Technical Guidance on:

Underwater Sound in Relation to Dredging

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World Organisation of Dredging Associations

Central Dredging Association
Eastern Dredging Association
Western Dredging Association

WODA Technical Guidance on Underwater Sound

Relevant to a number of regulatory frameworks and processes, including the EU Marine Strategy Framework Directive, underwater sound has been identified by the Central Dredging Association (CEDA – *see Acknowledgements*) as an issue that needs further consideration

Preamble

As a result a CEDA Working Group on Underwater Sound (CEDA WGUS) was founded in 2011 that recently published a position paper on underwater sound in relation to dredging (CEDA 2011).

The paper was met with great interest both from within as well as outside CEDA. Based on the success of the previous achievement, a WODA Expert Group on Underwater Sound (WODA WEGUS – see Acknowledgements) was established. The task of the WEGUS was to extend the previous achievements to a broader international audience with an emphasis on the following specific objectives:

- Production of a further state-of-the-art review of ambient sound, dredging-induced underwater sound and their impact on aquatic biota
- Development of an underwater sound monitoring protocol/procedure
- Provision of technical guidance on\ how to assess underwater sound by dredging.

In this paper, the WODA WEGUS presents the results of the work. In discussions it became apparent that the outcome goes beyond the previous paper by providing guidance for decision makers, stakeholders and scientists on how to manage impacts of underwater sound from dredging and other sources. The document follows a risk-based approach (see Boyd *et al.* 2008).

The paper begins with some background on why underwater sound is an important issue. Then, the risk-based approach is described, which gives the framework for the chapters that follow. They cover issues such as impacts of sound on aquatic life, how to measure sound, the presentation of knowledge on dredging-related sound sources, and recommendations on how to manage and mitigate potential risks due to dredging-related sound impacts in offshore and coastal areas, estuaries and inland waters.

1. Why is underwater sound an important issue?

Water is an excellent medium for sound transmission. Sound travels more than four times faster underwater than in air and absorption is less compared to air (see *Underwater Sound* information box). The sensory modalities of vision, touch, smell and taste are limited in range and/or the speed of signal transmission. As a consequence many aquatic organisms use sound as their primary mode of communication – to locate a mate, to search for prey, to avoid predators and hazards, and for short- and long-range navigation. Activities generating underwater sound can affect these functions and, since sound can be far ranging, the spatial scale of impacts can be quite large.

Concerns for underwater sound impacts on marine mammals, fishes, and other forms of aquatic organisms have arisen primarily with the conduct of military operations, seismic exploration, and various forms of construction in aquatic environments (see OSPAR 2009). Pile driving is a prominent example of the latter category of concern (see Gill *et al.* 2012).

Although underwater sound is a concern recognised by environmental agencies, specific regulation addressing it is rare. In general, laws in Europe, the United States, and elsewhere, aim at reducing or limiting potential impacts of human activities on aquatic environments. These include the Habitats Directive in Europe and the National Environmental Policy Act in the United States, to name just two. Yet until recently there was no regulatory framework specifically addressing underwater sound.

This changed in Europe with the introduction of the EU Marine Strategy Framework Directive (MSFD). The aim of the MSFD is to protect, conserve, and where possible restore the marine environment in order to maintain biodiversity and provide diverse and dynamic oceans and seas which are clean, healthy and productive. The Directive requires Member States to achieve or maintain 'Good Environmental Status' (GES) in their marine environment by 2020 at the latest. The MSFD lists the 11 qualitative descriptors for GES, one of which states that '*the introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*'.

The EU has decided on two indicators that further specify GES for this descriptor:

- Indicator 1 addresses the distribution in time and place of loud, low- and mid-frequency impulsive sounds
- Indicator 2 deals with continuous low frequency sound (details in EC 2010).

Whereas indicator 1 will require an annual desk-based assessment of activities generating low frequency pulses, such as pile driving and seismic surveys, indicator 2 will most likely involve measuring and modelling ambient sound, perhaps at a regional level which would represent huge progress in identifying trends in existing pressures such as those from shipping or dredging (see Tasker *et al.* 2010). Details of requirements for such monitoring are currently being investigated by an EU expert group and are anticipated to emerge as soon as 2013 to meet the very ambitious timeline of the Directive.

