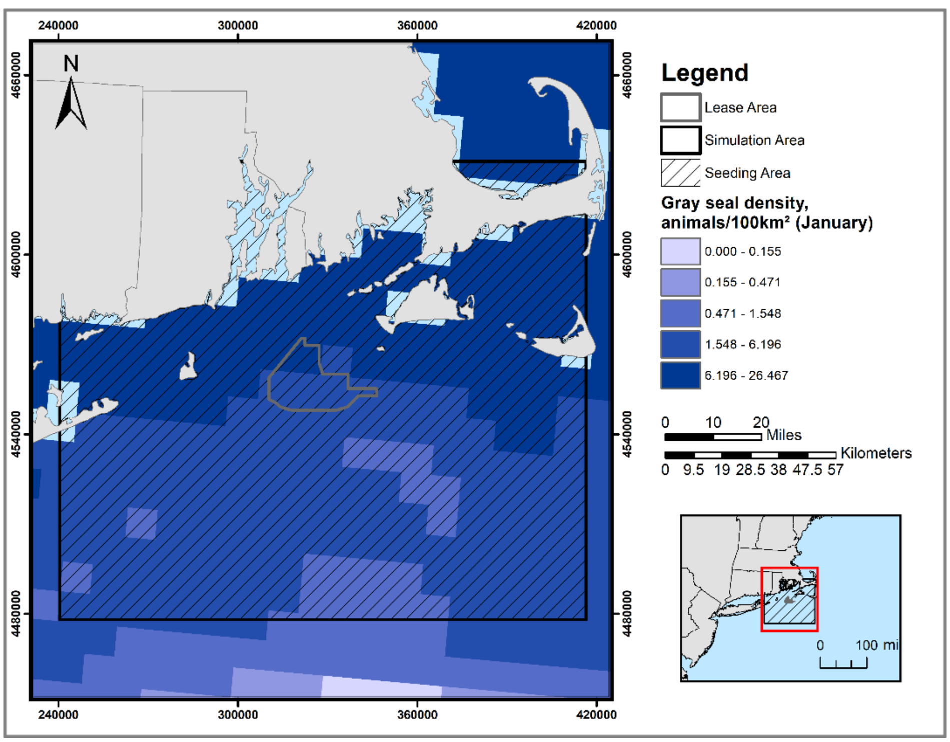

Figure J-15. Map of gray seal animat seeding range for January, the month with the highest density.

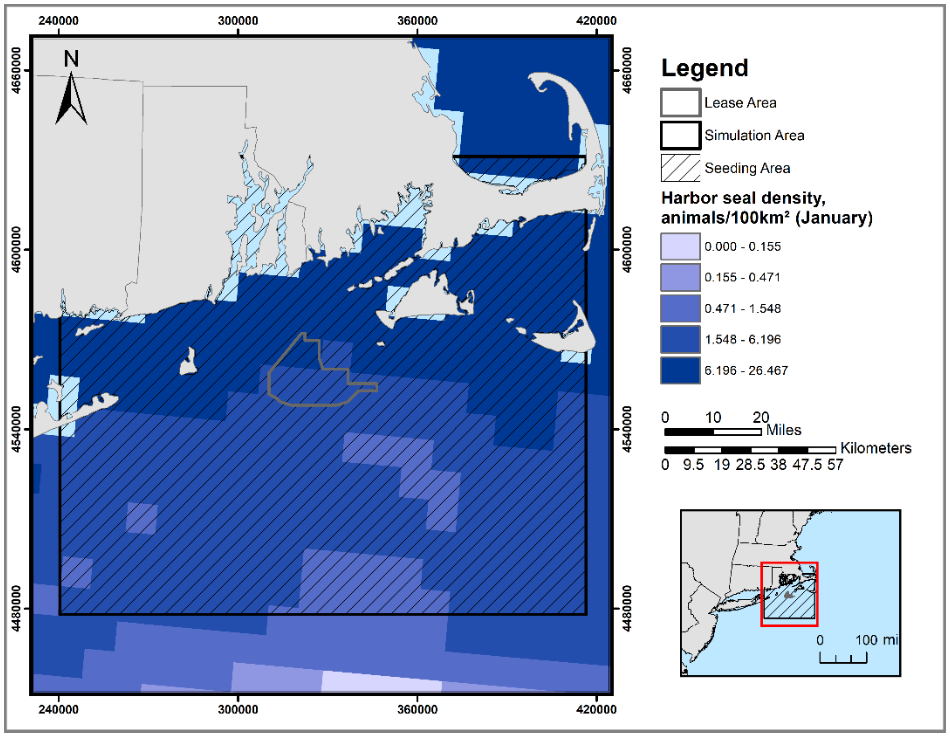

Figure -J-16. Map of harbor seal animat seeding range for January, the month with the highest density.

