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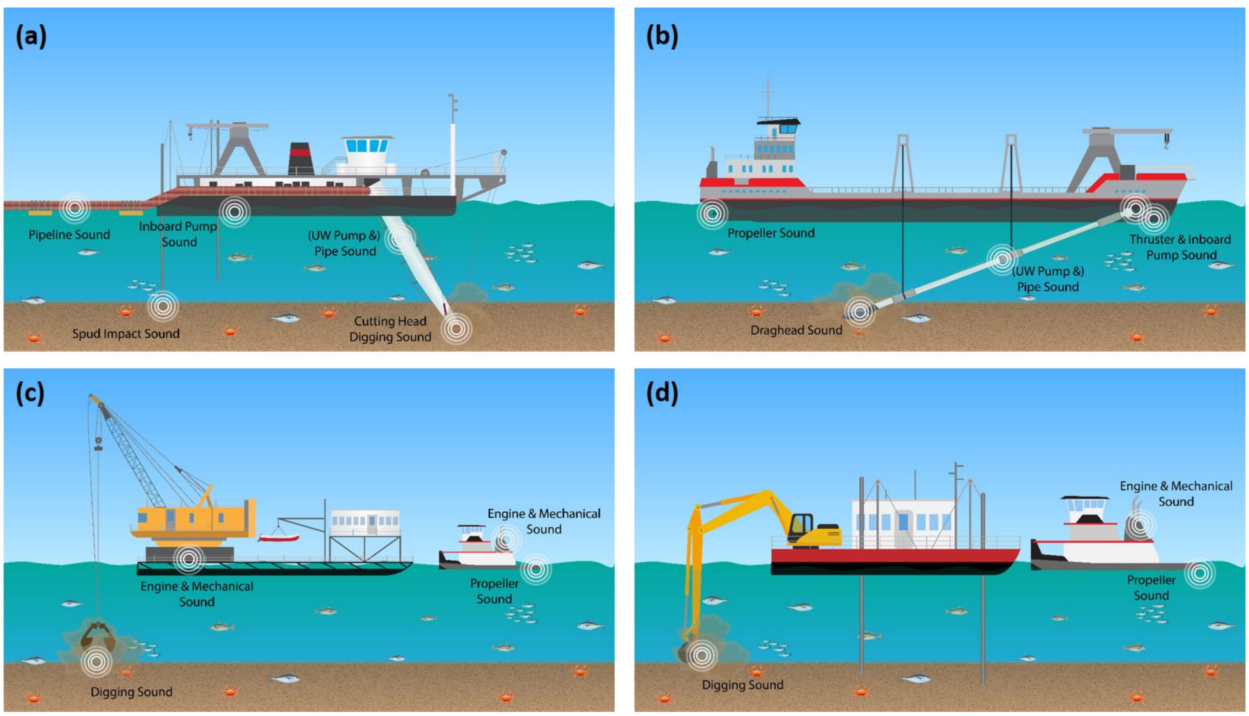

Potential sound sources associated with common dredge types.

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IN THIS ISSUE

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REVIEW OF THE ADVERSE 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 bottom sediments. The objective of this research was to conduct a focused literature review to identify and document adverse biological effects of underwater sound from dredging and other anthropogenic sources to discern potential ecological risks of dredging activities. 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. Based on the observations of dredge-induced sound effects on marine mammals, the available data indicate that dredging 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. To improve understanding of the ecological risks associated with dredging sounds, a risk-based approach is needed that maximizes the available data and other site-specific information to evaluate the underwater sound of concern.

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

INTRODUCTION

Underwater sounds are important sensory functions for many marine organisms and are used for a variety of purposes, including communication, orientation, predator avoidance, and foraging (Popper 2003; Hawkins 2008; OSPAR 2009a,b). As our understanding of the underwater soundscape advances, there is increased scrutiny regarding the input and biological consequences of anthropogenic sources. Low-frequency, non-impulsive sounds can originate from construction of marine infrastructure and industrial activities such as drilling, subsea mining, vessel movements, and dredging (Suedel et al. 2018). Underwater sounds can have a variety of adverse effects on

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aquatic life, ranging from subtle to strong behavioral reactions, even death. However, mortality of aquatic biota is generally limited to high intensity impulsive sounds (e.g., explosions). In terms of non-impulsive sounds, documented sub-lethal effects include auditory threshold shifts, masking (diminished ability to detect relevant sounds), startle response, habituation, attraction to or avoidance of the sound source, altered swimming behavior and habitat avoidance (e.g., feeding or spawning grounds) (OSPAR 2009a; Erbe 2011; Hawkins and Popper 2016).

In efforts to understand the potential biological effects associated with underwater sounds, it is vital to develop an understanding of the sound characteristics (exposures) to predict the biological consequences (responses). Research on the effects of underwater sound on aquatic life has been conducted for several decades, but there are still many uncertainties, especially with regards to the effect of sound from dredging activities. Important data gaps include the impacts of dredging-induced sound (e.g., excavation, transit, and placement) on aquatic biota and the potential impacts of dredging-induced sound in the context of other anthropogenic sources.

