JRC Scientific and Technical Reports

MARINE STRATEGY FRAMEWORK DIRECTIVE

Task Group 11 Report

Underwater noise and other forms of energy

APRIL 2010

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Joint Report

Prepared under the Administrative Arrangement between JRC and DG ENV (no 31210 – 2009/2010), the Memorandum of Understanding between the European Commission and ICES managed by DG MARE, and JRC's own institutional funding

Editor: N. Zampoukas

EUR 24341 EN - 2010

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JRC 58105
EUR 24341 EN
ISBN 978-92-79-15654-0
ISSN 1018-5593
DOI 10.2788/87079
Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

PREFACE

The Marine Strategy Framework Directive (2008/56/EC) (MSFD) requires that the European Commission (by 15 July 2010) should lay down criteria and methodological standards to allow consistency in approach in evaluating the extent to which Good Environmental Status (GES) is being achieved. ICES and JRC were contracted to provide scientific support for the Commission in meeting this obligation.

A total of 10 reports have been prepared relating to the descriptors of GES listed in Annex I of the Directive. Eight reports have been prepared by groups of independent experts coordinated by JRC and ICES in response to this contract. In addition, reports for two descriptors (Contaminants in fish and other seafood and Marine Litter) were written by expert groups coordinated by DG SANCO and IFREMER respectively.

A Task Group was established for each of the qualitative Descriptors. Each Task Group consisted of selected experts providing experience related to the four marine regions (the Baltic Sea, the North-east Atlantic, the Mediterranean Sea and the Black Sea) and an appropriate scope of relevant scientific expertise. Observers from the Regional Seas Conventions were also invited to each Task Group to help ensure the inclusion of relevant work by those Conventions. A Management Group consisting of the Chairs of the Task Groups including those from DG SANCO and IFREMER and a Steering Group from JRC and ICES joined by those in the JRC responsible for the technical/scientific work for the Task Groups coordinated by JRC, coordinated the work. The conclusions in the reports of the Task Groups and Management Group are not necessarily those of the coordinating organisations.

Readers of this report are urged to also read the report of the above mentioned Management Group since it provides the proper context for the individual Task Group reports as well as a discussion of a number of important overarching issues.

Contents

Executive summary

1. Summary sheet

TG11 Energy		
ATTRIBUTE	**Criteria** to assess the descriptor	**Indicators** to be measured
Underwater noise - Low and mid-frequency impulsive sound	High amplitude impulsive anthropogenic sound within a frequency band between 10Hz and 10 kHz, assessed using either sound energy over time (Sound Exposure Level SEL) or peak sound level of the sound source. Sound thresholds set following review of received levels likely to cause effects on dolphins; these levels unlikely to be appropriate for all marine biota. The indicator addresses time and spatial extent of these sounds.	The proportion of days within a calendar year, over areas of 15’N x 15’E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re 1µPa^2.s (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1µPa$_{peak}$ (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz
Underwater noise – High frequency impulsive sounds	Sounds from sonar sources below 200 KHz that potentially have adverse effects, mostly on marine mammals, appears to be increasing. This indicator would enable trends to be followed.	The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least *x*% per year starting in [2012].
Underwater noise – low frequency continuous sound	Background noise without distinguishable sources can lead to masking of biological relevant signals, alter communication signals of marine animals, and through chronic exposure, may permanently impair important biological functions. Anthropogenic input to this background noise has been increasing. This indicator requires a set of sound observatories and would enable trends in anthropogenic background noise to be followed.	The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year [2012] or 100 dB (re 1µPa rms; average noise level in these octave bands over a year).

The report outlines the limited extent of knowledge of the effects of underwater energy, particularly noise, and particularly at any scale greater than the individual/group level. These limits on knowledge give difficulties in proposing indicators, more so than most other descriptors.

The report contains much background scientific information and has suggestions for possible further indicators in the future for noise, as well as on the assessment of the effects of electromagnetic fields and heat on the marine environment.

2. Summary

In relation to the underwater energy, Good Environmental Status certainly occurs when there is no adverse effect of energy inputs on any component of the marine environment. However, such an objective is probably not achievable if, for instance, behavioural disturbance or mortality of plankton (including planktonic larvae) is considered an adverse effect. Such an objective is probably not also measurable for a very large proportion of organisms in the marine environment. The Task Group aimed to provide an indicator or indicators of environmental status, not to define Good Environmental Status.

Energy input can occur at many scales of both space and time. Anthropogenic sounds may be of short duration (e.g. impulsive) or be long lasting (e.g. continuous); impulsive sounds may however be repeated at intervals (duty cycle) and such repetition may become "smeared" with distance and echoing and become indistinguishable from continuous noise. Higher frequency sounds transmit less well in the marine environment (fine spatial scale) whereas lower frequency sounds can travel far (broad spatial scale). There is however great variability in transmission of sound in the marine environment.

Organisms that are exposed to sounds can be adversely affected over a short time-scale (acute effect) or a long time-scale (permanent or chronic effects). Adverse effects can be subtle (e.g. temporary harm to hearing, behavioural effects) or obvious (e.g. worst case, death). These considerations have been described above in relation to sound, but can equally apply to other types of energy. With sufficient resources and research, it might be possible to develop indicators for these many facets of harm from energy input; however the initial indicators described below focus on sounds that affect relatively broad areas rather sounds that affect local parts of the marine environment.

The Task Group developed three possible indicators of underwater sound. In no case was the Task Group able to define precisely (or even loosely) when Good Environmental Status occurs on the axes of these indicators. This inability is partly to do with insufficient evidence, but also to no fully accepted definition of when, for example, a behavioural change in an organism is not good. The indicators all provide axes that would enable authorities to define targets that should be relatively easy to measure.

2.1. Indicator 1. Low and mid-frequency impulsive sounds

High amplitude, low and mid-frequency impulsive anthropogenic sounds are those that have caused the most public concern, particularly in relation to perceived effects on marine mammals and fish. These sounds include those from pile driving, seismic surveys and some sonar systems. Laboratory studies have found both physiological and behavioural effects in a variety of marine organisms, while field studies have shown behavioural disturbance and in some cases death (physiological effects are difficult to study in the field). There will be a variety of degradation gradients caused by such noise, the scale of these depending on the marine organism under consideration and the loudness, frequency and persistence of the sound. In principle, sound input is likely to have greater adverse effects at higher sound amplitudes (loudness) and with a greater number of inputs (persistence). Lower frequency sounds will affect a wider area, but this is complicated by the ability of organisms to detect a limited range of sound frequencies; sounds outside their range of detection will be less likely to have an adverse effect. The following initial indicator is proposed as a way of geographically quantifying the occurrence of loud impulsive anthropogenic noise.

Underwater noise indicator 1

The proportion of days within a calendar year, over areas of 15'N x 15'E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re 1µPa^2.s (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1µPa$_{peak}$ (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz.

This indicator would be based on reports of occurrence by those undertaking activities likely to generate these sounds, rather than on direct independent measurement. Recording would be on the basis of Regional Seas [or national parts of Regional Seas]. We would expect that sounds made by most commercial seismic surveys, by pile-driving, by low and mid-frequency sonar and by explosions to be included. We would expect most sources to be included therefore be quantifiable from either relevant impact assessments or reports from activities required under national licensing regimes. The proportion of days would be set by Member States and could be based on a review of relevant activities in the immediate past and on their view on sustainable impact.

The size of grid rectangle was chosen as a compromise. An index sensitive to small changes in activity would have small rectangles, while large rectangles are likely to be administratively easier to use. The Task Group recommends the choice of 15'N x 15'E/W rectangles, but other choices would be possible at approximately this scale. It should be noted that a rectangle off Shetland would be about 60% of the area of a rectangle off Gibraltar, so it might be possible to have variation of grid rectangle by regional sea.

The choice of frequency bandwidth (10Hz to 10kHz) is based on the observation that sounds at higher frequencies do not travel as far as sounds within this frequency band. Although higher frequency sounds may affect the marine environment, they do so over shorter distances than low frequency sounds. This choice of bandwidth also excludes most depth-finding and fishery sonars.

The indicator is focussed on those impulsive noise sources that are most likely to have adverse effects. The source levels will include all classes of high intensity sounds that are known to affect the marine environment adversely for which the activities that generate such sounds are routinely licensed or are assessed, but not to include some lower intensity sounds that are rarely subject to licence. The Task Group recommends that these levels be reviewed in the future in the light of any new scientific publications.

2.2. Indicator 2. High frequency impulsive sounds

Depth sounding sonar systems on small vessels typically use frequencies between 50 and 200 kHz. Sonar usage, particularly on leisure boats, is increasing and is unregulated. These vessels tend to operate in coastal areas throughout the EU; these waters are often important for some marine mammals. These animals use frequencies up to about 180 kHz for communication and thus there is an overlap in frequency usage. There has been little research on the effects of these sonar systems and the scientific evidence for adverse effects is limited. However, the sounds are similar to those used in acoustic alarms (pingers) that are designed to scare away small cetaceans from gill and tangle nets used in the fishery, and can therefore be expected to cause adverse effects. A precautionary approach would be to reduce the usage of sonar systems working at frequencies below 200 kHz. Frequency is related to depth range; however in shallow areas, 200 kHz would be sufficient for most purposes and would not affect marine mammals. A possible initial indicator for high frequency impulsive noise would be:

Underwater noise indicator 2:

> **The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least x% per year starting in [2012].**

This indicator does not include a measure of the use of small vessels, or the use of sonar on them, since this is virtually impossible to monitor, but the number of vessels with such sonar systems will be a sufficient proxy. The target percentage decrease (x) in usage would be set by Member States depending on how rapidly a reduction is deemed necessary.

2.3. Indicator 3. Low frequency, continuous sound

Ambient noise is defined as background noise without distinguishable sound sources. It includes natural (biological and physical processes) and anthropogenic sounds. Research has shown increases in ambient noise levels in the past 50 years mostly due to shipping activity. This increase might result in the masking of biological relevant signals (e.g. communication calls in marine mammals and fish) considerably reducing the range over which individuals are able to exchange information. It is also known that marine mammals alter their communication signals in noisy environments which might have adverse consequences. It is further likely that prolonged exposure to increased ambient noise leads to physiological and behavioural stress. Thus chronic exposure to noise can permanently impair important biological functions and may lead to consequences that are as severe as those induced by acute exposure. A possible initial indicator for low-frequency, continuous noise would be:

Underwater noise indicator 3

> **The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year [2012] or 100 dB (re 1µPa RMS; average noise level in these octave bands over a year)**.