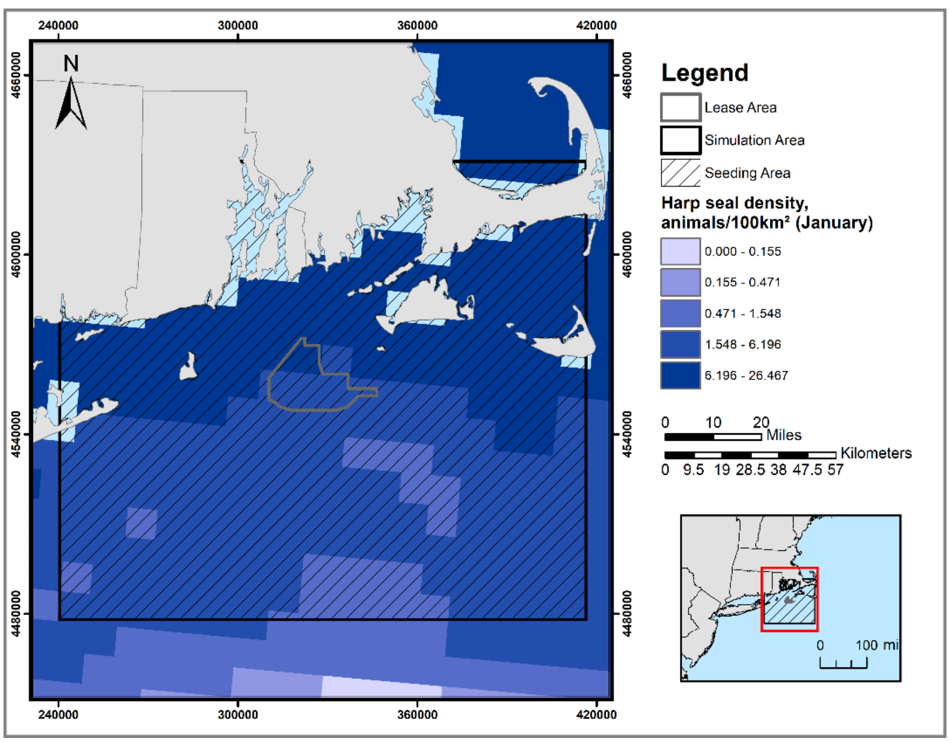

Figure J-17. Map of harp seal animat seeding range for January, the month with the highest density.

