# EVALUATING BIOLOGICAL EFFECTS OF DREDGING-INDUCED UNDERWATER SOUNDS

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## ABSTRACT

There is increasing concern related to adverse biological effects associated with anthropogenic input of sounds to the underwater soundscape. Dredging activities generate underwater sound by extraction, transit, and placement of material. The goal of this research was to document adverse biological effects of underwater sound from dredging and other anthropogenic sources to discern potential ecological risks of dredging activities. A focused literature review was conducted to identify and document what is currently known about the adverse effects from underwater sound on aquatic species. Sound exposure data available from dredging operations indicate that underwater dredging sounds are typically low-intensity (i.e. sound pressure levels [SPLs] < 190 dB re 1µPa at 1 m) and non-impulsive, with frequencies below 1,000 kHz. Dredging sound exposure characteristics, in terms of SPLs and frequencies, are similar to sounds emanating from commercial ship traffic, indicating the influence of dredge transit (i.e., vessel propulsion) to the overall soundscape relative to other extraction and placement operations. Effects data generated from exposures to anthropogenic sound sources indicate that dredging induced sounds do not pose a significant risk to direct injury or mortality to aquatic biota. A notable exception, and much less common, is blasting activities used to remove rock and other hard substrata in navigation channels. In terms of potential non-lethal responses, low-frequency sounds produced by dredging overlap with the hearing frequency ranges of select fish and mammal species, which may pose risk for auditory temporary threshold shifts, auditory masking, and behavioral responses. Recently updated technical guidelines have been developed by the NOAA National Marine Fisheries Service (NMFS) that proposed acoustic exposure criteria for select marine mammals. The NMFS (2016) technical guidance document does not address dredging sounds and the proposed thresholds are not broadly applicable to dredging. Therefore, to better understand the ecological risk associated with dredging sounds, a risk-based approach is needed that utilizes the available data and other site-specific information appropriate for evaluating underwater sound. Overall, the information reported herein can be used in an exposure assessment as part of a broader framework for assessing and managing underwater sound effects on aquatic life.

**Keywords:** Sound pressure level, frequency, adverse effects, marine mammals, fish

## INTRODUCTION

Underwater sounds can have a variety of adverse effects on aquatic life, ranging from subtle to strong behavioral reactions, even death. Some documented sub-lethal behavioral differences include startle response, habituation, attraction to or avoidance of the sound source, altered swimming behavior and avoidance to habitat (e.g., feeding or spawning grounds) (Hawkins and Popper 2016). It is well documented that short and impulsive sounds such as those produced from pile driving strikes, seismic airguns, and military sonar can cause behavioral reactions by fishes and cetaceans (i.e., whales, dolphins and porpoises) up to distances of several miles from the sound source. Certain sounds can also mask communication between whales or fish (Clark et al. 2009; Erbe 2011). Masking may be particularly important for soniferous fishes (e.g., cods, croakers, groupers) which produce sounds associated with spawning behavior, aggregating behavior, and orientation (Erbe 2011). Factors observed to influence organism responses to sound stimuli include life history stage, size relative to wavelength of sound, anatomical differences, and location in the water column relative to the source (Hawkins and Popper 2016). Research on the effects of underwater sound on

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aquatic life has occurred for several decades, but there are still many uncertainties, especially with regards to the significance of sound risks due to dredging activities. In particular, the extrapolation of effects on an individual to effects at the population or community level is highly uncertain. It is therefore important to develop a framework whereby the assessment of various sources of underwater sound can be made to improve the ability to manage such stressors.

There are multiple sources of underwater sound from natural and anthropogenic sources. Some natural sounds include vocalizations of marine life, and wind, waves, rain, and subsea volcanic and seismic activity. Some anthropogenic sources of sound originate from construction of marine infrastructure and industrial activities such as drilling, subsea mining, military activities, vessel movements, and dredging. An important data gap is the impacts of dredging-induced sound (e.g., excavation, transit, and placement) to aquatic biota and the potential impacts of dredging-induced sound in the context of other anthropogenic sources. The objective of this report was to perform a focused literature review of the available studies to develop an improved understanding of underwater sound effects of dredging on aquatic life. Understanding underwater sound effects of dredging in the context of other anthropogenic activities will allow for U.S. Army Corps of Engineers (USACE), who annually dredges approximately 200 million cubic yards of sediment, to more appropriately manage dredging operations when underwater sound is a primary concern.

### Approach

To address the stated objective, a review of peer-reviewed literature and government reports investigating underwater sound effects on aquatic life was conducted. Studies reporting underwater sounds emanating from operating dredges are limited to the last couple of decades. The Central Dredging and World Dredging Associations (CEDA and WODA, respectively) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) have recently published general overviews of underwater sounds produced by various dredge types (CEDA 2011; WODA 2013; OSPAR 2009a,b). Field studies have been performed which investigated the sounds produced during dredge operations, predominantly conducted in the United States (US) and United Kingdom (UK). In the US, investigators at the USACE published a series of reports on the underwater sounds produced by various dredge types operating in near shore and offshore scenarios. Nedwell et al. (2008) and the Marine Aggregate Levy Sustainability Fund (MALSF) published reports that documented the underwater sound generated from dredge operations in UK harbors. Numerous field studies have been performed by various investigators when the Port of Rotterdam was expanded in The Netherlands.

Additionally, there have been extensive efforts over the past decade to better understand biological responses to underwater sounds. For example, the Aquatic Noise Trust (organized by Popper, Hawkins et al.) has held four conferences on anthropogenic underwater sound research since 2007. The most recent of these was the 4th International Conference on the Effects of Noise on Aquatic Life held in Dublin, July 2016. Papers presented at previous conferences were published as extended abstracts in a variety of forums, including as: a Special Issue in the journal Bioacoustics (Hawkins 2008; Volume 17, Nos. 103); a book entitled "The Effects of Noise on Aquatic Life" (published in a special issue of Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_5 [2012]); and a third book "The Effects of Noise on Aquatic Life II" (Popper and Hawkins 2016).