This indicator would be based on direct independent measurements. The choice of representative sets of observation stations is left to Member States working together and should benefit from existing networks of underwater observatories (e.g. ESONET). Recording would be on the basis of Regional Seas [or national parts of regional seas].

The choice of these octave bands is on the basis of scientifically justifiable signatures of anthropogenic noise that avoids most naturally generated sources. The baseline year would be set at whenever the observatory system for a regional sea is established, while the suggested cap on ambient noise is suggested to avoid ambient noise levels that are likely to be harmful.

The Task Group recommends that these indicators are not combined, but are used separately – in other words if the sounds as expressed on one of the indicators is not of Good Environmental Status, then the whole descriptor is not at GES. The Task Group consider that if fewer than three of these indicators are chosen, then Indicators 1 and 3 are the most important.

2.4. Monitoring and research/development needs

The monitoring needs for Indicator 1 are essentially administrative monitoring of documents (e.g. EIA, licence reports) and plotting of activities that generate noises over the dB threshold. This could be done at a national level, but might be better (to avoid problems of recording activities in partial rectangles at national boundaries) to be carried out at a regional sea level. The Task Group recommends an immediate examination of records for recent years to determine the "starting level" of activity and as a baseline for future monitoring.

The monitoring needs for Indicator 2 might require, for instance, a register of leisure boats. The Task Group is unsure how widely such information exists at present but e.g. in Sweden there is a voluntary register that includes approximately 200,000 boats.

The monitoring needs for Indicator 3 require the establishment of a set of underwater noise observatories for each regional sea. The Task Group has not analysed this need in detail, but would expect that existing observatories or fixed oceanographic moorings could be used. Recommended recording bandwidth would be 16-1250 Hz. Further technical specifications of the recording of noise (e.g. sampling strategy, statistical modelling, etc.) need further development.

The Task Group recommends that assessments of each Indicator be made on an annual basis, at least in the early years of using this system in order to provide reliable input to the six-yearly assessment of Good Environmental Status and to fine tune the usage of the Indicators based on experience.

The Task Group emphasises that these indicators are only initial indicators. There has been no previous successful attempt globally to set wide area indicators of noise. All Indicators only implicitly consider the effects of sound on receiving parts of the marine ecosystem. This approach is due to the difficulty of measuring (or modelling) broad noise effects in the marine environment. Indicator 1 is based solely on noise-emitting activity records and does not consider the differences between multiple impulses and a single impulse. Indicator 2 considers only one source of high frequency acute noise. Indicator 3 deliberately uses signature narrow octave bands; these do not cover the higher frequency anthropogenic components of ambient sound that may be locally significant. The Task Group acknowledges that there are many other sources in this frequency range but considers that sonar usage is particularly widespread, pervasive (and is often unnecessary).

There are no indicators for non-impulsive transient noises, for behaviour or other effects on the marine environment or for energy other than sound proposed, but some text on these further issues is provided in the main report. The Task Group has identified a number of further needs for research and development to rectify these omissions and make the indicator for inputs of energy more attuned to the needs of the marine environment. The Task Group is certain that it has not described all such required research and recommends that either the Group, or an equivalent group, be asked to continue work in this area.

1 Introduction

This is a report concerning the Descriptor of Good Environmental Status under the EU's Marine Strategy Framework Directive (MSFD) for inputs of energy. The full text of the descriptor is:

Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

There are many kinds of anthropogenic energy that human activities introduce into the marine environment including sound, light, electromagnetic fields, heat and radioactive energy. Among these inputs, the most widespread and pervasive has been increasing levels of anthropogenic sound. It is likely that these levels, and associated effects on the marine ecosystem have been increasing since the advent of steam-driven ships, although there have been very few studies that have quantified this change. Radioactivity in the marine environment occurs in conjunction with the introduction of radioactive substances which have also spread widely in European seas. The emission of electromagnetic fields is growing due to the increasing number of power cables crossing our seas but these emissions are still relatively localised. Light and heat emissions are also relatively localised, but can have significant effects in those areas.

1.1. Focus of the report and definitions

In the following report, the main focus is on indicators of underwater noise, with some relation to impacts on the marine environment. Noise has been defined in many ways. For this report "noise" is taken to mean anthropogenic sound that has the potential to cause negative impacts on the marine environment (which in this case includes component biota but not necessarily the whole environment). The term "level" as used in the MSFD descriptor, is taken within this report in a wide sense not only to describe sound pressure levels but also other features of sound. Electromagnetic fields are described in some detail but the inputs of other forms of energy, such as light and heat, receive little or no coverage in this report. This is due partly to their relatively localised effects, partly to a lack of knowledge and partly to lack of time to cover these issues. Radioactive energy is considered alongside input of hazardous substances and therefore is dealt with elsewhere.

1.2. Possible links and overlaps with other descriptors

There is an overlap between this descriptor and the biodiversity descriptor (TG1) as well as the food web descriptor (TG4). The energy descriptor is primarily a 'pressure' descriptor that could have effects on the biodiversity descriptor (especially distributional aspects – species abundance) and food web descriptor (especially functions of life communities, balance in species assemblages), of which both describe generally the 'status' of biological components. As noted above, an overlap exists between radioactive energy and hazardous substances. This also applies to some sources of chemical energy. Hazardous substances are covered by TG8.

1.3. Policies and conventions related to the descriptor

The Task Group had insufficient time to review all national and international policies and conventions. The Task Group noted that at least the Convention of Migratory Species (CMS), the International Whaling Commission (IWC), the International Union for Conservation of Nature (IUCN), the International Maritime organization (IMO), OSPAR and HELCOM have all considered the negative effects of anthropogenic underwater noise.

Some links can be made to Article 12 of the Habitats Directive requirements on killing, injury and disturbance. A reasonably comprehensive review of national, European and international regulations has been compiled by the European Network of Excellence ESONET for a variety of geographical regions (ESONET, 2009).

A position paper on EU noise indicators was published in 2000 (EC, 2000). The working group compiling this report aimed to recommend "physical indicators to describe noise from all outdoor sources for assessment, mapping, planning and control purposes and to propose methods of implementation." Despite this term of reference theoretically including underwater noise, it focussed solely on airborne noise outside dwellings.

1.4 Underwater noise

Sound is a dominant feature of the underwater marine environment as a result of natural (biological sources, underwater earthquakes, wind) and human-made (anthropogenic) sound sources (Richardson *et al*. 1995; NRC 2003; Popper and Hastings 2009a,b). Human activities introduce sound into the environment either incidentally (by-product of their activities e.g., shipping, construction, fishing, windfarms) or intentionally for a particular purpose (e.g., sonars for bottom imaging, mapping and detection of objects or active seismic sources, such as airguns, for deep sub-bottom imaging of geological structures).

Anthropogenic sound sources have a broad range of characteristics, including source level (sound level 1 metre from the source), frequency content (expressed in Hertz [Hz] or kiloHertz [kHz]), duty cycle (pattern of occurrence) and movement (i.e., stationary or mobile). Sound sources can also vary between coastal and open ocean regions For example, shipping activity as a whole adds a component to ocean basin noise levels while an individual ship can create a dominant, but time-limited noise source within a local area.

Virtually all, marine vertebrates rely to some extent on sound for a wide range of biological functions, including communication, navigation, and detection of predators and prey (Richardson *et al*. 1995; Popper and Hastings 2009a). Various species (marine mammals, fishes, sea turtles, marine invertebrates, etc.) utilise and hear sounds differently. Baleen whales, most fishes, sea turtles, and invertebrates hear best at lower frequencies, while dolphins and porpoises can hear frequencies above (ultrasonic) our human hearing range (Budelmann 1992; Wartzok and Ketten 1999; Bartol and Musick 2003; Southall *et al*. 2007; Au and Hastings 2008; Webb *et al*. 2008). Additionally, marine fishes and invertebrates are also sensitive to acoustic particle motion, in addition to acoustic pressure (sound is composed of both an acoustic pressure and particle motion components; see text box below), to assess their environment (Packard *et al*. 1990; Horodysky *et al*. 2008; Kaifu *et al*. 2008; Popper and Hastings 2009a,b; Webb *et al*. 2008).

Anthropogenic underwater sound can have various impacts on marine species, ranging from exposures causing no adverse impacts, to behavioural disturbances, to loss of hearing, to mortality. Potential effects depend on various factors, including overlap in space and time with the organism and sound source, duration, nature and frequency content of the sound, received level (sound level at the animal), and context of exposure (i.e., animals may be more sensitive to sound during critical times, like feeding, breeding/spawning/nesting, or nursing/rearing young). There have been numerous publications describing these potential impacts (e.g., Richardson *et al*. 1995; NRC 2003, NRC 2005; Southall *et al*. 2007; Popper and Hastings 2009a,b; OSPAR 2009b,c; André *et al.* 2010). In areas with high levels of anthropogenic noise, listening horizons are significantly reduced by elevated background sound levels (Clark *et al*. 2009, NRC 2005).

Many populations of whales and fish have been reduced in abundance by commercial whaling and fishing. This reduction in abundance may have increased the separation between individual animals at the same time that noise may have reduced the range of communication. It is possible that these effects could affect the ability of these populations to recover (Tyack 2008).

The issue of noise exposure is complex with a wide variety of anthropogenic sound sources in the environment, numerous species inhabiting these environments, varying overlap in space and time between sources and receivers, and a range of potential impacts from exposure to noise, ranging from minor to severe.

Box 1. Sound pressure and particle motion

Sound in water is a travelling wave in which particles of the medium are alternately forced together and then 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 pressure is Pascal (Newton per square metre).

Each sound wave has both a pressure component (in Pascal) and a particle motion component, indicating the displacement (nm), the velocity ($m\ s^{-1}$) and the acceleration ($m\ s^{-2}$) of the molecules in the sound wave. Depending on their 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 also taking the physiology of marine life into account, it is customary to describe these through the use of a logarithmic scale. The most generally used logarithmic scale for describing sound is the decibel scale (dB).