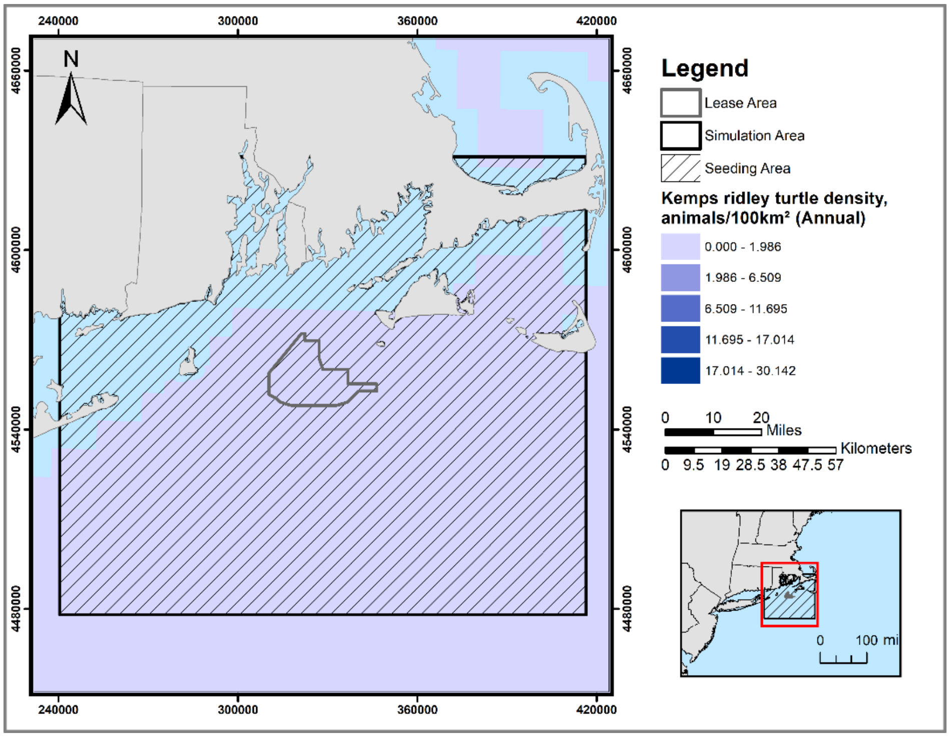

Figure J-18. Map of Kemp's ridley sea turtle with annual density from DoN (2017).

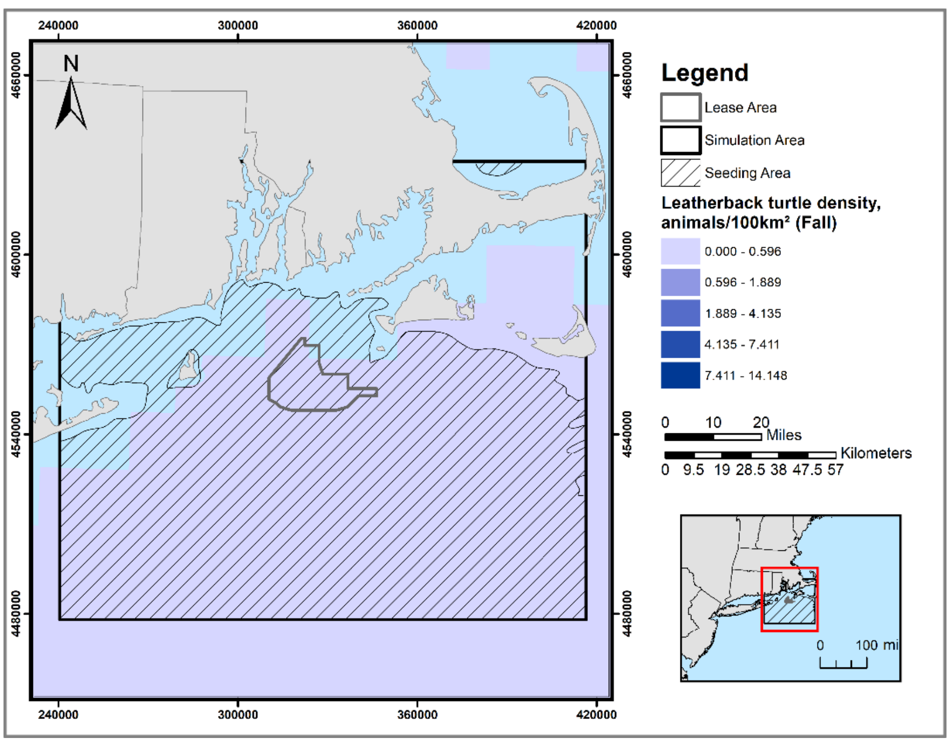

Figure J-19. Map of leatherback turtle with density from DoN (2017) for fall, the season with the highest density. Exposure estimates are calculated using average seasonal density from Kraus et al. (2016) for summer and fall.