In addition, a publically available library database for research related to underwater sound is supported by E&P Sound and Marine Life Program under the direction of the International Association of Oil and Gas Producers (IOGP). The online database provides access to project reports, peer-reviewed publications, factsheets, and content from IOGP funded research and can be found at http://www.soundandmarinelife.org

It should be noted that direct comparisons of SPLs across studies should be done cautiously, due to the lack of standardized underwater sound measurement techniques and methods for measuring biological responses (Thomsen et al. 2016; Erbe et al. 2016).

## RESULTS

### Review of Underwater Sounds Produced by Dredging Operations

Most dredges share three main categories of activities that produce most of the underwater sound: excavation, transit, and dredge material placement (CEDA 2011). Dredging produces sounds that are continuous, discontinuous and/or cyclic in nature. The two main categories of dredges are hydraulic and mechanical dredges.

### *Hydraulic Dredging*

Hydraulic dredges work by sucking a mixture of dredged material and water from the bottom. The two main types of hydraulic dredges are cutter suction dredges and trailing suction hopper dredges (CEDA 2011; WODA 2013). Cutter suction dredges (CSD) suck material through an intake pipe and then push the material out of a discharge pipeline directly into a transport barge or a placement site. A cutterhead at the suction end of the intake pipe rotates in contact with the sediment bed while swinging laterally into the sediment surface. Some cutterheads are capable of dredging rock-like formations such as basalt or limestone. The dredge incrementally advances forward by alternately swiveling on spud poles or pushing ahead on a travelling spud while anchored cables on each side of the dredge control lateral movement. Because CSDs use pipelines to dispose of dredged material directly into a transport barge or a placement site the operations are usually continuous (i.e., 24 h, 7 days a week) until the job is completed. Primary sources of continuous CSD sounds include: 1) dredge material collection sounds originating from the rotating cutterhead in contact with the sediment and intake of the sediment-slurry; 2) sounds generated by pumps and impellers pushing sediment-slurry through pipes; 3) transport sounds resulting from the movement of sediment-slurry through pipes; and 4) ship machinery sounds, including those associated with the lowering and lifting of spuds and moving anchored cables. The duration of production cuts in dredging activities depends on depth of cutterhead insertion, type of material being excavated, and width of the navigation channel (Reine et al. 2012b). Overall, source SPLs of CSDs range from 168 to 175 dB re 1µPa at 1 m (Greene 1987; Reine et al. 2012b; Reine and Dickerson 2014).

Trailing suction hopper dredges (TSHD) are ships with propulsion and large hoppers for containing dredged material. During dredging, long intake pipes, termed drag arms, extend from the ship and drag along the bottom. Erosion, teeth and water jets loosen the material, and pumps are then used to suck the material from the bottom into the hopper. When the hopper is full dredging stops and the ship travels to a dredged material placement site where the material is discharged from the bottom of the ship, or pumped out through a discharge pipeline. Continuous TSHD sounds are produced from the ship's propulsion during dredging and transit to the placement site. Sounds associated with dredging are considered discontinuous and cyclic because dredging stops when the hopper is full and the ship moves to and from the dredging area and placement site. During dredging, the draghead contacting the bottom substrate as it trails beneath the dredge during advancement produces continuous sounds. The sound produced during filling of the hopper is associated with propeller and engine sound with additional sounds emitted by pumps and generators. Overall, source SPLs of TSHDs range from 172 to 190 dB re 1µPa at 1 m (Nedwell et al. 2008; de Jong et al. 2010).

### *Mechanical Dredging*

Mechanical dredges remove material by scooping it from the bottom substrate. The two main types are grab dredges (GD) and backhoe dredges ([BHD] CEDA 2011, WODA 2013). Both dredge types are relatively stationary operations and commonly use barges to transport material to the placement site. The GD, also referred to as a clamshell or bucket dredge in US parlance, is a commonly used mechanical dredging method in the United States. The GD is a stationary operation with or without propulsion. Grab dredges can be held in place with spuds or anchors. Often several barges are used to store and transport the dredged material for placement. The dredging activity occurs in intervals and is regularly repeated whereby the grab is lowered, closed, hoisted, swung to the barge, and the bucket opened to release the material. Dickerson et al. (2001) and Clarke et al. (2002) described GD operations as a discontinuous and cyclic sound produced by winches and derrick movement, bucket contact with the substrate, digging into substrate, bucket closing, and emptying of material into a barge or scow. The sounds are repeated approximately every minute with intermittent interruptions due to barge maneuvering and maintenance activities. Overall, SPLs of GDs range from 107 to 124 dB re 1µPa at 154 m (Dickerson et al. 2001).

A BHD is a stationary platform with a hydraulic excavator having a single digging bucket positioned on the end of an articulated arm. The BHD digs by drawing bottom sediment backwards and are typically used to work in harder material than GDs. The BHD sits on a barge that is anchored and the position is maintained with spud poles to provide a stable platform to account for the reaction forces from digging. Similar to the GD, several barges are used to store and transport material dredged by the BHD. The workflow is also similar to the GD in that dredging occurs in regular intervals (discontinuous) and is repeated (cyclic) whereby the backhoe is lowered, drawn backwards to fill with sediment, lifted, swung to the barge, and the bucket inverted to release the material. Sound sources produced by BHD originate from several sources. Grinding and scraping sounds are produced when the backhoe is drawn backwards to fill with material. Sounds are produced by hydraulic pumps and the articulated bucket support arm during subsequent lifting of the material from the substrate through the water column. Sounds are transmitted through the hull of the receiving barge during placement into it. Onboard machinery associated with winches, generators, and engines also produce sounds. Other periodic sounds include the movement of spud poles or anchor cables. Engine sounds are produced by tugboats and tenders when they are used to transport barges with sediment to placement sites. Overall, source SPLs of BHDs range from 163 to 179 dB re 1µPa at 1 m (Nedwell et al. 2008; Reine et al. 2012a).