Underwater Sound

Sound Pressure

Sound in water is a travelling wave in which particles of the medium are alternately forced together and apart. The sound can be measured as a change in pressure within the medium, which acts in all directions, described as the sound pressure. The unit for sound pressure is Pascal (Newton per metre squared).

Each sound wave has a pressure component (in Pascals) and a particle motion component indicating the displacement (metres), the velocity (metres per second) and the acceleration (metres per second squared) of the medium in the sound wave. Depending on the receptor mechanisms, marine life is sensitive to either pressure or particle motion or both. The pressure can be measured with a pressure-sensitive device such as a hydrophone (an underwater microphone).

Due to the wide range of pressures and intensities and taking the hearing of aquatic organisms into account, it is customary to describe these using a logarithmic scale, of which the most generally used is the decibel scale (dB).

The sound pressure level (SPL) of a sound is given in decibels (dB) by:

$$\mathbf{SPL\ (in\ dB) = 10\ log_{10}\ (P^2/P_0^{\ 2})}$$

where P is the root mean square sound pressure and P_0 is the reference pressure. The reference pressure in underwater acoustics is defined as 1 microPascal (μPa). As the dB value is given on a logarithmic scale, doubling the pressure of a sound leads to a 6 dB increase in sound pressure level. As the reference pressure for measurements in air is 20 μPa, and water and air differ acoustically, the dB levels for sound in water and in air cannot be compared directly.

Particle Motion

Most terrestrial animals are sensitive to sound pressure. However, fish and many invertebrates are also sensitive to particle motion. Particle motion sensitivity has been shown to be important for fish responding to sounds from different directions.

Sound or Noise?

The terms noise and sound are not clearly distinguished. Commonly, sound is a very broad term including all acoustic waves, whereas noise refers to sound that is unwanted. But as we do not really know what marine organisms perceive as ‘unwanted’, this document uses the more neutral term ‘sound’. The only exceptions are scientifically established terms such as ambient noise or when reference is made to work using that term.

2. How should impacts of underwater sound be assessed?

A risk assessment framework, which Boyd *et al.* (2008) have suggested would result in a more systematic approach to sound impact studies, involves a stepwise procedure including:

- Risk identification – characterisation of the potential threats of a source
- Exposure assessment – specifying the number of individuals that might be exposed to the hazard
- Dose-response assessment – of the quantitative relation between received sound and the effect
- Overall characterisation of the risk – leading to risk management with appropriate mitigation measures (details in Boyd *et al.* 2008; see *Figure 1*).

In the following chapters we will outline major points by systematically following the steps of the framework.

Figure 1: Overview of the risk-based approach

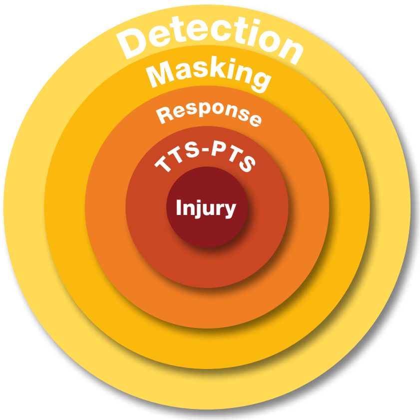
3. Risk identification: how can underwater sound affect aquatic life?

That the potential impacts of underwater sound are an emerging rather than historically recognised issue reflects the fact that scientific knowledge pertaining to the issue contains many gaps and uncertainties. It is vital to have the right conceptual framework when assessing sound-related impacts.

The ‘zone of influence model’ by Richardson *et al.* (1995) is based, at least partly, on the distance between the source and the receiver; the rationale is that sound intensity falls with increasing distance from the source and therefore impacts are likely to lessen, or at least to change, with distance. Richardson *et al.* (1995) defined a nested series of zones of influence centered on the source (see *Figure 2*).

The zone of *detection* or *audibility* is the most spatially extensive and is defined by the receiver’s ability to detect sound. It is dependent upon the hearing range and sensitivity of the receiver and on the background sound. Further factors are the frequency of the sound emitted, local

Figure 2: Sound impacts



Zones of sound influences after Richardson *et al.* 1995

conditions such as water temperature, viscosity, density, water depth and bottom conditions as well as the depth at which the signal is generated. Zones of audibility can thus be very variable and since they do not describe an effect *per se* they have not been dealt with in more detail here.