Objective

The objective of this study is to perform a focused literature review of the available underwater sound information related to dredging to develop an improved understanding of dredge-induced sound effects on aquatic life. To achieve this overall objective, the specific tasks were to: 1) document sound characteristics (i.e., sound pressure levels and frequencies) emanating from dredge operations, 2) document biological effects associated with dredge-specific sound exposures, and 3) summarize available non-impulsive sound exposure guidelines. This information will provide resources to dredging contractors, risk managers, regulators, and stakeholders to more appropriately manage dredging operations when underwater sound is a concern.

APPROACH

To address the stated objective, a review of peer-reviewed literature and grey literature (government, non-governmental organizations, and industry reports) investigating underwater sound effects on aquatic life was conducted. Studies reporting underwater sounds emanating from operating dredges have only been conducted since early part of the 21st century and include the following sources:

- 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 (OSPAR 2009a,b; CEDA 2011; WODA 2013).
- 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 U.S. Army Corps of Engineers (USACE) published a series of reports on the underwater sounds produced by various dredge types operating in near shore and offshore environments.

- 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.
- Field studies were performed by various investigators when the Port of Rotterdam was expanded in The Netherlands (Heinis et al. 2013).

There have also 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. Papers presented at previous conferences were published as extended abstracts in a variety of forums, including: 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, another book entitled “The Effects of Noise on Aquatic Life II” (Popper and Hawkins 2016).

In addition, a publicly available library database for research related to underwater sound is supported by the 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.

Underwater Sound Measurements and Metrics

Sound measurement devices (e.g., hydrophones) are used for accurate acoustic measurements in the area around a dredge sound source. The unit of sound pressure levels (SPLs) in decibels (dB) is commonly used to quantify underwater sounds. In addition to pressure, the frequency (described in units of Hertz [Hz]) is a characteristic of the wavelength that is important as it relates to the detectable (audible) frequencies detected by aquatic species. Frequency of sounds can be analyzed by separating sound pressures in 1 Hz intervals or separating the octaves into three parts (or bands), or 1/3 octave band. More detailed information about the fundamentals of underwater sound metrics and measurement techniques are available from multiple sources (e.g., Richardson et al. 1995; OSPAR 2009a,b; Nedelec et al. 2016; NMFS 2016; ISO 2017).

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 diversity of methods for measuring biological responses (Thomsen et al. 2016; Erbe et al. 2016). Additionally, it is crucial to understand the differences between sound source levels and organism received levels. For example, sound exposure level (SEL) is commonly used as a cumulative metric to describe the total received level by an organism from a sound event over a duration of time (e.g., 24 hours).

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 sediment placement (CEDA 2011). Dredging produces sounds that are non-impulsive, continuous, discontinuous, and/or cyclic in nature. The sounds generated by dredging vary by the type of dredge being used. The two main categories of dredges are hydraulic and mechanical dredges (Figure 1).