Dredging sounds are predominantly lower frequency, with reported peak spectral levels generally below 1,000 Hz. Underwater sounds produced by dredges and the radiated distance are dependent on several factors including substrate type, geomorphology of the waterway, site-specific hydrodynamic conditions, equipment maintenance, and dredge operator skill. The type of material dredged (e.g., rock, gravel, sand, mud) affects the frequency of underwater sounds. It is anticipated that within dredge types, larger dredges have higher SPLs as compared to smaller dredges. However, based on the currently available dredge sound data, there were no apparent relationships associated with installed power and underwater SPLs within dredge types. Cavitation sounds from propellers and pumps were the primary source of the highest continuous SPLs reported. Dredging activities producing the lowest SPLs generally included sand depositing, depositing in a scow or hopper, and bucket closing on the channel bottom. Overall, source level SPLs associated with dredging operations commonly range from approximately ~100 to 190 dB (root mean square [RMS]) re 1µPA at 1 m (Greene 1987; Dickerson et al. 2001; Clarke et al. 2002; Nedwell et al., 2008; de Jong et al. 2010; Reine et al. 2012a,b; Reine et al. 2014a,b; Reine and Dickerson 2014). In general, SPLs from dredging activities are similar to levels reported for underwater sound associated with commercial shipping (Figure 1). It should be noted that the acoustical characteristics are often summarized as single maximum recorded values near the dredge (i.e., 1 m from source). Additionally, a single sound event (e.g., propeller cavitation) can skew the calculated SPLs (RMS) and may not provide an accurate representation of the dredging operation.

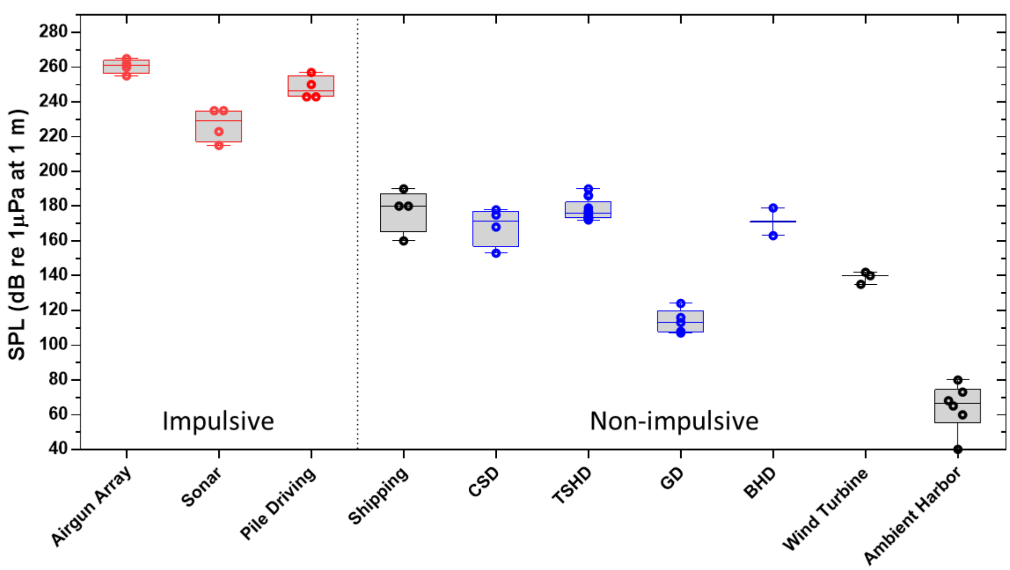


**Figure 1. Summary of underwater SPLs by sound source.**
**Note: Dredge-induced sounds (blue) include: cutter suction dredge (CSD); trailing suction hopper dredge (TSHD); grab dredge (GD); and backhoe dredge (BHD).**

### Review of Dredging-Induced Underwater Sound Effects

Sound is an important sensory function for many marine organisms (Hawkins 2008; OSPAR 2009b). Marine mammals, fish, and invertebrates have special mechanisms for emitting and detecting underwater sound (Popper 2003; OSPAR 2009b). Underwater sound is biologically important for communication, orientation, predator avoidance, and foraging (OSPAR 2009b). It is recognized that sound emanating from anthropogenic sources may have a diverse range of physiological and behavioral effects on marine biota (Southall et al. 2007; Popper et al. 2014), and there is a growing international focus to better understand these interactions (Popper and Hastings 2009). Only recently (past few decades) has the field of study developed investigating the potential effects associated underwater sound from industrial activities to various marine taxa (Williams et al. 2015).

A key principle to understanding and predicting adverse effects from underwater sound is to develop exposure-response relationships of underwater sound for environmentally relevant organisms (Boyd et al. 2008; Thomsen et al. 2016). Reported effects to marine biota following exposures to anthropogenic sounds (e.g., pile driving, sonar, and shipping) range from lethal to sub-lethal (behavioral effects). The spectrum of species responses to underwater sound is generally described by direct injury, effects on hearing, masking, and behavioral responses. Auditory effects are commonly described by permanent threshold shifts (PTS) or temporary threshold shifts (TTS). For some studies, biota "received levels" are described by sound exposure level (SEL). SEL is a cumulative metric to describe total sound produced from a sound event, and incorporates both the intensity and duration of a sound event.

Based on the characteristics of underwater sound associated with various dredging operations, there is general consensus that there is not a significant risk of mortality or permanent injury to marine biota when dredging bottom substrates (Todd et al. 2015). The effects of underwater sound emanating from dredging operations are anticipated to be limited to non-lethal effects (e.g., masking effects or alter behavioral responses; Hawkins et al. 2015). Dredging operations and other anthropogenic sounds (e.g., shipping vessels) can produce lower frequency sounds (20 to 1,000 Hz) that overlap the detectable frequency range of marine organisms (Figure 2).