The zone of *masking* is the area where sound interferes with the detection of biologically relevant signals such as echolocation clicks or social signals. This zone is highly variable.

Masking has been shown in acoustic signals used for communication among marine mammals (see Clark *et al.* 2009) and it's likely to be an issue for fish as well (Hawkins & Myrberg Jr 1983). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

The degree of masking is influenced by the auditory capabilities of the organism and the frequency range of the background sound. For example, masking of high frequency sounds may be of greater significance for some organisms than low frequency sounds, whereas the reverse may be true for other species.

The zone of *responsiveness* is the area within which the receiver reacts behaviourally to the sound. Altered behaviour can be manifested in many ways.

An encounter with an initial intense sound may elicit an escape or avoidance reaction. Reactions to less intense sounds may be evidenced by altered but less obvious movement patterns. Individuals within a species may react differently based upon the status of their auditory capability or behavioural state (e.g. hunger level during foraging, migratory motivation, diurnal/nocturnal resting cycle, reproductive condition, life-cycle stage etc.) or their physical surroundings (e.g. open deep water versus confined and shallow estuary).

Consequences of disrupted behaviour can be important for the individual as well as the population, although there continues to be some debate regarding the determination of biological significance of behavioral disruptions. For example, the degree to which stress induced by chronic exposure to anthropogenic sound sources affects aquatic organisms (e.g. by impairing their immune systems) may be reduced by habituation and adaptation over time.

The zones of temporary threshold shift (TTS), permanent threshold shift (PTS) and injury indicate the spatial extents to which sound exposures lead to *physiological effects*.

Injuries in fishes caused by pressure changes due to pile driving sounds have been documented to range from immediate lethality, rupturing of swim bladders, bleeding of various organs and tissues, over hematomas ('bruises') of various tissues to degrees of swim bladder deflation (Popper & Hastings 2009). A TTS involves a temporary elevation of the hearing threshold due to an exposure to sound. An intense short exposure can produce the same scale of TTS as a longer exposure to lower sound levels. Significance of the TTS would vary among species depending on their dependence on sound as a sensory cue for ecologically relevant functions. A PTS is a permanent elevation of the hearing threshold at certain frequencies and is considered an auditory injury.

We note here that although the Richardson model provides a useful starting point in assessing sound-related impacts, it is only a first approximation of the scope of the problem. For example, there is a common understanding that physiological effects are related to the dose of exposure, which involves the duration of impact (see Southall *et al.* 2007; Kastelein *et al.* 2012. Consequently, physiological effects can potentially occur at sound pressure levels that do not cause a behavioural response when the animals are exposed for a long period. That means that the influence zone for physiological effects can be larger than the zone of responsiveness. Furthermore, although zones of sound influence are a very useful starting point in classifying impacts, they can mislead. For example, behavioural reactions might lead to severe consequences such as stranding due to exposure to sonar sounds (see Cox *et al.* 2006) so that a zone where initial responsiveness occurs might well become the zone of injury or even death.

4. Exposure assessment: to what degree is aquatic life exposed to underwater sound?

Once possible risks associated with underwater sound have been indentified, it is necessary to specify the sound levels to which individual animals are exposed.

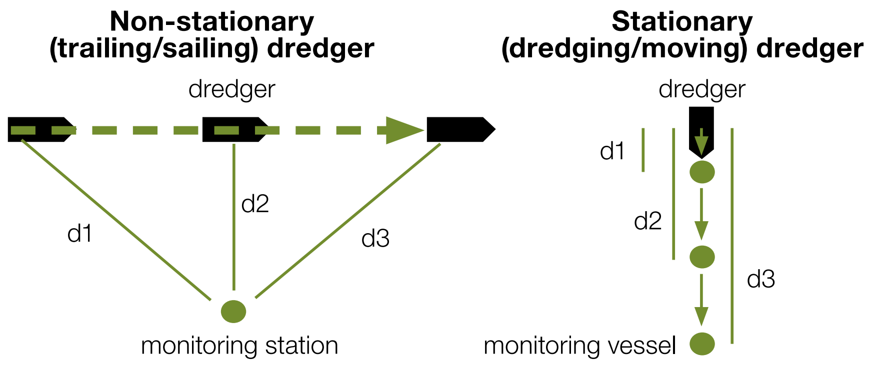
Ideally, each individual would have to be equipped with an acoustic sensor that monitors the precise sound exposure and with a device that records behaviour, but this is unrealistic. Exposure assessment thus has to be based on an analysis of the underwater sound distribution in the environment of interest, in combination with an assessment of the presence of animals in the environment during the time period of interest.