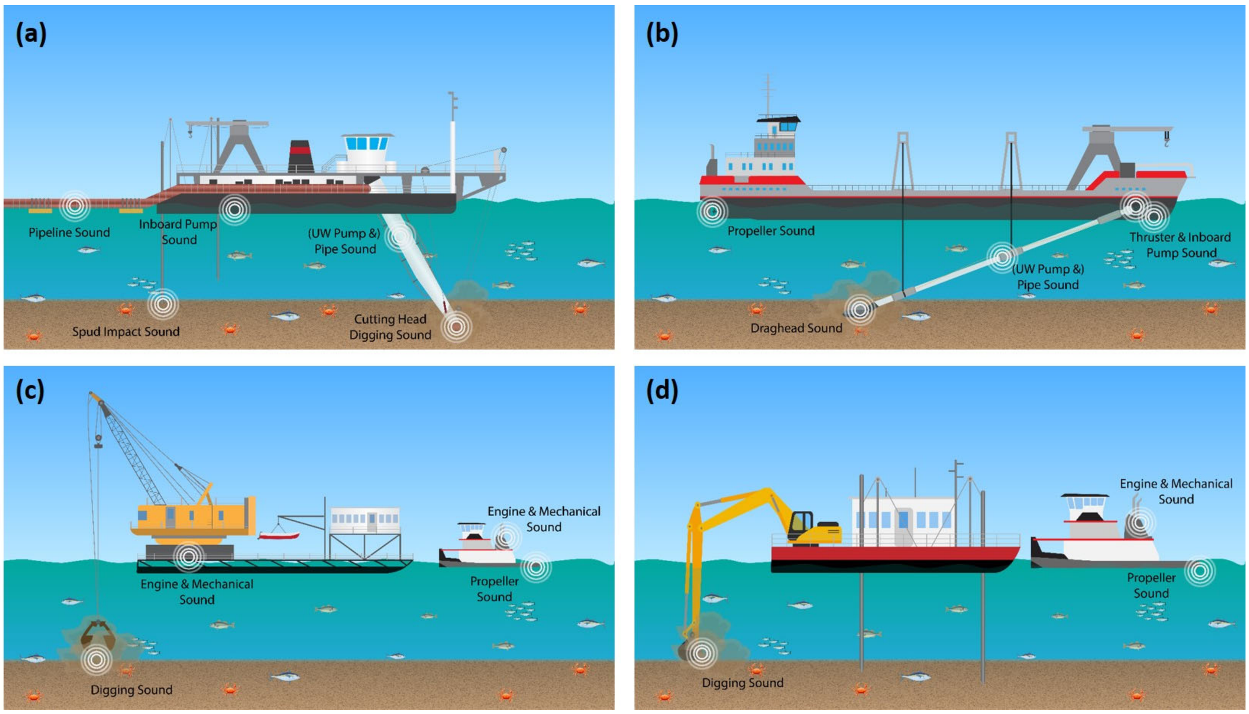

Figure 1. Examples of hydraulic (top) and mechanical (bottom) dredge types and potential sound sources (adapted from CEDA 2011). (a) cutter suction dredge (CSD); (b) trailing suction hopper dredge (TSHD); (c) grab dredge (GD); and (d) backhoe dredge (BHD)

Hydraulic Dredging

Hydraulic dredges work by sucking a mixture of sediment and water from the bottom substrate. The two main types of hydraulic dredges are cutter suction dredges and trailing suction hopper dredges (CEDA 2011; WODA 2013). Cutter suction dredges (CSD) use pumps to suck material through an intake pipe and is discharged through pipeline 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 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 place sediment directly into a transport barge or a placement site, the operations are usually continuous (i.e., 24 hours, 7 days a week) until the project is completed. Primary sources of continuous CSD sounds include:

1) dredged 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 discharging 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 dredging activities depends on the depth of cutterhead insertion, type of material being excavated, and width of the navigation channel (Reine et al. 2012a). Overall based on the literature review, SPLs occurring at the source (at 1 m) of CSDs range from 168 to 175 dB re 1µPa at 1 m (Table 1).

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 placement site where the sediment is discharged from the bottom of the ship, or discharged through a 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 sounds with additional sounds emitted by pumps and generators. Overall based on the literature review, source SPLs of TSHDs range from 172 to 190 dB re 1µPa at 1 m (Table 1).

Mechanical Dredging

Mechanical dredges excavate 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, 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 operation-based sound 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 based on the literature review, SPLs of GDs range from 107 to 124 dB re 1µPa at 154 m (Table 1).

Table 1. Reported underwater SPLs by dredging type.

Dredge Type	Vessel Name	Installed Power (kW)	Dredger Size Indicator	Sound Pressure Level	Reference
CSD	Beaver Mackenzie	1,100-1,300	Transfer rate: 100,000 m^3/day	168 dB re 1 µPA-m (80 Hz)[a]	Greene 1987
CSD	Aquarius	12,889	Transfer rate: 100,000 m^3/day	178 dB re 1 µPA-m (125 Hz)[a]	Greene 1987
CSD	Florida	25,400	10,000 hp with a 130" cutter	175 dB re 1 µPa-m	Reine et al. 2012a,b
TSHD	Cornelis Zanen	12,064	Capacity 8,000 m^3	142 dB (at 930 m)	Greene 1987
TSHD	Geophotes X (Inai Selasih)	15,384	Capacity 8,000 m^3	139 dB (at 430 m)	Greene 1987
TSHD	W.D. Gateway	13,870	Capacity 12,000 m^3	131 dB (at 1.5 km)	Greene 1987
TSHD	Columbia	2,800	-	177 dB re 1 µPa-m	Gerstein et al. 2006
TSHD	The City of Westminster	2 x 1,950	Capacity 2,700 m^3	186 dB re 1 µPa-m	Parvin et al. 2007
TSHD	-	-	-	190 dB re 1 µPa-m	Nedwell et al. 2008
TSHD	Dredger #1	8,000-30,000	Capacity 3,000-20,000 m^3	186 dB re 1 µPa-m (45 Hz)[a]	de Jong et al. 2010
TSHD	Dredger #2	8,000-30,000	Capacity 3,000-20,000 m^3	176 dB re 1 µPa-m (500 Hz)[a]	de Jong et al. 2010
TSHD	Dredger #3	8,000-30,000	Capacity 3,000-20,000 m^3	174 dB re 1 µPa-m (350 Hz)[a]	de Jong et al. 2010
TSHD	Dredger #4	8,000-30,000	Capacity 3,000-20,000 m^3	177 dB re 1 µPa-m (300 Hz)[a]	de Jong et al. 2010
TSHD	Dredger #6	8,000-30,000	Capacity 3,000-20,000 m^3	172 dB re 1 µPa-m (63 Hz)[a]	de Jong et al. 2010
TSHD	Dredger #7	8,000-30,000	Capacity 3,000-20,000 m^3	173 dB re 1 µPa-m (45 Hz)[a]	de Jong et al. 2010
TSHD	Liberty Island	12,353	Capacity 5,003 m^3	179 dB re 1 µPa-m	Reine et al. 2014a
TSHD	Dodge Island	6,972	Capacity 2,754 m^3	175 dB re 1 µPa-m	Reine et al. 2014a
TSHD	Padre Island	7,006	Capacity 2,754 m^3	173 dB re 1 µPa-m	Reine et al. 2014a
TSHD	Atchafalaya	2,209	Capacity 2,300 m^3	173 dB re 1 µPa-m	Reine et al. 2014a
GD	Viking	1,500	10 m^3 bucket	124 dB re 1 µPa (162.8 Hz, at 158 m)	Dickerson et al. 2001
GD	Crystal Gayle	-	-	107 dB re 1 µPa-m (91.5 Hz)	Dickerson et al. 2001
BHD	Manu Pekka	1,515	14m^3 bucket	163 dB re 1 µPa-m	Nedwell et al. 2008
BHD	New York	3,434	18 m^3 bucket	179 dB re 1 µPa-m	Reine et al. 2012a,b