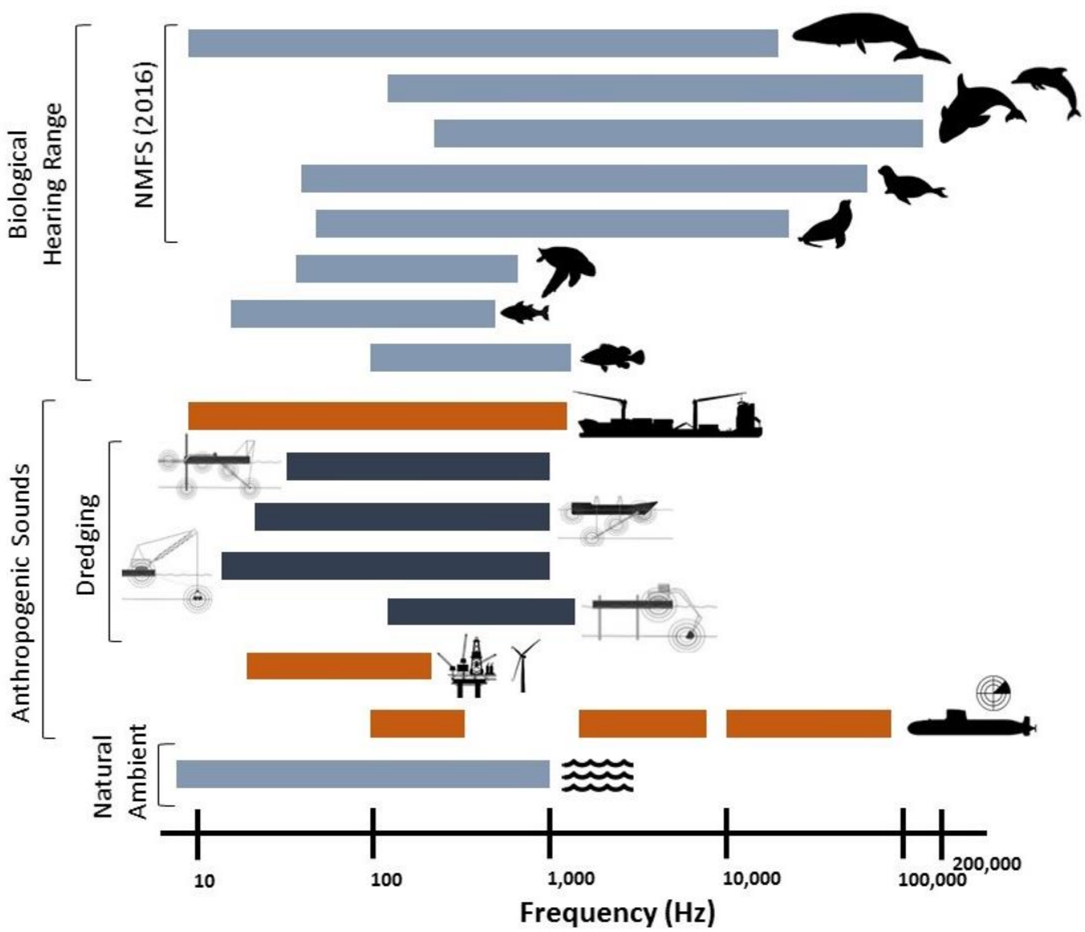


**Figure 2. Hearing frequency ranges of selected fish and mammal species and main energy frequencies reported for anthropogenic and ambient sources.**

### *Effects on Fish*

In general, fish have a lower sound frequency detection range as compared to marine mammals. Fish can detect frequencies ranges between 30 to 1,000 Hz (Erbe 2011), and some fish can even detect infrasound (< 20 Hz; e.g., Clupeid spp.) and ultrasound (> 20,000 Hz; e.g., Atlantic herring; Normandeau Associates 2012). More commonly the 100 to 400 Hz frequencies are detected by a majority of fish studied (e.g., see Offutt 1974; Yan 2001; Codarin et al., 2009; Parmentier et al. 2011). In general, this means that high-frequency (>10,000 Hz) sounds (e.g. sonar) are not expected to overlap with hearing frequencies of most fish species (Slabbekoorn 2016). Fish appear to be particularly well adapted to detecting lower frequency sounds (<1,000 Hz), like those emanating from shipping or dredging operations. To date, less than 100 fish species have audiograms of hearing thresholds which overlap with shipping vessel frequencies (Neenan et al. 2016). Although only a small percentage (<1%) of the total fish species (>30,000) have been part of bioacoustics investigations (Erbe 2011), these studies are improving our understanding of the potential risk to fish exposed to underwater sound.

SPLs are an important metric when considering the interaction with air-filled cavities (i.e., swim bladders) (Slabbekoorn 2016). However, fish are also sensitive to the particle motion of sound detected by auditory hair cells (OSPAR 2009a). A topic of future study that was identified at the WODA (2015) "Workshop on Underwater Sounds" included using particle motion as a metric for addressing underwater sound exposure to fish, as compared to the more commonly expressed sound pressure (dB) descriptions. In comparison to hydrophones, the use of underwater particle motion detectors is a relatively new method because only recently has the technology become commercially available (Nedelec et al. 2016). Therefore, particle motion data are not commonly reported as an acoustic measures describing anthropogenic sounds but it is likely to become an important component for evaluating effects to fish (Hawkins and Popper 2017).

To date, the authors are unaware of any studies which have directly measured effects of underwater dredging sounds to fish species. A few studies have estimated effects to fish by comparing sounds from field dredging operations to literature-derived TTS effects criteria. The currently available effects data from anthropogenic sources indicate that dredging induced sounds do not pose a significant risk to direct injury or mortality in juvenile or adult fish. Mortality of fish following exposures to anthropogenic sounds is generally limited to high intensity impulsive sounds (e.g. explosions, pile-driving, airguns). In terms of masking and behavioral responses, lower frequency sounds (<1,000 Hz) emanating from shipping and dredging are of particular interest due to the overlap of hearing detection of many fish species.