An important distinction must be made between interpretations of data based on sound pressure level (SPL) and sound exposure level (SEL) and whether the sound sources are continuous or pulsed:

- SPL is a measure of sound pressure expressed in decibel (dB) units referenced to a standard pressure of 1 microPascal (μPa), defined in terms of mean square sound pressure
- SEL is a time-integrated expression of the sound pressure squared level.

Both terms are useful in characterising biologically meaningful parameters: for continuous sound that is generated by ships and some dredgers, SPL is the most likely metric to govern direct animal behavioural response, while SEL is

Figure 3: Measuring dredging sound



Examples of procedures for measuring underwater radiated sound of dredgers during various operations (after de Jong *et al.* 2010). For a reliable estimation of the source level, measurements with one or more hydrophones are carried out at multiple distances (d1, d2, d3).

probably more relevant for physiological effects such as TTS and PTS (Southall *et al.* 2007).

Standardisation of underwater acoustic terminology and measurements

To facilitate comparison of results of different studies, it is very important to use a standard terminology in underwater acoustic research. In 2010, in the Netherlands, Germany and the United Kingdom, collaborative projects were set up to define and agree upon the terminology of underwater sound. The results of this collaboration are described in TNO 2011.

Technical Committee 43 on 'Acoustics' of the International Organisation for Standardisation (ISO) installed subcommittee SC3 on 'Underwater Sound' in June 2012. The TC43 SC3 Working Group 2 will use TNO 2011 as a basis for the development of a new ISO standard for underwater acoustic terminology.

There are also no specific national or international standards for measuring the radiated sound of dredgers, nor of other ships operating in shallow water.

The American National Standards Institute's ANSI-ASA S12.64/2009-Part 1 Report for measuring radiated sound of (transiting) ships in deep water formed the basis for the development of the international ISO Publically Available Specification 17208-1:2012 'Acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: General requirements for measurements in deep water'. ISO working groups TC43 SC3 Working Group 1 and TC8 SC2 Joint Working Group 1 are developing international measurement standards for ships in deep water. These groups have expressed the intention to address ship-radiated sound measurements in shallow water as a next step.

How can the spatial distribution of underwater sound be determined?

Underwater sound distribution depends on the sources that generate sound and on the propagation of sound in the environment. Because of practical limitations, it is not realistic to get a global overview of this distribution from measurements alone.

Underwater acoustic models, in combination with the relevant measurement data, can provide a pragmatic approach for the determination of the underwater sound distribution. Various types of shallow water propagation modelling techniques are available (Wang *et al.* 2013), all varying in the level of detail modelled and hence in the requirements for input data and in the resulting accuracy of the calculations.

These sound propagation models describe the sound source as an 'acoustic monopole', characterisd by an underwater acoustic 'Source Level' spectrum (TNO 2011). The received sound pressure level at positions in the environment is the difference between this monopole Source Level and the calculated Propagation Loss between source and receiver positions. The depth below the water surface of this assumed monopole is an important parameter, because it influences the radiated sound power and propagation loss for near surface sources at lower frequencies.

Hence, characterising the sound distribution of dredging activities requires measurement data of dredgers' radiated sound and a shallow water sound propagation model. Neither the measurement method for dredging sound, nor the propagation models are currently standardised.

Recent studies in the Netherlands (de Jong *et al.* 2010) and the UK (Robinson *et al.* 2011, Wang *et al.* 2013) have advocated the use of a source-image type of propagation model (Urick 1983) in combination with radiated sound measurements at various distances from the dredger. Care should be taken in the selection of an appropriate propagation model and assurance should be given that the model's details are reported fully.