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

$$SPL\ (dB) = 20\ \log10\ (P/P0)$$

P is the measured pressure level and P0 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. In conventional engineering measurements all these pressures are rms values (denoted dB). However, in some cases, either peak (dBp) or peak-to-peak (dBp-p) pressures is used.

Sound Exposure Level (SEL) is defined as ten times the logarithm to the base ten of the ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event (ANSI 1994)

As both the reference pressures for measurement and impedance differ between air and water, the dB levels for sound in water and in air cannot be compared directly (see Urick, 1983 and OGP, 2008 for more details).

Particle Motion

Sound can also be considered in terms of particle motion, acting in particular directions (usually along the axis of propagation), described as the particle displacement, particle velocity or particle acceleration. The ratio between sound pressure and particle velocity is constant far from the source and is defined by the acoustic impedance of the medium. Close to a source or close to reflecting objects or surfaces (like the sea surface) this ratio changes

1.5. Assessing Impacts from Noise Exposure

A simplified means of assessing impacts from noise exposure on the marine environment is the basic 'source-path-receiver' model, where 'source' refers to the noise source of interest, 'path' refers to the propagation of sound through the water, and 'receiver' refers to the marine organism of interest (Richardson *et al*. 1995; Rossing 2007). Each of these components has their own set of characteristics and complexities.

At the source, sounds can be broadly categorised as either impulsive or non-impulsive. Impulsive sound sources are typically brief, have a rapid rise time (large change in amplitude over a short time; this characteristic often makes these types of sounds more damaging to auditory structures), and contain a wide frequency range, which is commonly referred to as broadband (ANSI 1986). Impulsive sounds can occur as a single event or be repetitive, sometimes with a complex pattern of occurrence. Non-impulsive signals can be broadband or more tonal (containing one or few frequencies), brief or prolonged, continuous or intermittent, and do not have the rapid rise time (typically only small fluctuations in amplitude) characteristic of impulsive signals (ANSI 1995). Examples of impulsive sounds are those from explosions, airguns, or impact pile driving, while non-impulsive sounds result from sources like ships, construction (e.g., drilling and dredging), or wind farm operation. Sonar signals can be either brief or more prolonged and could arguably fall into both of the above categories depending on the signal. For simplicity, sonar signals are treated as impulsive in this report. It is recognized that different sound types (i.e., non-impulsive or impulsive) can result in different risks to marine organisms, especially in terms of injury and severity of impacts, with impulsive sounds (due to level and rise time) typically presenting the greatest risk (Southall *et al*. 2007). There have been numerous reviews of the physics associated with various sound sources (e.g., Urick 1983; Ross 1987; Richardson *et al*. 1995).

The path is also important when considering the potential impacts of noise to the marine environment as it is not solely the source level that determines the level of impact but rather the received level. Received levels are either obtained by direct measurement using a underwater recording device (hydrophone) or indirectly estimated by propagation models (understanding the way sound travels through the water column and the seabed). Various factors such as bathymetry, temperature, nature of the seabed, characteristics of the sound source (e.g., frequency) affect the received level at an organism a certain distance from the sound source. Ambient noise levels (background sound levels) affect what signal can be detected. There have been numerous reviews on sound propagation (e.g., Urick 1979, 1983; Ross 1987; Medwin 2005). Nevertheless, accurately describing propagation is difficult, partly due to insufficient environmental (e.g. oceanographic and geological) information and can vary greatly over time and space, especially since the overlap (space and time) between sources and receivers can also vary.

The impact of any particular received level also varies greatly with the receiving organism and its context. Most organisms can only detect and therefore be affected by a limited range of frequencies; organisms vary in their ability to detect sound levels. A species may change these abilities through time or season. The nature of effects on organisms can range from the extreme (death) to subtle alterations in behaviour.

The source-path-receiver model is a simplistic way to understand the basic physics associated with a sound source but it only provides limited information. The assessment of impacts on the marine environment requires a more complete understanding of the variability and consequences (e.g., impacts on individuals, impacts on populations, impacts on species, and impacts on ecosystems) of exposure to various levels of sound or exposure to different types of sound. Much more is known about sound sources and the propagation of sound through the environment compared with the impacts of that sound on organisms in the marine environment, as well as appropriate indicators for describing these impacts. For these reasons, in this report the focus is on the source to provide indicators for defining good environmental status. It is acknowledged that there is a broad range of anthropogenic sound sources present in the marine environment. Nevertheless, we have decided to focus on those that have the greatest potential for risk: 1) high amplitude, low and mid-frequency impulsive sounds, 2) high-frequency impulsive sounds, and 3) low-frequency continuous sounds (i.e., contributing to ambient or background noise levels). In all three cases the overall aim is to provide indicators that could be used to show reductions in intense sources that could damage hearing and sources that contribute to increasing ambient noise levels.

2. Identification of relevant temporal / spatial scales for indicators for underwater noise

2.1. Assessing scales of noise related effects

Sound travels in water about five times faster than in air and absorption is less compared to air. Not surprisingly, sound is an important sensory modality for many marine organisms, especially since other senses such as vision, touch, smell or taste are limited in range and/or speed of signal transmission. Due to its relatively good transmission underwater, sound acts at considerable spatial scales. Transmission varies with frequency: low frequency signals typically travel further whereas higher frequencies attenuate more rapidly, therefore fewer individuals might be exposed. Persistence of sounds is also very variable – ships on passage generate continuous sound; explosions are very short-term and there is much temporal variance in between these.

Studies so far have shown that underwater noise can affect marine life at various distances from the source, from very close ranges to tens of kilometres. When noise does cause effects, there may be temporary changes in behaviour, such as startle responses or changes in swimming patterns, but there may also be long lasting effects such as long-lasting exclusion from important habitats, injury or, in extreme cases, death of the exposed animal (for reviews, see Richardson *et al.* 1995; Würsig & Richardson 2002; Popper & Hastings 2009a; OSPAR 2009b, André *et al.* 2010).

TG11 examined three related frameworks for assessing the temporal and spatial scale of noise related effects in the marine environment:

1) the concept of zones of noise influence (Richardson *et al.* 1995),

2) the Population Consequences of Acoustic Disturbance Model (NRC 2005), and

3) the application of risk assessment frameworks in noise-effect studies (MMC 2007; Boyd *et al.* 2008).

2.2. Zones of noise influence

Richardson *et al.* (1995) defines several theoretical overlapping zones of noise influence (from a single noise source), depending on the distance between the source and the receiver. The zone of audibility is the largest and the zone leading to the death of an individual receiver, the smallest. This model (Figure 1) has been used very often in impact assessments where the zones of noise influence are determined based on sound propagation modelling or sound pressure level measurements on the one hand, and information on the hearing capabilities of the species in question on the other. It should be noted that this model gives only a very rough estimate of the zones of influence as sound in the seas is always three-dimensional. The interference, reflection and refraction patterns within sound propagation will inevitably lead to much more complex sound fields than those based on the model by Richardson *et al.* (1995). This complexity may lead to effects such as increases of received sound energy with distance, especially when multiple sound sources are used simultaneously, (i.e. seismic surveys; see OSPAR 2009b).

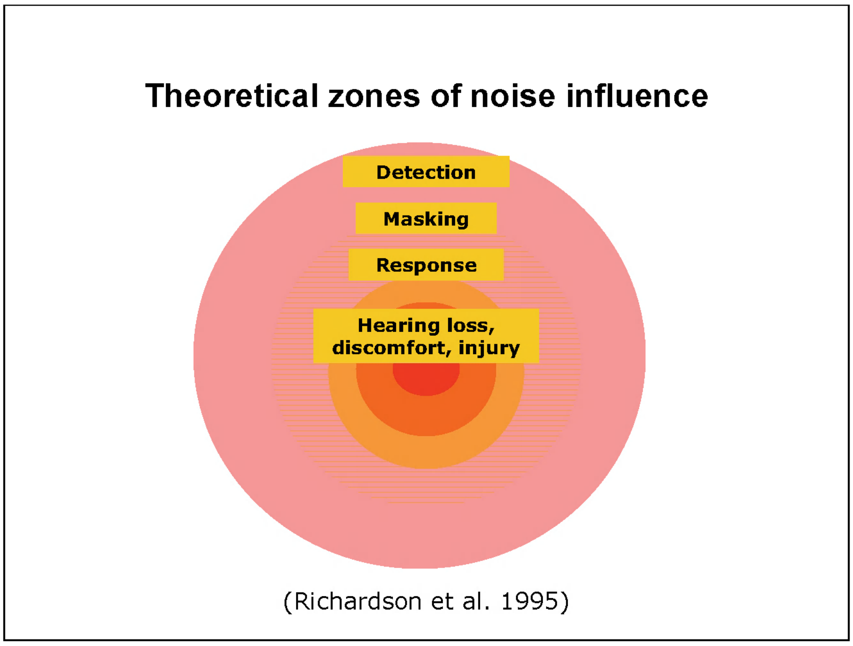

Figure 1. Theoretical overlapping zones of noise influence (after Richardson *et al.* 1995).

It is evident that the physical properties of the sound when it arrives at the receiver will be important in determining its effect. Many physical properties are relevant including sound pressure level, pattern of occurrence, particle motion, kurtosis ("peakedness"), frequency, duration, rise time etc). Distance between source and receiver relates to some of the properties such as received sound pressure level and duration, yet it is not the determining factor *per se*. Therefore, caution should be taken in applying the Zones of Noise Influence model. It can, however, provide a starting point in investigating the relationship between spatial scale and temporal scale of effects. Long-term effects such as permanent hearing loss and auditory injury might happen only relatively close to the source, whereas short-term effects such as disruption of behaviours might happen at longer ranges.