(CSD) Cutter suction dredge
(TSHD) Trailing suction hopper dredge
(GD) Grab dredge
(BHD) Backhoe dredge

[a] 1/3rd octave band

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 is often 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. Sounds 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 based on the literature review, source SPLs of BHDs range from 163 to 179 dB re 1µPa at 1 m (Table 1).

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/ placement, depositing of dredge material in a scow or hopper, and bucket closing on the channel bottom. Overall, source level SPLs associated with dredging operations were found in the existing literature to 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 found in the existing literature from dredging activities are similar to levels reported for underwater sound associated with commercial shipping (Figure 2). 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. Based on these factors, the dredging SPLs reported herein (i.e., Figure 2 and Table 1) are considered conservative.

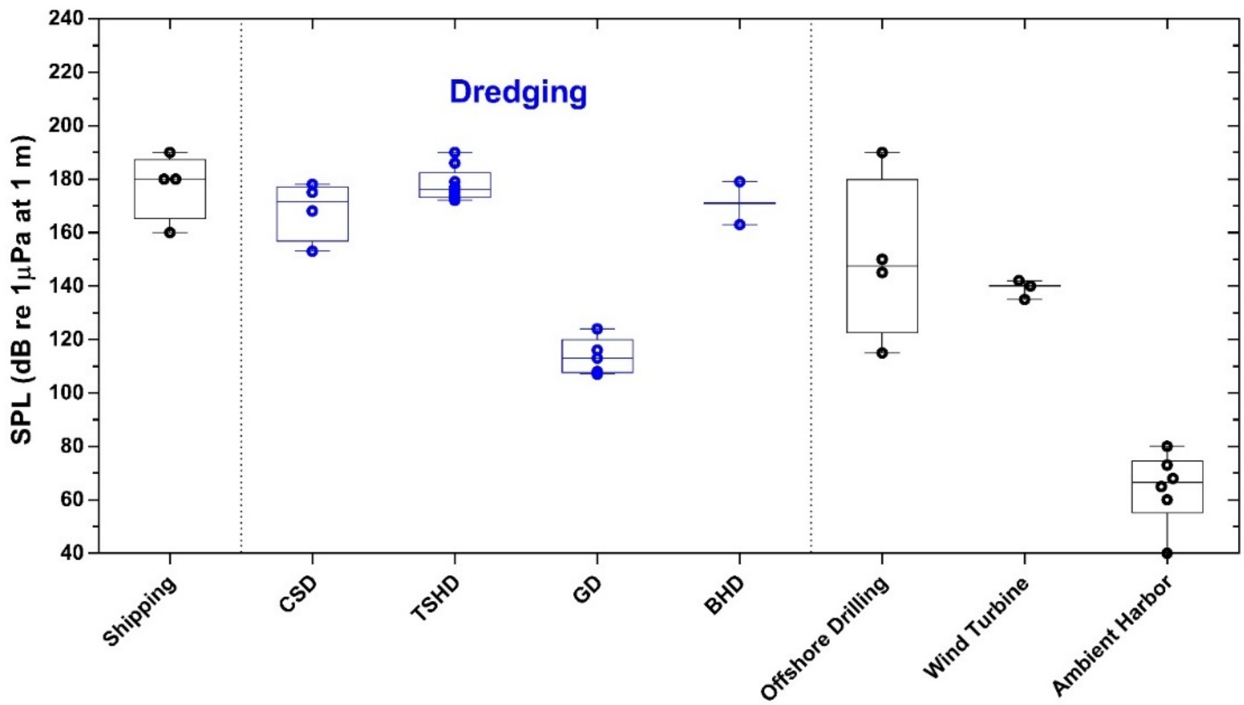

Figure 2. Summary of non-impulsive underwater SPLs by sound source. Dredge-induced sounds (blue) include: cutter suction dredge (CSD); trailing suction hopper dredge (TSHD); grab dredge (GD [recorded 158 m from source]); and backhoe dredge (BHD). References: shipping (OSPAR 2009a; Reine et al. 2014b; Merchant et al. 2016); offshore drilling (Richardson et al. 1995; OSPAR 2009a); wind turbines (OSPAR 2009a); ambient harbor (Wenz 1962; Reine et al. 2014b; Merchant et al. 2016).