Measuring the underwater radiated sound of dredgers

Until measurement standards become available, the approach followed in recent studies in the Netherlands (de Jong *et al.* 2010) and the UK (Robinson *et al.* 2011, Wang *et al.* 2013) can provide guidance for measuring the radiated sound of dredgers. These approaches will be proposed for the future international standard development, which are urgently required to arrive at an internationally accepted protocol for risk assessment.

Underwater radiated sound measurements of dredgers require the use of hydrophones, deployed from a quiet vessel or from a buoy, or mounted on the seabed at a minimal distance of about one ship length from the dredger. Data from acoustic measurements at a fixed position while the dredger passes the hydrophones, or at a number of measurement positions at various distances from a stationary dredger, are required to obtain an assessment of the source level of the dredger.

Positions of the hydrophones relative to the dredger need to be monitored, e.g. by means of GPS. *Figure* 3 provides an example of measurements involved in monitoring both a moving and a stationary dredger. These arrangements can be adapted to other types of dredgers.

5. Exposure assessment: what do we know about dredging sound?

As outlined in the CEDA position paper on underwater sound from dredging (CEDA 2011), the dredging process involves a variety of sound generating activities, which can be broadly divided into sediment excavation, transport and placement of the dredged material at the disposal site.

It is also important to recall that for the majority of projects one or more of four basic types of dredgers are used: Cutter Suction Dredger (CSD), Trailing Suction Hopper Dredger (TSHD), Grab Dredger (GD) and Backhoe Dredger (BHD) as depicted in *Figure* 4. The potential sound sources are manifold and described in detail in CEDA 2011.

Although information on sound levels from the different types of dredgers and activities is still limited, recent investigations have led to interesting results:

De Jong *et al*. (2010) measured underwater sounds produced by seven TSHDs during the construction of Maasvlakte 2, a 2,000 hectare harbour extension of the Port of Rotterdam. Using a propagation model for the shallow water environment in which the measurements were taken, they provide an estimation of the dipole source level spectra covering a wide frequency band (see *Figure* 5).