2.3. Population Consequence of Acoustic Disturbance Model

The links between the receiving of a sound by an individual organism and any changes in the biology of that organism can be complex, especially for any population level effect. In theory, a temporary change in an individual's behaviour could lead to long term population level consequences. These links are addressed by the Population Consequence of Acoustic Disturbance Model (PCAD model, NRC 2005, Figure 2). The model, developed for marine mammals but in theory applicable to other parts of the marine environment as well, involves different steps from sound source characteristics through behavioural change, life functions impacted, and effects on vital rates to population consequences. As can be seen in Figure 2, most of the transfer functions and variables of the PCAD model are currently unknown. Challenges to fill in gaps can come in many ways, due to uncertainties in population estimates for several species / regions, difficulties in weighting noise against and accumulating with other stressors, difficulties in quantifying noise impacts etc. (see NRC 2005 for a detailed discussion and Thomsen *et al.* in prep. for cases studies).

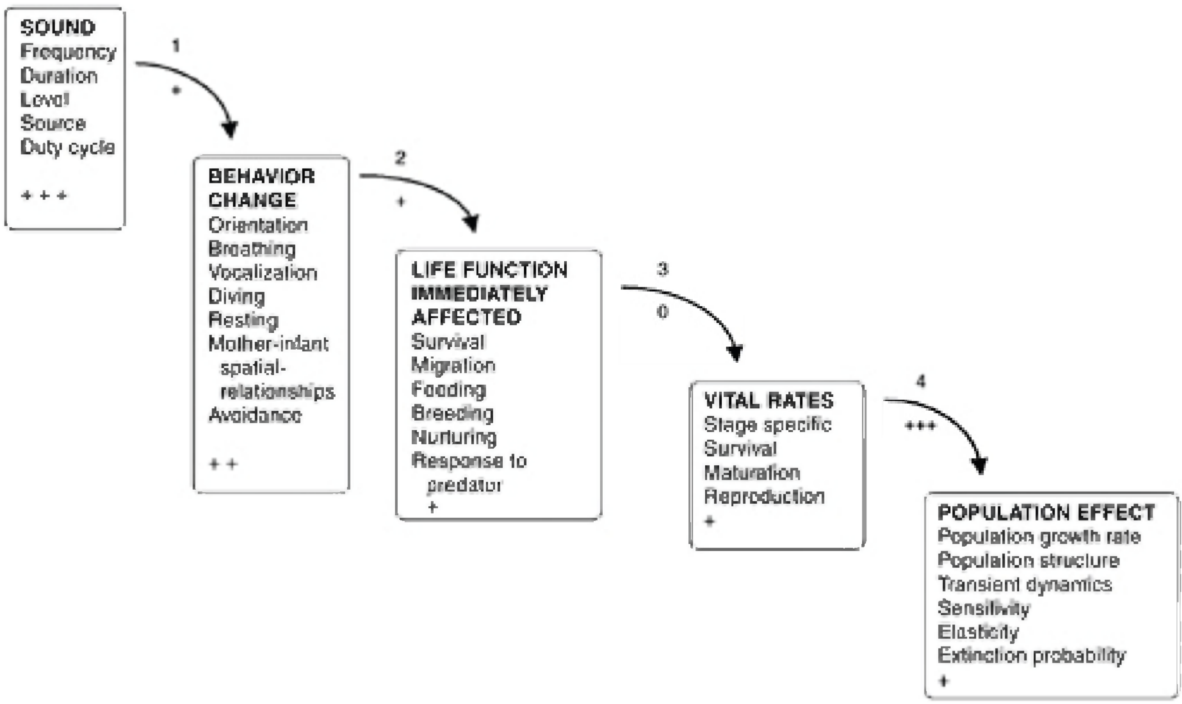

Figure 2. Overview of the PCAD-model by NRC (2005).
The + signs within the boxes indicate how well these features can be measured, while the + signs under the transfer arrows indicate how well these transfer functions are known. As can be seen, some transfer functions are not at all well known.

It should be noted here that assessment of the spatial scale of biological effects requires good information on the distribution and abundance of marine life. This is relatively good for some cetacean species in some areas (see for example Hammond *et al.* 2002), but very poor for others mammals and most other marine taxa (see Thomsen *et al.* in prep.).

No study has found a population (or stock) level change in marine mammals caused by noise exposure. A detailed review by Thomsen *et al.* (in prep.) found little response by cetacean populations to human acoustic disturbance in four case study areas. There are at least three explanations for the lack correlation between noise exposure and negative population trend.

1) it is difficult to count many marine mammal species accurately;

2) often a relatively subtle change in individual behaviour that does not scale well to higher levels of aggregation (see PCAD model), or that individuals are able to adapt and thereby compensate for negative effects.

3) Finally, the benefits that come with staying in an area of high value (for example a spawning ground) might outweigh the costs caused by human disturbance.

It is likely that no factor alone is harmful enough to cause a decline directly in marine life, yet, together they may create conditions leading to reduced productivity and survival in some cases. It is evident that potential impacts of sound have to be placed in a wider context, addressing the consequences of acoustic disturbance on populations in conjunction with other factors (OSPAR 2009a,b; André *et al,* 2010; Thomsen *et al.* in prep.).

2.4. Risk assessment frameworks

Many studies dealing with the temporal and spatial scale of effects of noise on marine life are often not well documented and/or anecdotal, and there is often a relatively high amount of speculation instead of evidence based conclusion (for critical reviews see Hastings & Popper 2005; Nowacek *et al.* 2007; OSPAR 2009b; Popper & Hastings 2009a; Southall *et al.* 2009; André *et al,* 2010). The application of risk assessment frameworks, originally developed for examining the impacts of chemicals, provide a tool for a more systematic approach and has been conceptualised for marine mammal noise impact studies by scientific bodies in Europe and the U.S. (MMC 2007;Boyd *et al.* 2008).

The risk-based assessment follows a stepwise approach:

1) Hazard identification: what are the actual and potential threats from each activity e.g. sound sources.

2) Exposure assessment (determine exposure to hazards): marine mammal numbers and distribution (results of baseline); characteristics of hazard and overlap between mammals and hazard (spectral, temporal, and spatial).

3) Exposure response assessment (determine range of possible responses): marine mammal sensitivities at the species level (and higher levels if possible) establishing dose-response relationships.

4) Risk characterisation: assessment of the overall risk of the impact including establishment of likelihoods and uncertainties.

5) Risk management: mitigation (for more details see Boyd *et al.* 2008).

Point 2) deals with scales of potential impacts by looking at received sound pressure levels at various ranges in relation to animal density to identify the number of individuals potentially affected. The investigation of the overlap between sources and exposed organisms is crucial, as areas of high density might indicate a relatively high value of the habitat, and activities would impact a relatively high proportion of individuals of any given population. On the contrary, in areas of low density, only a few individuals might be affected and with regards to populations, impacts might therefore be negligible. In addition, low density areas may indicate that a species/local population has already been exposed to other threat factors, and therefore should be even more strictly protected. One example is the harbour porpoise population in the central and eastern Baltic.

Table 1. Overview of observed effects of underwater noise on marine life (from OSPAR 2009b after Richardson *et al.* 1995; Würsig & Richardson 2002; Hastings & Popper 2005).

Impact	Type of effect
Physiological *non auditory*	- damage to body tissue: *e.g.* massive internal haemorrhages with secondary lesions, ossicular fractures or dislocation, leakage of cerebro-spinal liquid into the middle ear, rupture of lung tissue - induction of gas embolism (Gas Embolic Syndrome, Decompression Sickness/DCS, 'the bends', Caisson syndrome) - induction of fat embolism - disruption of gas-filled organs like the swimbladder in fishes, with consequent damage to surrounding tissues
auditory (Sound Induced Hearing Loss)	- gross damage to the auditory system – *e.g.* resulting in: rupture of the oval or round window or rupture of the eardrum - vestibular trauma – *e.g.* resulting in: vertigo, dysfunction of co-ordination, and equilibrium - damage to the hair cells in fishes - permanent hearing threshold shift (PTS) – *e.g.*, a permanent elevation of the level at which a sound can be detected - temporary hearing threshold shift (TTS) – *e.g.*, a temporary elevation of the level at which a sound can be detected
Perceptual	- masking of communication with con-specifics - masking of other biologically important sounds
Behavioural	- stranding and beaching - interruption of normal behaviour such as feeding, breeding, and nursing - behaviour modified (less effective/efficient) - adaptive shifting of vocalisation intensity and/or frequency - displacement from area (short or long term)

Point 3) concerns the responses as such and will lead to conclusions on the temporal scale of noise related effects. Note that dose-response studies are not good at detecting sub-lethal behavioural responses that could lead to subtle impacts over time. Animal behavioural statistics/models might well be a better match for many acoustic situations. Table 1 gives an overview of observed effects of noise on marine life. The first column lists physiological and auditory effects; the second column lists perceptual and behavioural effects. We might conclude that some of the physiological and auditory effects are permanent, for example in the case of injury and permanent threshold shift. Most of the perceptual and behavioural effects are rather short term with the important caveat that in some cases, noise might mask communication signals over relatively long periods and that short term behavioural responses might lead to long term population level consequences (see above).

2.5. Temporal and spatial scales of chronic exposure to noise

Exposure to short duration noise is mostly concerned with high intensity sound sources and can lead to a wide variety of effects such as behavioural changes, ranging from very subtle reactions to consistent avoidance, temporary changes in hearing threshold (TTS), permanent changes in hearing threshold (PTS), auditory injuries and non-auditory damage (see OSPAR 2009b).

The human transition to mechanical ship propulsion, increase in number of vessels, and other ocean activities has lead to increasing ocean noise (Hildebrand 2004). The global commercial shipping fleet expanded from around 30 000 vessels in 1950 to over 85 000 vessels in 1998 (NRC 2003). Noise from maritime transportation is likely to be more widely distributed in the future as the Arctic becomes accessible, and as the number and size of vessels increase (Hatch & Fristrup 2009). A strong component of anthropogenic sound sources is transient, brief, atonal, mostly impulsive and sometimes repetitive sounds. Those sounds generate impulsive waves of short duration, high peak pressure, and a wide frequency bandwidth, and may consequently have an effect on marine organisms (ICES 2005). This type of sound is herein considered as short duration noise. It is furthermore characterised by a relatively rapid rise-time to maximum or minimum pressure followed by a decay that may include a period of diminishing and oscillation maximal and minimal pressures (Southall *et al.* 2007). Impact assessments are generally concerned with those anthopogenic activities that overlap in frequencies with the hearing range of marine organisms in question. However, for very loud sounds, which in most cases relate to short duration noise, the frequency becomes less relevant and peak pressure becomes the decisive factor (OSPAR 2009b).