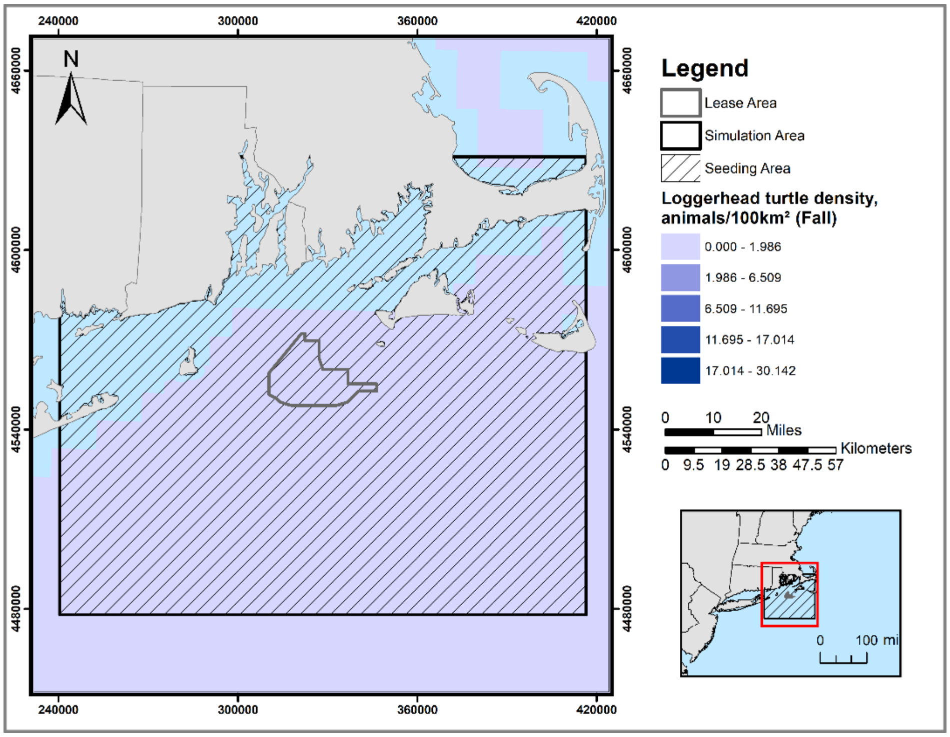

Figure J-20. Map of loggerhead turtle with density from DoN (2017) for fall, the season with the highest density. Exposure estimates are calculated using average seasonal density from Kraus et al. (2016) for summer and fall.

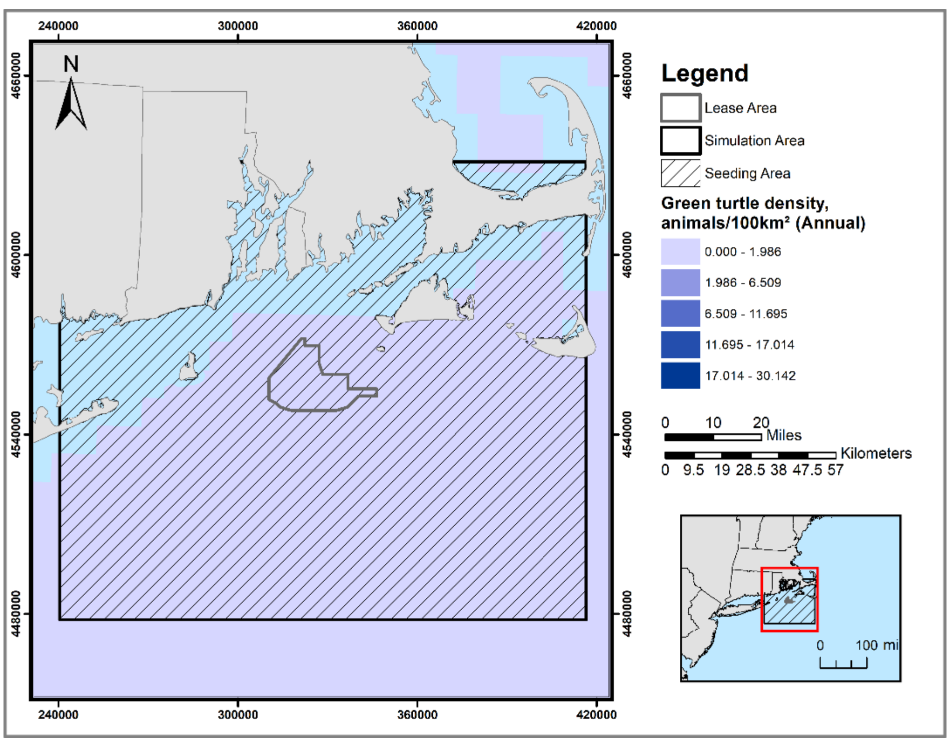

Figure J-21. Map of Green sea turtle, showing Kemp's ridley sea turtle annual density from DoN (2017) as an estimate.