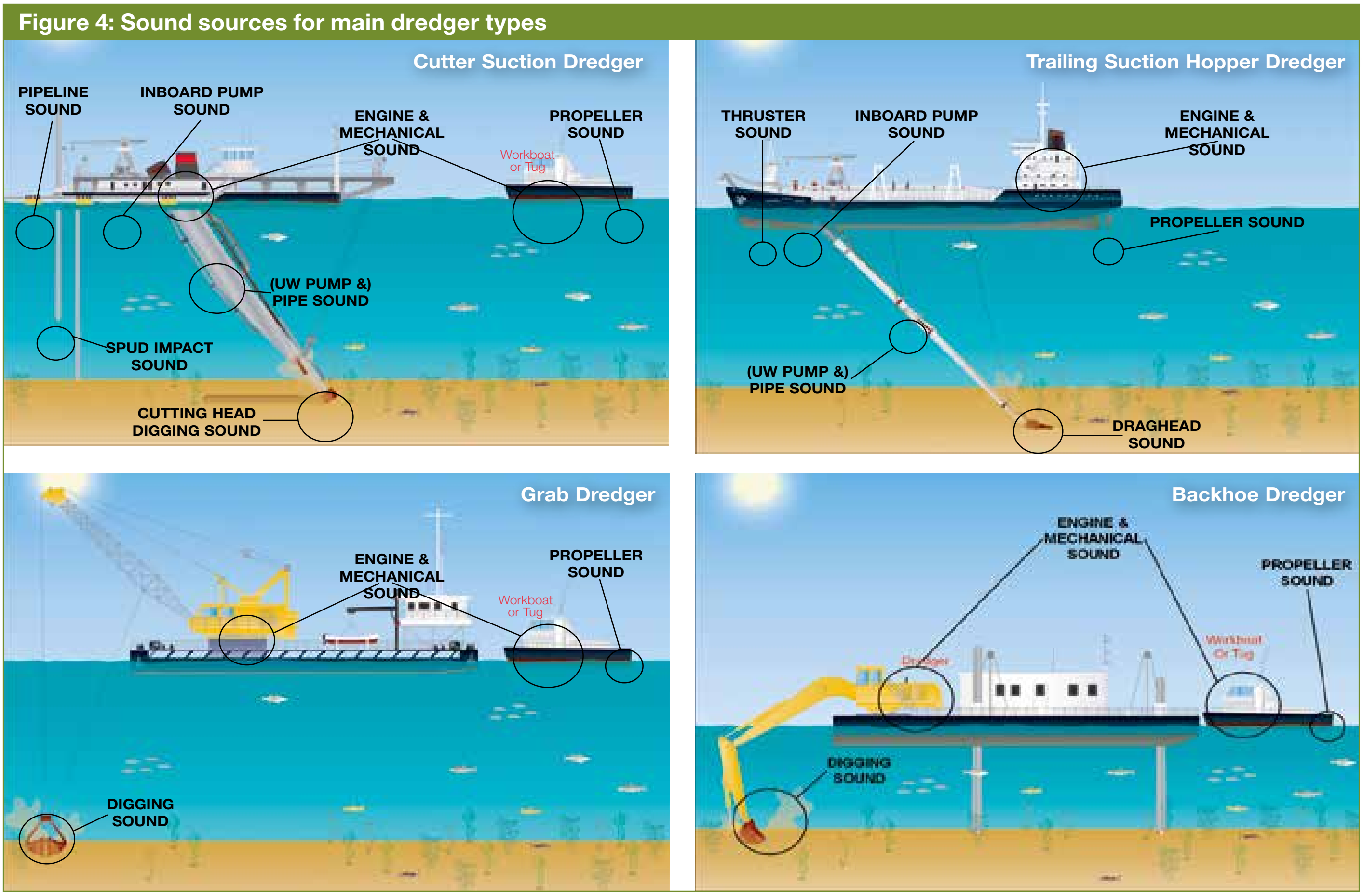
The investigations allowed for a direct comparison of the maximum source levels from different activities associated with TSHD dredging (i.e. the dredging process itself, transit, placement, pumping and rainbowing – the latter being the aerial discharge of dredged material as in a fountain). The results presented in *Figure* 5 showed that dredging itself did not produce louder sounds than those produced by the dredger during transit between the dredging and placement sites. It is important to consider that in this case the sediment mainly consisted of sand and that therefore the conclusion could be different for TSHD dredging of gravel or broken rock. The maximum broadband sound above 100 Hz was similar for all activities except 'sand placement'.

Robinson *et al*. (2011), in a similar investigation using the same methodology to calculate source levels, found that six TSHDs emitted sound levels at frequencies below 500 Hz, comparable to a deep-draft draught cargo ship travelling at modest speed (i.e. between 8 and 16 knots). Interestingly, source levels at frequencies above 1 kHz were relatively high. There were strong indications that the aggregates pumped through the pipe were the source of these elevated levels at higher frequencies. Extraction of coarse gravel generated about 5 dB higher sound levels at frequencies above 1 kHz than sand (Robinson *et al*. 2011).

Itap (2007) measured sounds from a TSHD performing sand extraction off Sylt, Germany. Based on a 14 log (R / 1m) scaling, the dredger had an estimated source level around 184 – 188 dB re 1 μPa^{2}m^2 (main energy between 100 and 500Hz).

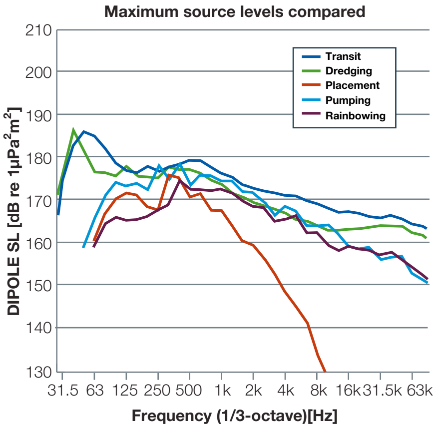
Reine *et al*. (2012b) recorded and analysed underwater sounds generated by a large hydraulic CSD fracturing rock while engaged in the New York & New Jersey Harbour Deepening Project. Based on a 15 log (R /1m) scaling, the calculated source levels reached 175 dB re 1 μPa^{2}m^2. Most sound energy was below 2.5 kHz. The intensity of sounds varied depending on the amount or hardness of the material to be removed.