In order to describe a good environmental status (GES) of the marine environment it is essential to consider the occurrence of this type of noise and its effects on marine biota. In this context it is important to assess the effects of single and multiple exposures over time as well as the effects of simultaneous exposures to sounds from different sound sources. The history of exposure may also need to be taken into account.

The effects of exposure to short duration sound sources reach intensities with a potential of causing a variety of effects in the marine fauna ranging from:

1 indirect effects (such as the reduction of habitat availability, reduced availability of

prey);

2 chronic effects (such as cumulative and synergistic impacts, sensitisation to sound exacerbating other effects, habituation to sound);

3 perceptual (masking of communication with conspecifics and other biologically important sound, interference with the ability to acoustically interpret the environment and with food finding);

and

4 behavioural effects (stranding and beaching, interruption of normal behaviour such as feeding, breeding and nursing, behaviour modified (less effective/efficient), loss in efficiency, antagonism toward other animals, displacement from area (short or long term, adaptive shifting of vocalisation intensity and/or frequency);

to

- physiological effects of the categories auditory (TTS, PTS, vestibular trauma, gross damage to auditory system), non-auditory (damage to non-auditory body tissue, embolism) and stress-related (compromised viability of individuals, suppression of immune system and vulnerability to disease, decrease in reproductive rate) (OSPAR 2009b).

High amplitude, low and mid-frequency impulsive sounds are those that have caused the most public concern, particularly in relation to perceived effects on marine mammals and fish. These sounds include those from offshore constructions such as pile driving, the use of airguns during seismic surveys, various types of sonar and explosions. Source levels vary widely and can be very powerful, e.g. in case of seismic explorations reaching 255 dB_{peak} re 1 µPa@1 m (Richardson *et al.* 1995). Shockwaves due to explosions reach even levels of >280 dB_{peak} re 1 µPa@1 m (Nützel, 2008) and due to ship shock trials (10 000 lb. TNT) 299 dB_{peak} re 1 µPa@1 m (Hildebrand 2004). Some activities such as seismic surveys are routinely conducted over several weeks, with repetition rates of several signals per minute but on a global scale, the number seismic vessels is relatively limited. In contrast, sonars in the form of depth sounders and fish-finders are far less powerful yet the number of units in operation on a daily basis is nearly impossible to determine.

Currently short duration noise is mainly considered in relation to physiological effects as well as physical impairment or damage of marine mammals, fish and some invertebrates. Laboratory studies have found both physiological and behavioural effects in a variety of marine organisms, while field studies have shown behavioural disturbance and in some cases death (physiological effects are difficult to study in the field). Fish use sound in many of the ways that marine mammal do: to communicate, defend territory, avoid predators, and, in some cases, locate prey (Popper *et al.* 2003). Potential effects of short duration noise encompass the risks of immediate auditory damage or injury of the body from intense sound sources (OSPAR 2009b). On the population level, however effects on the behaviour of marine organisms or long term stress could be equally or even more important in relation to habitat exclusion, foraging success, health and reproduction. The cumulative impact of behavioural changes poses a further threat from noise. Many now hypothesise that the mechanism(s) underpinning the phenomenon of beaked whale mass strandings linked to naval sonar are initially triggered by a behavioural response to acoustic exposure rather than a direct physical effect of acoustic exposure (e.g. ICES 2005).

There will be a variety of degradation gradients caused by such noise, the scale of these depending on the marine organism under consideration and the amplitude, frequency and number of inputs of the sound. In principle, sound input is likely to have greater adverse effects at higher sound amplitudes and with a greater number of inputs. As noted above, lower frequency sounds will affect a wider area, but this is complicated by the ability of organisms to detect a limited range of sound frequencies; sounds outside their range of perception will be less likely to have an adverse effect. Also, amplitude would be the greatest concern for immediate hearing damage or adverse startle responses, but the duration is highly significant for displacement impacts.

These multiple complexities in defining "adverse impact on the marine environment" and when it might occur led to the Task Group considering that the most suitable indicator for this type of sound would be a "pressure" indicator that quantified the amount of these sounds emitted. Member States would then determine where on this indicator GES might occur, or might instead decide to set a level of reduction in the indicator value as a way of moving towards GES. Alternatives that quantified "effect" were considered very difficult if not impossible to set and were likely to be highly selective in terms of biota considered.

The spatial scale of any indicator looking at acute exposure to noise is dependent on the effect that has to be investigated and the abundance and distribution of sensitive marine life in the region in question. TG11 notes that the spatial scales of behavioural effects are very difficult to quantify and results are highly equivocal (see also reviews by Nowacek *et al.* 2007, Southall *et al.* 2007, OSPAR 2009b; Popper & Hastings 2009a,b; Southall *et al.* 2009). With regards to TTS, most studies so far indicate a relatively high threshold both for marine mammals and fish, leading to comparably small ranges of impact (Popper *et al.* 2006; Southall *et al.* 2007, but see recent studies by Lucke *et al.* 2009). Yet, we have to consider that thresholds vary with exposure time / number of received signals with an increase in both factors resulting in much lower thresholds and therefore much higher impact ranges (see Popper *et al.* 2006; Southall *et al.* 2007). PTS, other auditory damage, non auditory injury and death will happen only at relatively close ranges to the source (see OSPAR 2009b). Any indicator must be associated to a monitoring area large enough to be implemented in a realistic cost efficient way, but small enough to avoid spatial smoothing effects. A 15'X15' rectangle was considered to be a good compromise.

2.5.1. Temporal and spatial scale of masking

In marine mammals (cetaceans and pinnipeds) and in fishes, sound can be important in communication, in orientation, in predator avoidance, and in foraging. It is very likely that some cetaceans listen to sounds of their prey or conspecifics in order to obtain biologically relevant information (Tyack & Clark 2000; Janik 2005). Social signals of some cetaceans species have very large detection ranges of up to more than 1,000 km and at least in theory, communication networks might cover very large areas (Janik 2005, see Table 2). Many marine fish species produce sounds for communication and predator avoidance, and it has been suggested that they also use sounds for orientation (Ladich *et al.* 2006, Montgomery *et al.* 2006).

The social signals of some cetacean species have very large detection ranges (some probably more than 1000 km) and communication networks could potentially cover very large areas (Janik 2005). The “active space” of a cetacean is defined as range up to which sounds can be perceived by members of the same species (Janik 2000). Table 2 shows some measured active spaces but it should be noted that the size of these spaces is dependent on many factors (e.g. source level, background noise, transmission loss, critical ratio of the dolphins hearing) and that some of these are highly site and/or individual specific. The values in the table are therefore only valid for the area where the research was undertaken.

Table 2. Maximum distances from which marine mammals can be detected and estimated active spaces of some odontocete signals (taken from Janik 2005).

Species	Frequency range (kHz)	Distance (km) of recording
Sperm whale	0.1 - 30	37
Bowhead whale	0.025-3.5	17
Humpback whale	0.02-8.2	15 / 160 (2 studies)
Fin whale	0.01-0.75	> 20
Blue whale	0.012-0.39	600 / 1,600 (2 studies)

Species	Frequency range (kHz)	Active space (km)
Bottlenose dolphin whistle	4 - > 20	20-25 max, 16 average
Killer whale call	1 - 20	26
Sperm whale click	0.1 - 30	60

Masking occurs when noise is strong enough to impair detection of biologically relevant sound signals used in the contexts described above. The zone of masking is defined by the range at which sound levels from the noise source are received above threshold within a 'critical band' of frequencies centred on the signal (NRC 2003). It starts when the received sound level of the masking sound, for example noise from a nearby ship, is equal to the ambient noise within the critical band. Masking can shorten the range over which sounds can be detected and conspecifics are able to communicate for example mother and calf pairs of odontocetes (Richardson *et al.* 1995; Janik 2005). A number of studies have examined the impacts that masking has on a variety of species, and have considered and/or modelled the extent to which low frequency (< 1 kHz) noise from shipping and other activities can greatly reduce communication ranges for marine animals (see Payne & Webb 1971; Erbe & Farmer 2000, Erbe 2002; Thomsen *et al.* 2006, Southall *et al.* 2007). The greatest potential for masking exists for marine life that produce and perceive sounds primarily within the lower frequencies contained in noise; this includes the baleen whales, seals, sea lions, and fish, as well as the lowest social sounds of some of the toothed whales (overviews in Ladich *et al.* 2006; Perrin *et al.* 2008). Noting the lower transmission of higher (1-25 kHz) sounds in water, the potential for masking at these frequencies exists when the vessel is in close proximity to the exposed organism. In these circumstances, other marine mammals, including many toothed whales (e.g., beaked whales, sperm whales, dolphins and porpoises) may also experience masking from vessel noise. Because of the logarithmic nature of sound and what is known about hearing systems in mammals, seemingly small changes in background noise levels may result in large reductions of marine animals' communication ranges (Janik 2005; OSPAR 2009b).