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 (early 21st century) has the field of study developed to investigate the potential effects of underwater sound generated from industrial activities on 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 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. 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).

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). For example, both the intensity (pressure) and waveform (non-impulsive) of sounds produced by dredges are notably different as compared to higher intensity impulsive sounds (e.g., underwater blasting, air guns, pile-driving) which have been documented to cause tissue injury and mortality. 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 3). Therefore, the available literature evaluating biological effects from dredge sounds are appropriately focused on auditory effects, masking, and behavioral responses.

Underwater Sound Effects on Marine Mammals

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. Only a few studies were found that 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). 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 returned to the areas after the dredging activity ceased (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 vessel sounds (Gerstein et al. 2006). Based on the reviewed marine mammal effects data available for dredge-specific sounds, no adverse auditory impacts were observed, and biological responses were limited to avoidance and potential masking (Table 2).

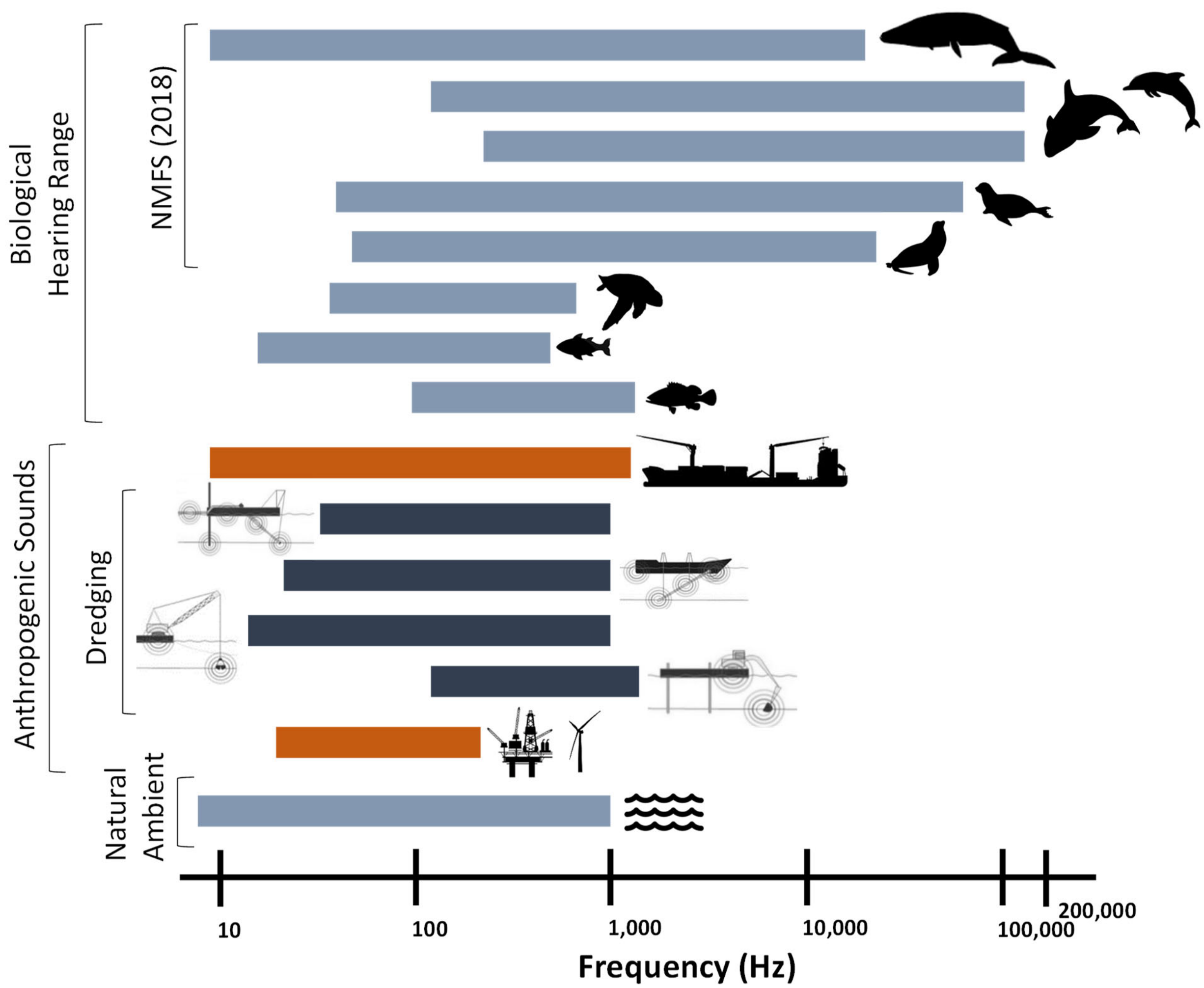

Figure 3. Hearing frequency ranges of selected fish and mammal species and main energy frequencies reported for anthropogenic and ambient sources (from Suedel et al. 2018 and data presented herein).