Figure 4: Sound sources for main dredger types



The same team analysed underwater sound produced by a BHD removing the fractured rock created by the CSD (Reine *et al*. 2012a). Again, with a 15 log (R/1m) scaling the most intense bottom grab sound was estimated by back calculation to be 179.4 dB re 1 μPa^2m^2 (frequency range 3 Hz – 20 kHz, peak frequency = 315 Hz). Hydraulic ram sounds were approximately 15 dB lower than the grab sounds. Reine *et al*. 2012a provided information on sound levels from a number of additional components of the dredging process as well.

Figure 5: Dredging sound



Comparison of the upper envelope of the measured dipole source level spectra for seven TSHDs, while transiting, dredging, placement, pumping and rainbowing in front of Maasvlakte 2 (from de Jong *et al*. 2010)

Nedwell *et al*. (2008) took a series of underwater sound measurements during harbour dredging by a large BHD, the Manu Pekka, at Lerwick, Shetland (UK). Based on a 'conservative' 10 log (R/1 m) scaling, the estimated source level of the BHD during periods when the material was being excavated from the seabed was 163 dB re 1 μPa^2m^2. The measurement data indicated that dredging activity increases the underwater sound at frequencies from 20 Hz to approximately 20 kHz. A consistent sound was recorded over the low frequency range from 20 to 80 Hz, with peak spectral levels of sound occurring between 35 and 45 Hz.

It has to be noted that the results of these studies are not directly comparable as the X log (R/1 m) scaling is not an actual propagation loss correction and hence does not produce a source level that is independent of the environment in which the measurements were taken. It is thus important to refer to the original reports before making interpretations.

6. Dose-response assessment: how does dredging sound affect aquatic life?

To date, auditory and non-auditory injuries (see chapter 3) have not been observed or documented to occur in association with dredging projects of any kind (with the exception of cases involving underwater blasting prior to substrate removal by conventional dredgers). Lower levels of impact may take the form of recoverable damage to auditory tissues and hearing loss attributable to temporary threshold shifts (TTS) if animals are exposed for a long period of time and stay in the vicinity of the dredger. Behavioural response is the most likely effect.

CEDA 2011 noted the scarcity of studies quantifying impacts from dredging with documented effects limited to behavioural changes in gray and bowhead whales (see Richardson *et al*. 1995) and a recent investigation by Diederichs *et al*. (2010) showing that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. This latter investigation is of special interest as harbour porpoises are very commonly encountered in busy dredging areas in Europe, for example off the UK, the Netherlands and Germany. The species is also protected under the European Habitats Directive.

For their investigation Diederichs *et al*. (2010) used automated porpoise click detectors that register high frequency echolocation sounds that the porpoises use for navigation and finding prey. They found that when the dredging vessel was closer than 600m to the porpoise detector location, it took three times longer before a porpoise was again recorded than during times without sand extraction. However, after the ship left the area, the clicks were registered at the usual rate.

The results are relevant as sound levels emitted from the dredger were reported (see Itap 2007). However, as sound transmission differs substantially between sites, the distance of 600m is only valid for this specific dredging project and cannot be generalised to other dredging projects. Visual surveys using airplanes did not document any impacts. The results of the study demonstrated that passive acoustic monitoring methods are a promising tool for the investigation of dredging-related impacts on harbour porpoises and perhaps also for other marine mammal species that emit recognisable sounds.

To our knowledge, no other recent studies have been performed on the impacts of dredging sound on marine life, thus reiterating the need to gather more data on impacts on aquatic life from dredging.

7. How should we manage dredging-related sound risks?

WODA recommends following a risk-based approach in assessing sound-related impacts from dredging.

With regard to risk identification it is advised to use an appropriate framework whereby risks can be divided into the categories of masking, response, TTS-PTS and injury. However, it is important to recognise that these impact zones are partially overlapping and are not simply related to distance between the source and the exposed organisms.