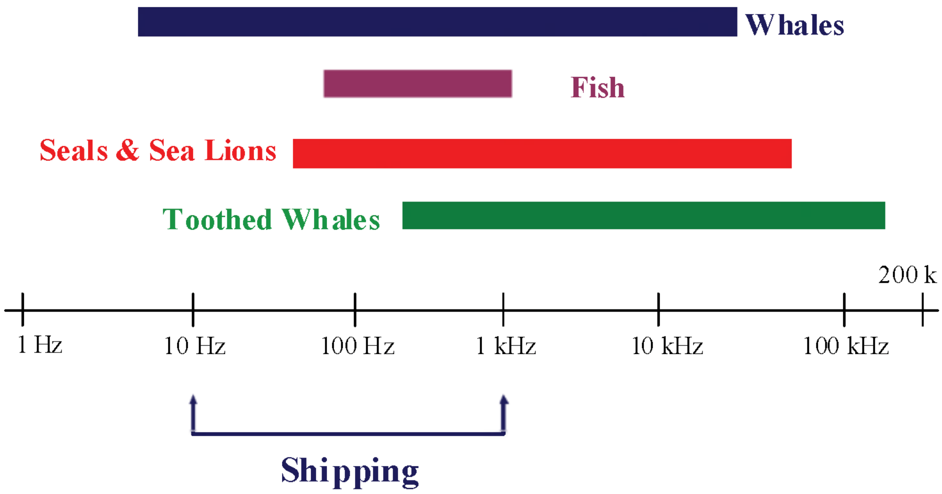

Figure 3 Typical frequency bands of sounds produced by marine mammals and fish compared with the nominal low-frequency sounds associated with commercial shipping (taken from OSPAR 2009b). Note that some organisms are sensitive to frequencies beyond those that they produce,

There are very few data on current ambient noise levels in most regions, and even less accessible historical data. Information on trends is not available in any European waters. According to the Marine Mammal Commission (MMC 2007), underwater ambient sound levels will increase over time with more human activity (shipping, offshore construction) in the marine environment. For example, projections indicate a doubling of shipping activity in the first 50 years of the 21st century and therefore one might assume an increase in noise around shipping lanes (MMC 2007). Yet, due to advances in technology most modern ships are perhaps quieter than their predecessors (for an overview of such techniques, see Renilson 2009). It should be further noted that the potential increase in ambient sound levels will not affect all areas equally but specific regions where offshore activity is high, for example some of the Exclusive Economic Zones around North West Europe (see OSPAR 2009b). Potential effects might not be proportionate to input due to variation in sound propagation and - most importantly - the distribution of marine life that is sensitive to sound (for an overview of marine mammal distribution, see Perrin *et al.* 2008; case study example off the UK, see Thomsen *et al.* 2009; case study in Spain, see André *et al.* 2010).

From the perspective of an animal receiving sound, it should be noted that the possibility of detecting a far distant signal does not mean that the receiver makes use of it (Janik 2005).

Furthermore, most animals use a range of frequencies to communicate and it is therefore unlikely that the full range of frequencies would be masked over long time periods. Nevertheless, most fish use sound over a relatively narrow frequency band and in a major shipping lane or on a fishing ground it is likely that their ability to detect and respond to sounds is affected for long periods. Documented mechanisms to compensate for masking include altering the timing and the design of social signals (Miller *et al.* 2000; Foote *et al.* 2004). The costs of these behavioural compensations are unknown and it is only recently that studies on the effects of masking on marine life have started.

Nevertheless, important information *can* be lost through masking even if detection is not masked over the full hearing range and the average level of background (a combination of ambient natural and anthropogenic noise) noise in a year (=sound budget) of some areas may be increased chronically, e.g. near shipping routes. If biological important functions such as foraging or finding mates are interrupted, masking can potentially have adverse effects. The issue of increasing ambient noise levels and resulting effects on marine life has been identified by various scientific bodies as one of the top priorities for further research (IACMST 2006; Southall *et al.* 2007, 2009; OSPAR 2009c; André *et al*. 2010).

2.5.2. Stress and indirect effects

Based on extrapolations from investigations in terrestrial mammals, Wright *et al.* (2007) speculate that underwater noise, including chronic exposure, can act as a stressor in marine mammals with consequences to individual health and population viability.

In this context, the term stress is used to describe physiological changes that transpire in immune (and neuroendocrine) systems following exposure to sound. Stress indicators in marine mammals have been recorded but physiological responses to stress are still not completely known. For example, dolphins undergo changes in heartbeat rhythm in response to sound exposure (Miksis *et al.* 2001).

Cetaceans reveal stress symptoms much in the same way as other mammals and can be extremely sensitive to over stimulation of the adrenal cortex (Thomson and Geraci 1986). It is therefore highly feasible that cetaceans living in areas of high density maritime traffic or coastal areas and affected by relentless high intensity noise are continually at risk from stress related to that noise.

2.5.3. Biological sound

It is important to note that in many areas ambient sound may be dominated by sound of biological origin from sources including snapping shrimps and fish.

3. Indicators for underwater noise

3.1. Low and mid-frequency impulsive sounds

The Task Group first proposes an indicator for the occurrence of high amplitude, low and mid-frequency impulsive anthropogenic sounds.

The Task Group suggests an indicator based on the incidence of sounds in a specified area. The indicator would be based on reports of occurrence by those undertaking or regulating the generation of these sounds, rather than direct independent measurements. Recording would be based upon regional seas (or national parts of regional seas).

The indicator is based on the proportion of days on which impulsive sounds (defined below) exceed a specified level which produces definable harm to animals. The affected days are those where the level exceeds a specified value on at least one occasion. The Task Group chose a single occasion because it could find no obvious way of justifying any particular number of occasions. Just one occasion when the level exceeds the specified value may have an effect; if there is no occasion when the level is exceeded then there will be no effect.

The choice of frequency bandwidth (10Hz to 10kHz) is based on the observation that sounds at higher frequencies do not travel as far as sounds within this frequency band. Although higher frequency sounds may affect the marine environment, they do so over shorter distances than low frequency sounds. This choice of bandwidth also excludes most depth-finding and fishery sonars.

The indicator is focussed on those impulsive noise sources that are most likely to have adverse effects. Sources which exceed particular source levels will be used for the indicator. The recommended source levels are based on a comprehensive review of scientific literature published in 2007 (Southall *et al.* 2007) for received levels that cause physiological effects on cetaceans – in this case temporary impairment of hearing. Southall *et al.* (2007) proposed the use of dual criteria to combine information on the Sound Exposure Level (SEL) that integrates received sound energy over time and the Sound Peak (Pressure) Level (SPL) of the sound source. The sound duration as well as the sound level is important in estimating the damage that may be caused by a sound (ICES 2005).

As noted earlier, there has been insufficient research to define a received level above which there will be no harm to all receiving organisms. Adverse effects may occur at lower levels than those that TG11 suggests. For fish, Popper *et al.* (2006) suggested interim sound pressure criteria for injury of fish with swim-bladders which are exposed to pile driving operations, with values for both SEL and for peak sound pressure, as suggested for marine mammals. However, many fish are sensitive to particle motion rather than sound pressure, and many of them lack swim-bladders. Values for injurious levels of both particle motion and sound pressure have yet to be determined for these species. Levels of particle motion which cause recognisable levels of damage are a particular research priority.

It is important to realise that such criteria are based on very limited data with respect to noise induced injury. In particular, there are very few data on the cumulative effects of repeated exposure. The Task Group recommends that these levels be reviewed in the future in the light of any new scientific publications.

The size of area to be considered must be a compromise. An index sensitive to small changes in activity would have small rectangles, while large rectangles are likely to be administratively easier to use. TG11 recommends the choice of 15'N x 15'E/W rectangles, but other choices would be possible at approximately this scale. It should be noted that a rectangle off Shetland would be about 60% of the area of a rectangle off Gibraltar, so it might be possible to have variation of grid rectangle by regional sea.

The sources encompassed by the indicator will include all classes of high intensity impulsive sounds which are known to affect the marine environment adversely, for which the activities that generate such sounds are routinely licensed or are assessed. Some lower intensity sounds that are rarely subject to licence would not be included. The Task Group would expect that sounds made by most commercial seismic surveys, by impact pile-driving, by low and mid-frequency sonar and by explosions to be included. The Task Group would not expect depth-finding and most fishery sonar to be included. Those sources that will be included therefore should be quantifiable from either relevant impact assessments or reports from activities required under national licensing regimes.

Based on these arguments, we put forward the following indicator (Indicator 1) for high amplitude, low and mid-frequency impulsive sounds:

Underwater noise indicator 1

> **The proportion of days within a calendar year, over areas of 15'N x 15'E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re 1µPa^2.s (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1µPa$_{peak}$ (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz**

At present the Task Group cannot advise on current (background) figures for the proportion of days but would expect that these figures could be readily established once the recording areas were agreed.

3.2. High frequency impulsive sounds

Depth sounding sonar systems on small vessels typically use frequencies between 50 and 200 kHz. Sonar usage, particularly on leisure boats, is increasing and is unregulated. These vessels tend to operate in coastal areas throughout the EU; these waters are often important for some marine mammals. These animals use frequencies up to about 180 kHz for communication and thus there is an overlap in frequency usage. There has been little research on the effects of these sonar systems and the scientific evidence for adverse effects is limited. However, the sounds are similar to those used in acoustic alarms (pingers) that are designed to scare away small cetaceans from gill and tangle nets used in the fishery, and can therefore be expected to cause adverse effects. A precautionary approach would be to reduce the usage of sonar systems working at frequencies below 200 kHz. Frequency is related to depth range; however in shallow areas, 200 kHz or more would be sufficient as a depth sounder for most purposes and would not affect marine mammals. A possible initial indicator for high frequency impulsive noise would be:

Underwater noise indicator 2 – high frequency impulsive sounds

> **The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least *x*% per year starting in [2012].**

This indicator does not include a measure of the use of small vessels, or the use of sonar on them, since this is virtually impossible to monitor, but the number of vessels with such sonar systems will be a sufficient proxy. The target percentage decrease (x) in usage would be set by Member States depending on how rapidly a reduction is deemed necessary.

3.3. Low frequency continuous sound

Ambient noise is defined as background noise without distinguishable sound sources (see Wenz 1962; Urick 1983). It includes natural (biological and physical processes) and anthropogenic sounds. Research has shown increases in ambient noise levels in some areas in the past 50 years mostly due to shipping activity. This increase might result in the masking of biological relevant signals (e.g. communication calls in marine mammals and fish) considerably reducing the range over which individuals are able to exchange information. It is also known that marine mammals alter their communication signals in noisy environments which might have adverse consequences. It is further likely that prolonged exposure to increased ambient noise leads to physiological and behavioural stress.

Ambient noise in most areas varies greatly with weather, daily and seasonally (see for example, Wenz 1962; Nedwell *et al.* 2007; Figure 4) and consistent changes can therefore only be measured on a large time scale e.g. over decades.