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 to 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 1 µPa^2·s 24-hour exposure)	0.5 to 10	Modeled seal behavior (AQUARIUS)	did not exceed TTS risk threshold[a]	Heinis et al. 2013
	180 (SEL dB re 1 µPa^2·s 24-hour 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)

Underwater Sound Effects on Fish

The published literature on the effects of underwater sound on fish is notably less extensive than that for marine mammals (William et al. 2015). In general, fish have a lower sound frequency detection range as compared to marine mammals. Fish can detect frequencies ranging 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 audiograms of hearing thresholds have been developed; these studies indicate overlap with shipping vessel frequencies (Neenan et al. 2016; Figure 3). Although only a small percentage (<1%) of the total fish species (>30,000) have been subject to 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 in fish (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 metric describing anthropogenic sounds, but it is likely to become an important component for evaluating effects to fish in the future (Hawkins and Popper 2017).

To date, the authors are unaware of any studies that have directly measured effects of underwater dredging sounds on fish species. A few studies have estimated effects on fish by comparing sounds from dredging operations to literature-derived auditory threshold or behavioral effects data (Table 3). 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, air guns). 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 3). In terms of adverse effects to smaller bodied fish, Heninis et al. (2013) compared the measured underwater acoustics of dredging and shipping sounds to fish TTS criteria developed by US Fish Hydroacoustic Working Group (Oestman et al. 2009) for pile-driving noises. Although behavioral effects of fish were not directly measured, Heinis et al. (2013) estimated based on a "worst case" scenario that smaller bodied fish (<2 g) were at risk within the immediate vicinity of the sound source (<20 m; Table 3).

Underwater Sound Effects on Sea Turtles

Significant data gaps exist in terms of sea turtle responses to underwater sound, and there are no studies that the authors are aware of that specifically investigated dredge-specific (non- impulsive) sounds. Willis (2016) reports that the vocalizations and best hearing frequencies for turtles are around 300-500 Hz. Only a few species have 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 non-impulsive sounds (Ketten et al. 2005; Popper et al. 2014). There is no direct evidence of mortality or injury of turtles to shipping sounds (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.

Table 3. 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 1 $\mu Pa^2 \cdot s$; 24-hour exposure)	0.5 to 10	ND (modeled fish exposure)	No TTS risk fish >2 g; Exceeded TTS risk threshold for fish <2 g[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 1$\mu Pa^2 \cdot s$; fish >2 g = 187 dB re 1$\mu Pa^2 \cdot s$; (Oestman et al. 2009)

REVIEW OF UNDERWATER SOUND EXPOSURE GUIDELINES

Guidelines for Marine Mammals

Recently updated technical guidelines have been developed by the NOAA National Marine Fisheries Service (NMFS) that proposed acoustic exposure criteria for select marine mammals (NMFS 2016; NMFS 2018a). Prior to this document, NMFS relied on generic acoustic threshold studies to assess the auditory impacts on marine mammals. In the 1990s, the PTS for cetaceans was set at RMS SPL 180 dB and RMS SPL 190 dB for pinnipeds (e.g., NOAA 1998; HESS 1999). Due to lack of sound effects data at the time, NMFS set conservative and generic thresholds as single points of reference which could not account for the varied noise sources and hearing sensitivities of marine mammals. Since then, more comprehensive data sets for underwater sound effects on marine mammal have become available (Southall et al. 2007; Finneran 2015; Erbe et al. 2016). The resulting information required a new comprehensive study of the current state of the science and the acoustic thresholds that were deemed sufficient to develop revised technical guidance.

The NMFS's 2018 technical guidance is a comprehensive review and study of peer-reviewed literature and government reports on the impacts of underwater sound on marine mammals. The technical guidance relied heavily upon the Finneran (2016) technical report "Auditory Weighting Functions and TTS/PTS Exposure Functions for Marine Mammals Exposed to Underwater Noise" which updated the underwater acoustic thresholds for TTS and PTS in marine mammals only. From the Finneran (2016) study, the NMFS updated the acoustic thresholds to a new standard to estimate PTS onset from all sound sources and used it to determine estimates for TTS from underwater impulsive and non-impulsive sounds. The NMFS 2018 acoustic thresholds are more complex than previous thresholds, but are more representative of the current scientific knowledge in regard to marine mammal hearing thresholds and potential responses to underwater sounds (Table 4).