For the exposure assessment a standardisation of acoustic terminology is a prerequisite and examples are given of papers that can be referred to. It is easy to misuse the many different notations of underwater sound and make comparisons based on the dB values that are inconsistent. Great care must be taken in any reference to inferred sound pressure levels based on the source strength and the distance between the source and the observation location.

The underwater sound distribution should be described using underwater acoustic models supported by empirical field data to the fullest extent practical. Measuring the underwater sound from dredgers can be undertaken following the simple setup as outlined in *Figure* 3.

With regard to characterisation of dredging sounds, progress is being made and a lot more is known now than some years ago. Very detailed measurements on a number of TSHDs have been performed. Information on Grab and Backhoe Dredgers has become available as well. That said, we do not yet have a complete understanding of dredging sound as not all sources that are shown in *Figure 4* are covered and measurements are still not fully standardised.

It is noted that dredgers operating in comparatively deep offshore waters may produce sounds detectable at much greater distances than dredgers in shallow, estuarine environments with comparatively higher suspended sediment loads.

Background sound levels may also be considerably higher in busy port settings, exacerbating masking effects. On the other hand, marine species migrating through harbours and rivers may not be able to avoid exposure to dredging sound like they can in open waters. Looking at the receiver it is necessary to define the population that will be subject to the assessment. This, however, is very challenging due to variability in population estimates (Thomsen *et al*. 2011).

Most information gaps still pertain to the dose response assessment as the numbers of studies dealing with dredging impact are very limited. One remaining challenge is assessment of the relationship between dose (e.g. properties of the received sound) and response, as results from studies investigating the effects of sound on marine mammals, fish and other aquatic life are, to date, highly equivocal.

It has to be remembered that very little scientific evidence indicates which acoustic metric correlates with which effect on aquatic organisms. The hypothesis most often used is that physiological effects correlate with the total dose of acoustic energy exposure, expressed in terms of the cumulative SEL. Other metrics may also be relevant for physiological effects (peak sound pressure, rise time, kurtosis, etc.) but lack data. Behavioural effects are usually related to SPL, for a stated averaging time (either the duration of the transient signal or a 'long term' average for ambient sound).

Due to the above uncertainties, the management of risks related to dredging sound is not an easy task. It is clear that dredging sound has the potential to impact aquatic life and it is assumed that most of these impacts would concern disruption of communication due to masking or alteration of behaviour patterns.

Cumulative and long-term exposure leading to TTS has to be considered – at least for marine mammals (Kastelein *et al*. 2012) – though PTS or other auditory injuries are unlikely. If the assessment concludes that there is a high risk of an adverse effect, the risk management could involve mitigation measures. OSPAR (2009) discusses several options including technical and operational ones (see also JNCC 2009).

One very effective sound mitigation measure might simply be adequate maintenance of the dredge plant, including lubrication and repair of winches, generators, propulsion components and other potential sources as well-maintained dredgers are much less likely to be 'loud' dredgers.

The WODA advice is to identify, assess and manage the risk following the framework outlined above. In conclusion, assessments of dredging sound-induced impacts may require different approaches depending on the organisms and effects of concern and the type and location of the project. ■

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This Technical Guidance has been prepared by the WODA Expert Group on Underwater Sound under the remit of the WODA Environment Commission and reviewed by experts from various professional groups.

Members of the WODA Expert Group on Underwater Sound:

- Frank Thomsen (chairman), DHI Water & Environment, Denmark
- Fabrizio Borsani, Cefas, UK
- Douglas Clarke, US Army Engineer R & D Center, USA
- Frederik Goethals, Dredging International (DEME), Belgium
- Martine Holtkamp, MTI Holland, the Netherlands
- Christ de Jong, TNO, the Netherlands
- Gerard van Raalte, Royal Boskalis Westminster, the Netherlands
- Elena San Martin, ABPMer, UK
  Philip Spadaro, The Intelligence Group, USA
- George Yesu Vedha Victor, International Seaport Dredging, India
- Pim de Wit, Port of Rotterdam, the Netherlands

Contact WODA at:

c/o Central Dredging Association:
Radex Building, Rotterdamseweg 183c,
2629 HD Delft,
The Netherlands
T: +31 (0)15 268 2575
E: ceda@dredging.org
W: www.woda.org