Of the few studies available which evaluated sub-lethal effects of dredging-induced sounds (i.e., DEFRA 2003; Nedwell et al. 2008; Heinis et al. 2013), there was no evidence of risk for auditory injury (TTS) or behavioral effects for larger bodied fish (>2 g; Table 1). In terms of adverse effects to smaller bodied fish, Heinis et al. (2013) estimated based on "worst case" scenario that smaller bodied fish (<2 g) were at risk in the immediate vicinity of the sound source (<20 m).

**Table 1. Reported biological responses of fish to dredge-induced underwater sounds.**

| Source | Exposure Level | Frequency (kHz) | Species | Effect | Reference |
|---|---|---|---|---|---|
| Dredging | 190 (SPL dB re 1 µPa RMS) | 0.08 to 1 | Atlantic salmon | no significant behavioral effects | Nedwell et al. 2008 |
| | 163 (SPL dB re 1 µPa RMS) | 0.08 to 1 | Atlantic salmon | no significant behavioral effects | Nedwell et al. 2008 |
| | 117-122 (SPL dB re 1 µPa at 50 m) | <1 | Clupeidae and flat fish | no auditory injury risk | DEFRA 2003 |
| Shipping + Dredging | 186 (SEL dB re 1µPA2·s; 24 h exposure) | 0.5 to 10 | ND (modeled fish exposure) | No TTS risk fish > 2g; Exceeded TTS risk threshold for fish < 2g[a] | Heinis et al. 2013 |

RMS = root mean square; SEL = sound exposure level; TTS = temporary threshold shift

[a]TTS risk thresholds for fish < 2 g = 183 dB re 1µPa2·s; fish > 2 g = 187 dB re 1µPa2·s; (Oestman et al. 2009)

### *Effects on Marine Mammals*

The published literature on the effects of underwater sound on marine mammals is more extensive than that for fish (William et al. 2015). Many of the controlled experiments conducted on marine mammals were tonal or playback sounds. Only a few studies were found which estimated effects of dredging-related sounds on marine mammals (Richardson et al. 1990; Gilmartin 2003; Gerstein et al. 2006; Hoffman 2010; Heinis et al. 2013; Table 2).

As reported in the literature, the effects of underwater sound on marine mammals range from direct mortality, auditory and non-auditory physiological effects, masking, and behavioral responses (Erbe 2011). Field surveys collected synoptically with naval sonar exercises, seismic surveys, and pile-driving activities provide sound exposure data for potential adverse effects to marine mammals (Foote et al. 2004; Tougaard et al. 2009; Brandt et al. 2011; Tyack et al. 2011). In addition, controlled laboratory experiments have also been conducted investigating threshold levels of auditory effects from sound playbacks (Finneran et al. 2002; Kastelein et al. 2012, 2013a,b). The NOAA (National Marine Fisheries Service) NMFS’s 2016 technical guidance is an additional resource which provides a comprehensive review and study of peer-reviewed literature and government reports on the impacts of underwater sound on marine mammals (NMFS 2016).

**Table 2. Reported biological responses of mammals to dredge-induced underwater sounds.**

| Source | Exposure Level | Frequency (kHz) | Species | Effect | Reference |
|---|---|---|---|---|---|
| Dredging | 177 (SPL dB re 1 µPa RMS) | 0.1 to 10 | Modeled manatee masking zone | 512-4,096 m auditory masking zone | Gerstein et al. 2006 |
| | 115-117 (SPL dB re 1 µPA "received level") | 0.02 to 1 | Bowhead whales (field observations) | no observable behavioral response | Richardson et al. 1990 |
| | 94-122 (SPL dB re 1 µPA "received level") | 0.02 to 1 | Bowhead whales (dredging sound playback) | inconclusive behavioral responses | Richardson et al. 1990 |
| | NR | NR | Hawaiian monk seals (field observations) | no adverse behavioral response | Gilmartin 2003 |
| | NR | NR | Beluga whales (impact assessment) | no adverse effects reported | Hoffman 2010 |
| | NR | NR | Bottlenose dolphins (field observations) | avoidance behavior | Pirotta et al. 2013 |
| Shipping + Dredging | 182 (SEL dB re 1µPA2·s24 h exposure) | 0.5 to 10 | Modeled seal behavior (AQUARIUS) | did not exceed TTS risk threshold[a] | Heinis et al. 2013 |
| | 180 (24 h exposure) | 0.5 to 10 | Modeled harbor porpoise behavior (AQUARIUS) | did not exceed TTS risk threshold[b] | Heinis et al. 2013 |

NR = not reported; RMS = root mean square; SEL = sound exposure level; TTS = temporary threshold shift

[a]Calculated SEL values were below the TTS threshold values of 183 (seal; Southall 2007)

[b]Calculated SEL values were below the TTS threshold values of 195 (harbor porpoise; Southall 2007)

There are numerous marine mammals for which auditory sensitivities and vocalization patterns overlap sounds generated by anthropogenic activities. Echolocating marine mammals (e.g., dolphins and porpoises) have acute hearing and may be particularly sensitive to lower frequency sounds (Kats 2009). In general, available sound effect data are limited to pinnipeds (seals, sea lions), and odontocetes (dolphins, whales), with limited data available for sirenians (manatees). Common metrics of sound related auditory injury to mammals are described by PTS or TTS. The TTS criterion is generally accepted as a reliable metric for estimating sound related injury and has been used for establishing exposure limits due to the relative sensitivity of the inner ear of mammals to sound exposures (Southall et al. 2007) and the ability to reliably measure TTS in captive marine mammals (Tougaard et al. 2009).