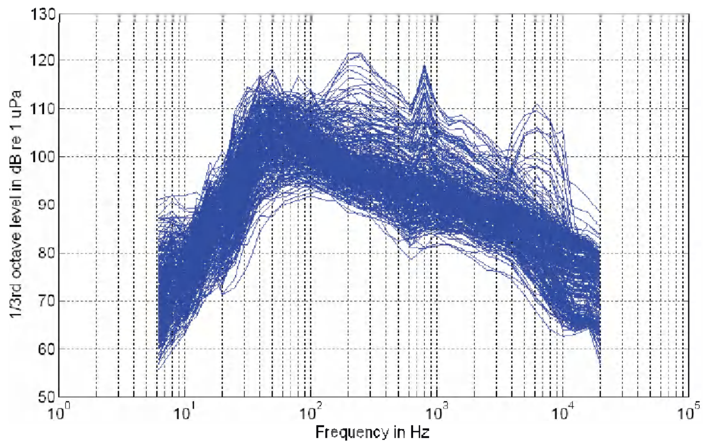

Figure 4 Spectra of ambient noise in a location near a main shipping route in the North Sea over a period of 10 days in May 2008. Large fluctuations and high levels of ambient noise result from shipping and variable weather conditions (K. Betke, pers. comm.).

Since ambient noise profiles undergo significant variations over daily and seasonal scales, the measurements have to be continuous or at least covering appropriate intervals. For the sake of practicality and efficient analysis of data, an appropriate sample interval has to be chosen. One possible sample period: total period ratio could be 1:60. One possible minimum period of sampling could be 1 min.

There is no single answer to an appropriate spatial scale at which measurements should occur; the effects of continuous sound are likely to be felt at all scales varying with the different marine biota affected – some marine mammals can communicate over relatively large scales, while fish perceive sound over much smaller scales. The Task Group suggests using the Regional Seas as suitable areas, with stations being chosen to represent each of those seas.

A possible initial indicator for low-frequency, continuous noise would be:

Underwater noise indicator 3

> **The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year [2012] or 100 dB (re 1μPa RMS; average noise level in these octave bands over a year)**.

This indicator would be based on direct independent measurements. The choice of representative sets of observation stations is left to Member States working together and should benefit from existing networks of underwater observatories (e.g. ESONET). Recording would be on the basis of Regional Seas [or national parts of regional seas].

The choice of these octave bands is on the basis of scientifically justifiable signatures of anthropogenic noise that avoids most naturally generated sources (see Wenz 1962). Unless relevant data already exists, the baseline year would be set at whenever the observatory system for a regional sea is established. The proposed threshold (100 dB, ref 1μPa in the band) is based on being 10 log B above the current known maximum to take into account the fact that the measurement is integrated on one octave. This level can be seen in Figure 4 and is corroborated by measurements provided by Thomsen *et al*. (2006). Madsen *et al*. (2006) reviewed Third Octave Band Levels (TOLs) for their review on the effects of offshore wind farm sound on marine mammals. These sources indicate that 100 dB would be at the upper end of what has been measured and therefore would indicative of 'poor environmental status'.

Systematic coverage of ambient noise levels in large areas will be costly. Instead sampling in representative areas at appropriate spatial scales may be sufficient. It may be possible to set up a monitoring network by using existing infrastructure such as the wavenet system of buoys off the UK (see http://www.cefas.co.uk/data/wavenet). Furthermore, focussing on bands where most shipping noise is concentrated (e.g. 63 and 125 Hz 1/3 octave bands) would be a cost effective approach.

4. Potential future indicators

The Task Group acknowledge that the three suggested initial indicators do not cover all anthropogenic sources of noise in the marine environment. The Task Group notes below one noise source that Member States may wish to monitor or limit in future. The Task Group would be willing, if provided with time and resources to attempt to develop an indicator for these sources. Other future indicators could be derived for other sources of energy, including electromagnetic fields and heat. Some background to these potential future indicators is described below. These suggestions are for indicators that could be developed with a little research in the short-term. Section 5 deals with indicators and concepts that would require further research in the medium and longer term.

4.1. Devices to deter marine mammals

Acoustic Deterrent Devices (ADDs or 'pingers') and Acoustic Harassment Devices (AHDs or 'seal scarers') are designed to displace porpoises/dolphins and seals, respectively, from the immediate vicinity of fishing and aquaculture gear and construction work. Source level is typically between 130 and 150 dB re 1 µPa@1m peak-to-peak (or up to 150 dB re 1 $\mu Pa^2 s$ @1m (Shapiro *et al*. 2009). ADDs are available commercially in two basic varieties:

a) mid-frequency (10 kHz) tonal, with and without higher harmonics, and

b) broad spectrum, multi-harmonic and frequency modulated with a frequency range between 5 and 160 kHz.

The pulse duration is typically 200-900 ms, and the pulse interval varies between fixed 4s to semi-randomly varying between 4s and 30s (Shapiro *et al*. 2009).

ADDs are an important tool in reducing harbour porpoise bycatch and are required in certain fisheries under EU regulation 812/2004 and their use has been recommended in other fisheries (ASCOBANS Baltic Sea harbour porpoise recovery plan, ASCOBANS North Sea harbour porpoise conservation plan). However, their effect is to displace marine mammals from parts of their habitat, possibly with adverse consequences. Typically nets with ADDs have soak-times ranging from few hours to one day (Prout 1993, Tregenza *et al*. 1997). Their effects therefore depend partly on the intensity and distribution of the fisheries. ADD's may also be used in connection with marine operations to keep animals out of the zone of physical damage. In these cases ADD's will typically have fixed positions over longer periods of time.

Studies on captive harbour porpoises exposed to ADD's clearly show avoidance reactions, change in dive and echolocation behaviour as well as changes in heart rate (Kastelein *et al*. 2000; Teilmann *et al*. 2006).

AHDs were originally designed to keep seals away from e.g. stationary fish farms and fixed fish traps (Milewski 2001), but they can also exclude cetaceans from large areas (Johnston 2002, Olesiuk *et al.* 2002, Morton and Symonds 2002). In the case of killer whales (Morton and Symonds, 2002), avoidance persisted as long as the devices where in operation. The results of this study are difficult to interpret as it did not include any controls. Like the ADDs, AHDs are also used to displace marine mammals from areas with noisy marine operations that may cause physical damage, like pile driving in connection with wind mill construction (Tougaard *et al*. 2009).

Commercially available AHDs operate in a frequency range of 5–30 kHz with a pulse duration of 250-500 ms and with source levels of 187-195 dB re 1 µPa peak-to-peak @ 1m (Richardson *et al*. 1995) or exceeding SEL 170 dB re 1 μPa^2s @1m (Northridge *et al*. 2006). The pulse interval varies; in one commonly used AHD there is a long interval (83-96 s) in between a bout of 9-17 signals with short (1.5-2s) intervals (Fjälling *et al*. 2006).

AHDs require considerable more power than ADDs and cannot be easily moved around, and typically are placed at fixed positions, almost exclusively in coastal areas, and over long periods of time. Concern has also been expressed that some of the AHDs used at aquaculture sites may inflict physical damage to animals nearby (Northridge *et al*. 2006). Logically, an animal would avoid the immediate vicinity of an AHD, but with sporadic and unpredictable emission, it is quite possible that an animal would come close enough to suffer auditory damage. Theoretical studies suggest that auditory damage would be possible for cetaceans within 10m of an AHD. Seals, with less sensitive hearing, would need to be closer to suffer damage (Gordon and Northridge, 2002; Taylor *et al*. 1997).

Although the source level of most deterrent devices are below the source level suggested for indicator 1, their repetition pattern (long lasting transmissions for several months) and their widespread (mostly coastal) use may generate long term behavioural changes that could affect GES. TG11 suggests that the extent of the use of both ADDs and AHDs could be documented and an indicator for one or both of them could be developed and introduced in the future.

4.2. Electromagnetic fields (EMF)

The term electromagnetic fields (EMF) encompass two fundamentally different fields, the electric field and the magnetic field. Whereas the strength of electric fields is measured in volts per metre ($V\ m^{-1}$) the respective measure of magnetic fields is tesla (T). The well known geomagnetic field of the earth varies with the latitude and reaches about 50 µT in the North Sea. Naturally occurring electric fields in the sea are constantly induced by the movement of seawater in the geomagnetic field and about 25 $\mu V\ m^{-1}$ is regarded the natural ambient level in the North Sea (Poléo *et al*. 2001, Koops 2000).

Anthropogenic EMF is introduced into the marine environment whenever electric energy is transmitted from one point to another and therefore generally is linked to operational submarine cables. Power cables are in use to supply islands with electricity, to connect the terrestrial grids of or between countries or to transmit electric energy produced by offshore wind farms or by wave and tidal energy plants to the mainland. Oil and gas pipelines may be electrically heated to prevent wax and hydrate formation which can reduce flow and potentially block pipelines.

Electric current is also used to transport information via coaxial cables, the former standard of telecommunication cables. Modern submarine telecommunication systems are fibre optic cables using pulses of light to transport information, but at least long-distance optical cables require repeaters and thus also need a constant electrical power supply.

4.2.1. Technical background

In principle, the strength of emitted EMF increases proportionally to the electricity transmitted. Electric fields are generated by voltage and increase in strength as voltage increases. Hence, high voltage transmission in general produces stronger electric fields than medium or low voltage transmission. Magnetic fields are generated by flow of current and increase in strength as current increases. Another aspect to be considered is the induced electric field generated by the interaction between the magnetic field around a submarine cable and the surrounding seawater.

In addition, the occurrence and strength of EMF generated during power transmission depend on the setup of the submarine transmission system. There are two technical different solutions for power transmission: determined by both the capacity and length of the transmission line. Alternating Current (AC) or High Voltage Direct Current (HVDC) is used. In general, HVDC cables produce stronger EMF than AC cables. The time-varying magnetic field outside the cable (AC) induces (Faraday's induction law) an electric field in surrounding conductive materials (e.g. seawater, seabed) whereas the movement of seawater through a magnetic field (constant in case of DC) also generates (Lorentz law) an induced electric field.

For DC transmission it is distinguished between monopolar and bipolar systems. In a monopolar configuration the return current is carried by seawater (or a separate return conductor) whereas in bipolar systems two similar conductors of opposite polarity are installed providing bi-directional transmission capacity. In case of a bipolar system the (electro)magnetic fields emitted compensate each other depending on the distance between the two conductors and reaching ideally a 100 % neutralisation when using a coaxial-cable. AC transmission uses normally three separate conductors. Again, if combined in a single three-phase AC transmission cable the EMFs emitted are almost neutralised at the cable surface. Emission of magnetic fields is thus best limited by field compensation whereas directly generated electric fields are regarded to be controllable by adequate shielding.