Because of differences between the new weighting factors and single reference point values, the NMFS acknowledges that the approach provided makes general or direct comparisons between the updated acoustic thresholds and previous thresholds difficult. Also, NMFS acknowledges the new marine mammal weighting functions and SEL metrics may be difficult to implement in practice. For this reason, NMFS developed a set of tools to incorporate these new metrics (this is addressed in Appendix D of the technical guidance (NMFS 2018a) and User Spreadsheet (NMFS 2018b); both of which can be found at http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm).

The technical guidance is not meant to represent the entirety of an effects analysis, but rather provide an additional tool to evaluate the adverse effects of underwater sound for marine mammals (NMFS 2018). NMFS recommends its use to aid in discerning adverse effects, but note that user groups/stakeholders are not required to use the Technical Guidance, as other scientifically rigorous methods were also deemed acceptable.

Table 4. Summary of marine mammal groups and estimated TTS and PTS thresholds for non-impulsive sounds. SEL thresholds are in dB re 1 µPa²s (from NMFS 2018a Technical Memorandum Appendix A). Note: SELs are not directly comparable to SPLs.

Marine Mammal Group	Non-impulsive Sounds	
	TTS Threshold	PTS Threshold
	SEL	SEL
Low-frequency cetaceans	179	199
Mid-frequency cetaceans	178	198
High-frequency cetaceans	153	173
Sirenians	186	206
Otariids	199	219
Phocids	181	201

Guidelines for Fish

For non-impulsive sounds, there are relatively limited resources that estimate acoustic exposure thresholds for fish species. To date, the most comprehensive resource for sound exposure guidelines for fish is the American National Standards Institute (ANSI) technical report "Sound

Exposure Guidelines for Fishes and Sea Turtles" (Popper et al. 2014). Popper et al. (2014) provides qualitative and quantitative guidelines for lethal and sub-lethal endpoints for non-impulsive sounds (i.e., commercial shipping and continuous sounds) (Table 5). Two pertinent studies used in the development of the ANSI quantitative endpoints (Smith et al. [2006] and Amoser and Ladich [2003]) are discussed below.

Smith et al. (2006) investigated the regenerative capabilities of the inner ear of fish following exposures to sound. The study measured the relationship between hair cell damage and physiological changes in auditory responses following noise exposures. Smith et al. (2006) exposed goldfish (*Carassius auratus*; hearing specialist) to "white noise" at 170 dB re 1 µPa RMS for 48 hours in a bandwidth ranging from 0.1 kHz to 10 kHz in laboratory experiments. Following exposures, fish had a mean TTS of 16 dB averaged across all frequencies in addition to statistically significant hair cell loss as compared to untreated control. Following sound exposures, fish were allowed to recover for 1 week. During the recovery period both hair cell regrowth and TTS were observed to recover to baseline. Hair cells regenerated at a linear rate following noise exposures. Hair cell loss was 85% immediately following sound exposures. After 7 days of recovery, hair cell loss decreased to about 47%. With hair cell regeneration, functional hearing also increased (i.e., TTS decreased). TTS decreased from 16 dB (immediately following exposures) to 4 dB at 7-day exposure (Smith et al. 2006). This study demonstrated the onset of inner ear damage to noise exposures and the regenerative responses of the hair cells and functional hearing during the recovery period.

Amoser and Ladich (2003) measured auditory shifts of two hearing specialists (goldfish [*Carassius auratus*] and catfish [*Pimelodus pictus*]) exposed to broadband "white noise" measurements in laboratory experiments. To discern potential effects of sound duration to the onset of hearing loss, the study was conducted using 12- and 24-hour exposure durations. Hearing effects were determined using auditory brainstem responses (ABR) and recovery was measured after 3, 7, and 14 days. Following exposures to broadband white noise at SPLs of 158 dB re 1 µPa, a significant loss of hearing was observed for both species with a loss of up to 26 dB in goldfish and 32 dB in catfish. The duration of sound exposure had no apparent effect on extent of hearing loss, with no differences in hearing sensitivity following 12- and 24-hour exposure durations. Both fish species recovered from hearing loss post-exposures, with recovery occurring within three days for goldfish and 14 days for catfish (Amoser and Ladich 2003).

Guidelines for Sea Turtles

To date, the authors are unaware of any dredging-relevant underwater sound threshold effects data reported for sea turtles. Popper et al. (2014) determined that there is insufficient data for evaluating thresholds for sea turtles.

Table 5. Shipping and continuous sounds qualitative and quantitative (grey shading) exposure guidelines for fish (reported in Popper et al. 2014).