In terms of mammal responses to dredging-induced sounds, there are limited data directly measuring the onset of auditory injury. Based on the data available for mammal responses to other anthropogenic underwater sounds, risks associated with dredging are likely limited to masking and behavioral effects (Thomsen et al. 2016). Only a single study to date has estimated the onset of PTS and TTS from dredging sounds (Heinis et al. 2013). During the expansion of the Port of Rotterdam, long-term monitoring of TSHD and shipping sounds were used to estimate the potential risks for harbor porpoises and seals using exposure modeling. Results from this study did not indicate that harbor porpoises or seals would exceed PTS or TTS thresholds during dredging operations (Heinis et al. 2013).

In terms of behavioral responses to dredging activities observed in the field, whales and seals had no adverse reactions or avoidance behavior near active dredging operations (Table 2). Following simulated playback sounds from dredging activities, bowhead whales sometimes exhibited avoidance or altered feeding behaviors (Richardson et al. 1990). A one-year field study evaluating avoidance behavior in harbor porpoises revealed that there may be short term avoidance of areas near dredging activity; however, these effects were short-term and porpoises return to the areas after the dredging activity was completed (Diederichs et al. 2010). Based on observational studies, pinnipeds (seals) did not exhibit avoidance or altered behavior near dredging activities (Gilmartin 2003). There is some evidence that sirenians (manatee) may be susceptible to low-frequency sounds masking boating sounds (Gerstein et al. 2006).

### *Effects on Other Marine Species*

Significant data gaps exist in terms of sea turtles responses to underwater sound. Willis (2016) reports that the vocalizations and best hearing frequencies for turtles are around 300-500 Hz. Only a few species having published audiograms (exceptions are: loggerhead turtle [*Caretta caretta*]; green turtle [*Chelonia mydas*]; Kemp Ridley [*Lepidochelys kempi*]; and red-eared slider [*Trachemys scripta elegans*]). Preliminary data suggests sea turtles are somewhat resistant to high intensity explosives, inferring that they are also resistant to impulsive sounds (e.g. pile-driving, seismic airguns; Ketten et al. 2005; Popper et al. 2014). Based on the lower frequency hearing range of turtles, there may be potential for behavioral or masking effects of lower-frequency anthropogenic sounds.

## CONCLUSIONS

This literature review provides an improved understanding about underwater sound effects of dredging on aquatic life. Underwater sound from natural and anthropogenic sources are composed of many frequencies and amplitudes which produces a combination of acoustic waves that can be disordered or random and difficult to spatially quantify. The sound pressure levels (SPLs) in decibels (dB) is commonly used to quantify underwater sounds. Due to the diversity of acoustic metrics, it is critical to use caution when comparing reported sound levels across studies. Additionally, it is crucial to understand the differences between sound source levels and organism received levels (the latter is dependent on the sound source characteristics and the sound propagation in the aquatic environment, and the receptor sensitivity).

Dredge-induced underwater sounds are temporally and spatially dynamic, and dependent on site-specific activities and conditions. Dredging produces predominantly low-frequency (<1,000 Hz) sounds, which are typically continuous and non-impulsive (e.g., do not exhibit a rapid sound pressure rise time and decay). A notable exception is during blasting activities when rock and other hard substrata need to be removed in ship channels to ensure navigation safety. Dredging sounds are comparatively lower intensities in contrast to other activities (e.g., explosions, pile driving, seismic airguns, echosounders, and large ships). It should be noted that the acoustical characteristics are often summarized as single maximum recorded values near the sound source (i.e., 1 m from source). Additionally, a single sound event (e.g., propeller cavitation) can skew the calculated SPLs (RMS) and may not provide an accurate representation of the sounds being generated by a dredging operation.

Based on the results of the review of existing effects data, direct mechanical injury and mortality in aquatic species following underwater sound exposures are limited to high intensity impulsive sounds (e.g., explosions, pile-driving). The currently available effects data from anthropogenic sources indicate that dredging induced sounds do not pose a significant risk to direct injury or mortality to aquatic biota. In terms of potential non-lethal responses, low-frequency sounds produced by dredging overlap with the hearing frequency ranges of select fish and mammal species, which may pose risk for auditory temporary threshold shifts, auditory masking, and behavioral responses. Overall, there has been significant progress in the understanding of the characteristics of dredge related sounds in the last couple of decades. Although there are gaps of exposure-response data for dredging-induced sounds, in general there is no direct evidence of lethal effects to aquatic biota and limited observations of non-lethal effects (e.g., behavioral responses).

To improve understanding of the ecological risks associated with dredging sounds, a risk based approach is needed that maximizes the data and other site-specific information to evaluate the underwater sound of concern. Additional study is needed to improve our understanding of whether the updated thresholds developed by NOAA indicate potential risks during dredging rock-blasting activities and whether the thresholds are relevant to dredging in coastal waterways. Overall, the information reported herein regarding underwater sound produced by dredging can be used in an exposure assessment as part of a broader framework for assessing and managing underwater sound effects on aquatic life.

## REFERENCES

Boyd, I.L., Brownell, B., Cato, D.H., Clarke, C., Costa, D., Evans, P., Gedamke, J., Gentry, R. and Gisiner, B., (2008). “The effects of anthropogenic sound on marine mammals: a draft research strategy.” *ESF Marine Board Position Paper 13. European Science Foundation, Marine Board*. Oostende, Belgium. ISBN 2-912049-85-7.

Brandt, M.J., Diederichs, A., Betke, K., Nehls, G. (2011). “Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea.” *Mar Ecol Prog Ser* 421, 205-216

CEDA (2011). CEDA Position Paper: “Underwater Sound in Relation to Dredging.” *Terra et Aqua*, 125, 23–28.

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch, L., Van Parijs, S.M., Frankel, A., Ponirakis, D. (2009). “Acoustic masking in marine ecosystems: intuitions, analysis, and implication”. *Marine Ecology Progress Series*. 395, 201-222.

Clarke, D., C. Dickerson, and K. Reine. (2002). “Characterization of underwater sounds produced by dredges.” In *Dredging 2002*, *American Society of Civil Engineers, Orlando, Florida, USA*, 64-81.

Codarin, A., L. E. Wysocki, F. Ladich, and M. Picciulin. (2009). “Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy).” *Marine Pollution Bulletin* 58, 1880-1887.

Department for Environment, Food and Rural Affairs (DEFRA) (2003). “Preliminary investigation of the sensitivity of fish to sound generated by aggregate dredging and marine construction.” *Project AE0914 Final Report*.

Dickerson, C., Reine, K.J., Clarke, D.G. (2001). “Characterization of underwater sounds produced by bucket dredging operations.” *DOER Technical Notes Collection ERDC TN-DOER-E14*. Vicksburg, MS: US Army Engineer Research and Development Center.

Diederichs A., Brandt M., Nehls G. (2010). “Does sand extraction near Sylt affect harbour porpoises?” *Wadden Sea Ecosystem* 26, 199-203.

Erbe, C. (2011). *Noise and the Effects on Marine Mammals: A Pocket Handbook*. 3rd Edition. JASCO Applied Sciences.

Erbe, C., Ainslie, M.A., de Jong, C.A., Racca, R., Stocker, M. (2016). “Summary Report Panel 1: The need to protocols and standards in research on underwater noise impacts on marine life.” In *The Effects of Noise on Aquatic Life II* (pp. 1265). Springer New York.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A., Ridgway, S. H. (2002). “Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun.” *Journal of the Acoustical Society of America*, 111(6), 2929–2940.

Foote, A.D., Osborne, R.W., Rus Hoelzel, A. (2004). “Whale-call response to masking boat noise.” *Nature* (London), 428, 910.

Gerstein, E. R., Blue, J. E., Pinto, G. F., and Barr, S. (2006). “Underwater noise and zones of masking with respect to hopper dredging and manatees in the St. Johns River in Jacksonville.” *Journal of the Acoustical Society of America*, 120, 3145–3222.

Gilmartin,W. G. (2003). “Responses of Hawaiian monk seals to human disturbance and handling.” In *Workshop on the Management of Hawaiian Monk Seals on Beaches in the Main Hawaiian Islands*, p. 8. Marine Mammal Commission, National Marine Fisheries Service, Hawaii Division of Aquatic Resources, Kauai, Hawaii

Hawkins, A.D. (2008). “Effects of noise on aquatic life: The key issues.” *Bioacoustics* (special issue). 17, 7-12.

Hawkins, A.D., and Popper, A.N. (2016). “Developing Sound Exposure Criteria for Fishes”. In *The Effects of Noise on Aquatic Life II* (pp. 431). Springer New York.

Hawkins, A.D., and Popper, A.N. (2017). “A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates”. *ICES Journal of Marine Science*. 74 (3), 635-651.

Hawkins, A. D., Pembroke, A. E., Popper, A. N. (2015). “Information gaps in understanding the effects of noise on fishes and invertebrates.” *Reviews in Fish Biology and Fisheries*, 25(1), 39-64.

Heinis, F., deJong, C., Ainslie, M., Borst, W., Vellinga, T. (2013). “Monitoring programme for the Maasvlakte 2, Part III - The effects of underwater sound.” *Terra et Aqua* 132, 21-32.

Hoffman, C. (2010). “Mitigating impacts of underwater noise from dredging on beluga whales in Cook Inlet, Alaska.” In *2nd International Conference on the Effects of Noise on Aquatic Marine Life*, p. 5. Cork, Ireland.

Kastelein, R.A., Gransier, R., Hoek, L. (2012). “Temporary theshold shifts and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4 kHz.” *Journal of the Acoustical Society of America* 132, 3525-3537

Kastelein, R.A., Gransier, R., Hoek, L. (2013a). “Comparative temporary theshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal (L).” *Journal of the Acoustical Society of America* 134, 13-17

Kastelein, R.A. Gransier, R., Hoek, L., Rambags, M. (2013b). “Hearing frequency thresholds of harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz tone.” *Journal of the Acoustical Society of America* 134, 2286-2292.

Kats, A.M. (2009). “Underwater noise in the North Sea – Effects on marine life and possible mitigation measures.” Internship Aquatic Ecology and Water Quality Management Report number P421. Wageningen University Msc. Management of Marine Ecosystems Profile Marine Ecology.

Ketten D.R., Cramer S., Arruda J. (2005). “Experimental measures of blast trauma in sea turtles.” *Symposium on Environmental Consequences of Underwater Sound*, Office of Naval Research, Arlington, VA

National Marine Fisheries Service (NMFS). (2016). “Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts.” p.178. Ed. by Resources O.O.P. U.S. Department of Commerce, Silver Spring, MD.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D., Merchant, N.D. (2016). “Particle motion: the missing link in underwater acoustic ecology.” *Methods in Ecology and Evolution* 7, 836-842.

Nedwell, J.R., Parvin, S.J., Brooker, A.G., Lambert, D.R. (2008). “Modelling and measurement of underwater noise associated with the proposed Port of Southampton capital dredge and redevelopment of berths 201/202 and assessment of the disturbance to salmon.” *Subacoustech Report, 805R0444*.

Neenan, S.T., Piper, R., White, P. R., Kemp, P., Leighton, T.G., Shaw, P.J. (2016). “Does Masking Matter? Shipping Noise and Fish Vocalizations.” In *The Effects of Noise on Aquatic Life II* (pp. 747). Springer New York.

Normandeau Associates, Inc. (2012). "Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities." *A Workshop Report for the U.S. Dept. of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031.* 72 pp. plus Appendices.

Oestman, R., Buehler, D., Reyff, J.A. Rodkin, R. (2009). "Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish." Prepared for California Department of Transportation. http://www.dot.ca.gov/hq/env/bio/files/bio_tech_guidance_hydroacoustic_effects_110215.pdf (last accessed 25 April 2017).