Fish Type	Mortality/ Injury Potential	Impairment (sub-lethal)			
		Recoverable Injury	TTS	Masking	Behavior
Fish (swim bladder involved in hearing)	Low[1,2,3]	170 dB (RMS)[b] for 48 h	158 dB (RMS)[c] for 12 h	High[1,2,3]	High[1] Moderate[2] Low[3]
Fish (swim bladder is not involved in hearing)	Low[1,2,3]	Low[1,2,3]	Moderate[1] Low[2,3]	High[1,2] Moderate[3]	Moderate[1,2] Low[3]
Fish (no swim bladder)[a]	Low[1,2,3]	Low[1,2,3]	Moderate[1] Low[2,3]	High[1,2] Moderate[3]	Moderate[1,2] Low[3]

[a]Particle motion detection
[b]Derived from Smith et al. (2006); dB re 1 μPa RMS
[c]Derived from Amoser and Ladich (2003); dB re 1 μPa RMS

(1) near distance to source
(2) intermediate distance from source
(3) far distance to source

SUMMARY AND RECOMMENDATIONS

This literature review provides an improved understanding about underwater sound effects of dredging on aquatic life. Dredge-induced underwater sounds are temporally and spatially dynamic, and dependent on site-specific activities and conditions. Hydraulic and mechanical 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). Sound levels are typically low-intensity (i.e., SPLs <190 dB re 1μPa at 1 m).

The currently available data 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 many fish (e.g., herring, codfish, sea bass, carp, catfish) and mammal (e.g., dolphins, whales, seals) species, which may pose risk for auditory temporary threshold shifts, auditory masking, and behavioral responses depending on dredge type and local conditions. Overall, there has been significant progress in the understanding of the characteristics of dredge related sounds and the impacts on aquatic species over the last few 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 that maximizes the data and other site-specific information is needed to evaluate the underwater sound of concern. 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.

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MANUSCRIPT PREPARATION

Specific formatting requirements for manuscript submissions to the *Journal of Dredging* are described below. It may be useful to refer to a previous issue of the journal for format examples.

Preparation of the Text

Text should be single-spaced with full-justification on white 8½ x 11-inch paper. All margins must be 1 inch except the bottom margin of 1.5 inches, leaving an image area or block of text of 6.5" x 8.5". Do not leave additional margins. Do not include page numbers. Do not use headers or footers or draw a frame around your text. All text must be in 12-point Times New Roman font.

Title and Headings

The paper title should be all capitals and in bold font, centered 0.5 inches below the top margin. The title should not exceed 200 characters including spaces.

Headings should be centered and in bold font using only capital letters. Subheadings should be bold with the first letter of each word capitalized. All headings and subheadings should be preceded and followed by a single space as illustrated by these instructions. Sub-subheadings should be in bold font with the first letter of each word capitalized, placed at the start of the paragraph, and ending with a period.

Order of Contents

The order of contents for the paper should be:

1. Title
2. Author list (12-point Times Roman font; author affiliations, addresses, countries should be listed as footnotes starting with the first author)
3. Abstract (must not to exceed 300 words).
4. Keywords (five keywords that are not already contained in the title preceded by the phrase "Keywords:" left justified with one blank line between above and below.)
5. Introduction, main body, and following text, conclusions, nomenclature (if necessary), and references.

Equations

All symbols must be defined in the nomenclature section that follows the conclusions. The SI system of units should be used. If units other than SI units are included, they should be given in parenthesis after the relevant SI unit. Equations should be successively numbered (in parenthesis) flush with the right-hand margin (see example below).

$$y = a + b + cx^2 \tag{1}$$

References

References in the text should be formatted as Hunt (1995), (Hunt 1995), or (Jones et al. 2016). References should be listed alphabetically in the References section at the end of the paper. List the names and initials of all authors, followed by the title of the article and publication, the publisher and the year of publication. References to conference papers or proceedings should include the name of the organizers. References to articles published in journals should also include the name of the journal, the number of the issue and page numbers. Examples in the proper format are provided below. References to publications in a foreign language should give all details in the original language followed by a translation of the title.

Hunt, J.B. (1995). *Environmental Dredging*. Smith & Son, Inc., New York, NY.

Donegan, T.M., and Dinicola, W.J. (1986). *Turbidity Associated with Dredging Operations. Technical* Report, XYZ Consultants, Inc., Baltimore, MD., 60 p.

Jones, F., Doe, A., Hart, E.J.E., and Next, J.P.J. (2016). *The Design of Dredged Material Disposal Sites.* Proceedings XIVth World Dredging Congress, CEDA, Amsterdam, The Netherlands, pp. 350-368.

White, F.K. and J.M. Jones (1991). *The Analysis of Flow Fields around Dragheads.* Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 121, No. 5, pp. 1-16.

Figures and Tables

High quality figures and tables should be incorporated into the body of the text, placed at the first convenient location after being mentioned in the text. They are not to be placed at the end of the paper. Figure captions should be below the figure; table captions should be above the table. All tables and figures are to be numbered (separately) starting at 1 at the beginning of the paper.

Photographs must be sharp, high resolution images that are clear when reproduced in black and white. Lines and lettering on all figures must be clearly legible and suitable for clear reproduction.

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Dredging Creates a Strong Economy and Cleaner Environment