Offutt, G.C. (1974). "Structures for the detection of acoustic stimuli in the Atlantic codfish, *Gadus morhua*." *Journal of the Acoustical Society of America* 56, 665-671.

OSPAR (2009a). "Overview of the Impacts of Anthropogenic Underwater Sound in the Marine Environment." *OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic*. www.ospar.org.

OSPAR (2009b). "Assessment of the Environmental Impacts of Underwater Noise." *OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic*. www.ospar.org.

Parmentier, E., Mann, K., Mann, D. (2011). "Hearing and morphological specializations of the mojarra (*Eucinostomus argenteus*)." *Journal of Experimental Biology* 24, 2697-2701.

Pirotta, E., Laesser, B.E., Hardaker, A., Riddoch, N., Marcoux, M., Lusseau, D. (2013). "Dredging displaces bottlenose dolphins from an urbanised foraging patch." *Marine Pollution Bulletin*, 74, 396–402.

Popper, A.N. (2003). "Effects of anthropogenic sounds on fishes." *Fisheries*, 28 (10), 24-31.

Popper, A.N., and Hawkins, A.D. (Eds.). (2016). *The Effects of Noise on Aquatic Life II*. Springer, New York, New York.

Popper, A.N., and Hastings, M.C. (2009). "The effects of anthropogenic sources of sound on fishes". *Journal of Fish Biology* 75, 455-489.

Popper, A.N. Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Løkkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G., Tavolga, W.N. (2014). "Sound Exposure Guidelines for Fishes and Sea Turtles." *Springer Briefs in Oceanography ASA S3/SC1.4 TR-2014*, Springer.

Reine, K.J., Dickerson, D.D., Clarke, D.G. (1998). "Environmental windows associated with dredging operations." *DOER Technical Notes Collection TN DOER-E2.* U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer.*

Reine, K.J., Clarke D.G., Dickerson C. (2012a). "Characterization of underwater sounds produced by a backhoe dredge excavating rock and gravel." *DOER technical notes collection ERDC TN-DOER-E36*, US Army Engineer Research and Development Center, Vicksburg, MS.

Reine, K.J., Clarke D.G., Dickerson C. (2012b). "Characterization of underwater sounds produced by a hydraulic cutterhead dredge fracturing limestone rock." *DOER technical notes collection ERDC TN-DOER-E34*, US Army Engineer Research and Development Center, Vicksburg, MS.

Reine, K.J., Clarke D.G., Dickerson C. (2014a). "Characterization of underwater sounds produced by hydraulic and mechanical dredging operations." *J. Acoust. Soc. Am*. 135(5), 3280-3294.

Reine, K.J., Clarke D.G., Dickerson C., Wikel, G. (2014b). "Characterization of underwater sounds produced by trailing suction hopper dredges during sand mining and pump-out operations." *ERDC/EL TR-14-3*, US Army Engineer Research and Development Center, Vicksburg, MS.

Reine, K.J., and Dickerson C. (2014). "Characterization of underwater sounds produced by a hydraulic cutterhead dredge during maintenance dredging in the Stockton Deepwater Shipping Channel, California." *DOER technical notes collection ERDC TN-DOER-E38*, US Army Engineer Research and Development Center, Vicksburg, MS.

Richardson, W.J., Würsig, B., Greene, C.R., Jr. (1990). "Reactions of bowhead whales, *Balaena mysticetus*, to drilling and dredging noise in the Canadian Beaufort Sea." *Marine Environmental Research*, 29, 135-160.

Richardson, J.W., Greene, C.R., Malme, C.I., Thomson, D.H. (1995). *Marine mammals and noise*. Academic Press. 576 p.

Slabbekoorn, H. (2016). "Aiming for progress in understanding underwater noise impact on fish: Complementary need for indoor and outdoor studies." In *The Effects of Noise on Aquatic Life II* (pp. 1057). Springer New York.

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

Thomsen, F., Borsani, F., Clarke, D., de Jong, C., de Wit, P., Goethals, F., Holtkamp, M., San Martin, E., Spadaro, P., van Raalte, G., Victor, G.Y.V. (2016). "WODA Technical Guidance on Underwater Sound from Dredging." In *The Effects of Noise on Aquatic Life II* Springer New York. (pp. 1161).

Todd, V.L.G., Todd, I.B., Gardiner, J.C., Morrin, E.C.N., MacPherson, N.A., DiMarzio, N.A., Thomsen, F. (2015). "A review of impacts of marine dredging activities on marine mammals." *ICES Journal of Marine Science*. 72, 328–340.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., Rasmussen, P. (2009). "Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena*, (L.))." *J Acoustic Soc Am* 126, 11-14

Tyack P.L., Zimmer, W.M.X, Moretti, D., Southall, B.L., Claridge, D.E., Durban, J.W., Clark, C.W., D'Amico, A., DiMarzio, N., Jarvis, S., McCarthy, E., Morrissey, R., Ward, J., Boyd, I.L. (2011). "Beaked Whales Respond to Simulated and Actual Navy Sonar." *PLOS ONE* 6(3)

Williams, R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., Clark, C.W., Cullis-Suzuki, S., Daking, D.T., Erbe, C., Hammond, P.S., Merchant, N.D., O'Hara, P.D., Purserm J., Radford, A.N., Simpson, S.D., Thomas, L., Wale, M.A. (2015). "Impacts of anthropogenic noise on marine life: publication patterns, new discoveries, and future directions in research and management." *Ocean & Coastal Management*, *115*, 17-24.

Willis, K.L. (2016.) "Underwater hearing in turtles." In: *The Effects of Noise on Aquatic Life II* (pp. 1057). Springer New York.

World Organization of Dredging Association (WODA). (2013). "Technical guidance on underwater sound in relation to dredging." *World Organization of Dredging Associations*, Delft, The Netherlands.

Yan, H.Y. (2001). "A non-invasive electrophysiological study on the enhancement of hearing ability in fishes." *Proceedings of the Royal Society B.: Biological Sciences* 23, 15-26.

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