4.2.2. The impact of electromagnetic fields on marine species

A number of marine species including fishes, marine mammals, sea turtles, molluscs and crustaceans are sensitive to electromagnetic fields and use them for e.g. orientation, migration and prey detection (see Poléo *et al*. 2001; Gill *et al*. 2005; OSPAR 2008).

Some marine fish species use the earth's magnetic field and field anomalies for orientation especially when migrating (Fricke 2000). Artificial magnetic fields may impair the orientation of fish and marine mammals and affect migratory behaviour. Field studies at the offshore wind farm Nysted on fish provided first evidence that operating cables change migration and behaviour of marine fish (Klaustrup 2006). Elasmobranch fish can detect magnetic fields which are weak compared to the earth's magnetic field (Poléo *et al*. 2001; Gill *et al*. 2005).

Marine teleost (bony) fish show physiological reactions to electric fields at minimum field strengths of 7 mV m^{-1} and behavioural responses at 0.5-7.5 V m^{-1} (Poléo *et al*., 2001). Elasmobranchs (sharks and rays) are more than ten-thousand fold as electrosensitive as the most sensitive teleosts. Gill & Taylor (2001) showed that the spurdog *Scyliorhinus canicula* avoided electric fields at 10 µV cm^{-1}.

Mesocosm experiments by Gill *et al*. (2009) using EMF emission intensity (8 µT; 2,2 µV m^{-1}), which was towards the lower end of the range of detection for the elasmobranches, provided evidence that response to the presence of EMF is both species and individual specific. Small-spotted catshark *Scyliorhinus canicula* showed significant reactions whereas only some individuals of thornback ray *Raja clavata* and none of the spurdog *Squalus acanthias* did so. Presumably also related to the emission of EMF a number of failures of telecommunication cable due to bites of fish including sharks have been reported, one of them related to the above mentioned fibre-optic cable emitting an induced electric field of only 6.3 µV m^{-1} (Marra 1989).

In regard to effects on fauna it can be concluded that there is no doubt that electromagnetic fields are detected by a number of species and that many of these species respond to them. However, threshold values are only available for a few species and it would be premature to treat these values as general thresholds. In addition, the significance of the response on both individual and population level is uncertain if not unknown. More field data would be needed to draw firm conclusions but data acquisition under field conditions is complicated.

4.2.3. Anthropogenic introduction of electromagnetic fields into the marine environment

Following Gill *et al*. (2005) voltages and currents used in pipeline heating systems are understood to vary widely but no accurate figures are available and the magnitude of EMF produced is unknown. For 7500km transatlantic crossing with 100 repeaters, the total electrical requirement would be close to 10 KV. Concerning EMF emissions of telecommunication cables, Gill *et al*. (2005) cited only Marra (1989) who reported that a fibre-optic cable at the Canary Islands emitted an induced electric field of 6.3 µV m^{-1} @ 1m.

Information on the strength of electric and magnetic fields in the vicinity of submarine power cables mainly originate from calculations and only few data are the result of field measurements. For example, according to Koops (2000) a monopolar DC transmission line carrying 1500 A produces a magnetic flux density of approximately 300 µT on the seabed above the cable, falling off to 50 µT at a distance of 5 m above the seabed. Calculations of the respective electric fields are only related to the electrodes and range from approximately 1 V m^{-1} at a distance 10 cm to 0.07 V m^{-1} at a distance 1 m from the cathode, falling to levels in the range of 1 – 50 µV m^{-1} far from the sea electrodes. Matthäus (1995) calculated for the Baltic Cable (monopolar DC transmission, 450 kV, 600 MW) weak electric fields (1 µV cm^{-1}) occurring at distances of up to 10 km from the electrodes. A magnetic field occurs reaching up to 250 µT directly above the cable and decreasing to about 50 µT at a distance of 6 m. Data on EMF emitted by bipolar DC cables only could be found in unpublished EIA, e.g. Brakelmann (2004) who predicted a magnetic field of 30 µT at 1 m distance and of 10 µT at 2 m distance to the cable (1,333 A, 150 KV). This topic could usefully be researched and published in the refereed literature.

Calculations of the electromagnetic fields generated by a 132 kV three-phase submarine AC cable (350 A) with perfect shielding predicted a magnetic field in close proximity of the cable of about 1.6 µT. The respective induced electric fields reach around 91.25 µV m^{-1} above the cable if buried at a depth of 1 m. At 8 m distance the electric field strength is approximately

10 µV m^{-1} (CMACS 2003). Gill *et al.* (2009) measured at two different offshore wind farm cables (both three-phase AC, 36 kV, 100 A) electric fields of 30 µV m^{-1} and 110 µV m^{-1} close to the cables and magnetic fields of 0,23 µT and 6.5 µT respectively. No information is available on magnitudes of EMF generated by AC transmission using three conductors in separate cables.

4.2.4. Anthropogenic introduction of electromagnetic fields in the European seas

Available information on operational submarine cables is at: (http://atlantic-cable.com/Cables/CableTimeLine/index.htm; http://en.wikipedia.org/wiki/Submarine_cable). This includes their specific design and technical features but comprehensive compilations are missing. No information is available concerning location, frequency and duration of electrical heating of oil and gas pipelines. OSPAR (2009a) recently published a map showing telecommunication cables and power cables in its convention area (Figure 5). Similar maps of cables in other European seas are not available.

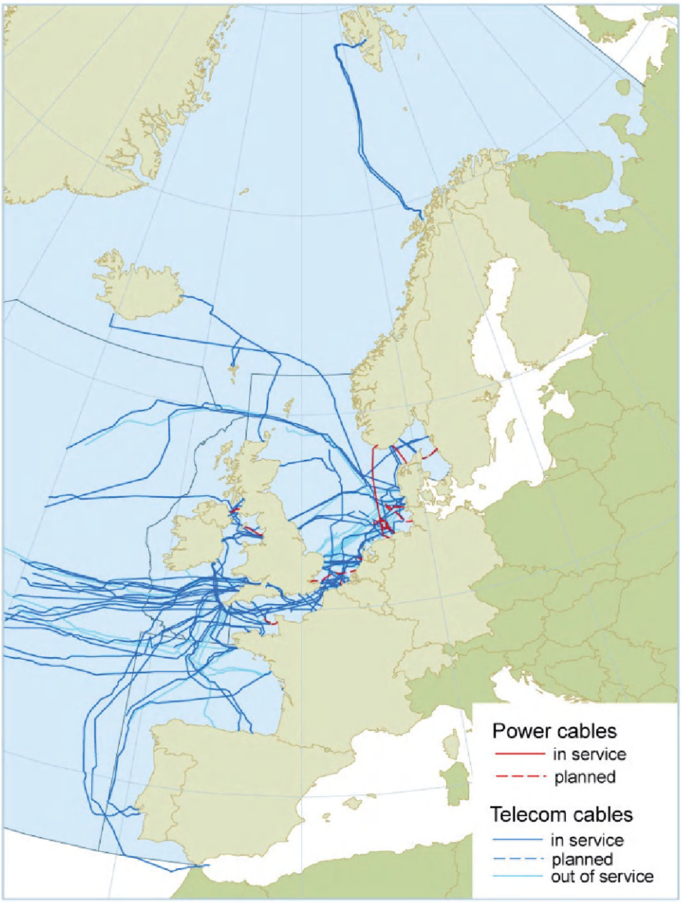

Figure 5. Submarine cables in the OSPAR Maritime area (OSPAR 2009a)

Most long-distance (especially transatlantic) submarine cables in this area serve telecommunication purposes. A number of short power cables are in use to supply islands with electricity from the mainland or to transmit electric energy produced by offshore wind farms to the terrestrial grids.

Longer-distance HVDC power cables in service connecting the grids of various countries as of Denmark and Sweden, Norway and Denmark, France and England, Norway and The Netherlands, England and The Netherlands or Scotland and Northern Ireland. Most of these HVDC connections use separate monopolar cables for much of their length, for example, the NorNed cable connecting Norway and The Netherlands consists of 270 km two-core cable (bundled) and 2 x 310 km stretches of single-core cable. (www.statnett.no) thus emitting much stronger magnetic fields than do bipolar cables or bundled systems of comparable capacities. The world's longest submarine AC cable links the Isle of Man with England (OSPAR 2009a). Similar power cables are in use in the Baltic Sea (e.g. connecting Sweden and Denmark, Germany and Sweden, Estonia and Finland) and in the Mediterranean Sea (e.g. between Italy and Corsica and Sardinia, Italy and Greece).

It is reasonable to assume that in the future more power cables will be required to allow exchange of electricity within the European grid. There will be an increasing number of cables entering service as the number of offshore wind farms increases in various European states. Beside the cables transporting electricity to the grids, windfarms also have cables connecting the turbines with each other and with transformer stations. In the medium-term, development of marine renewable energy projects (wave and tidal energy) will create a similar requirement for new cables.

4.2.5. Conclusion on EMF

The input of energy from electromagnetic fields to the marine environment is difficult to quantify due to their characteristics. For example, EMF do not disperse, they are localised to the close vicinity of the cables and they do not accumulate. Depending on the cable length they may be stretched out over hundreds of kilometres and they should be cumulatively assessed. If different sources of EMF (e.g. cables) are close to each other the strength of their fields cannot simply be added because of the directionality of their flux lines, i.e. the fields even may cancel each other out.

To assess the environmental status of the European seas concerning electromagnetic fields the ecological implication of the introduction of such form of energy should also be described. Because of the gaps in knowledge on the impacts of EMF on the marine biota in combination with the above mentioned problem in measuring the amount of EMF emitted into the environment no final conclusions can be drawn. In consequence, no final proposal can be given here on how to describe the environmental status concerning EMF and how to determine GES in this respect. An appropriate intermediate step would be to compile a comprehensive collation of number, length and location of EMF emitting cables in the various European seas.

4.3 Heat release

Ocean dynamics is governed by circulation laws related to the exchanges of water masses of various temperatures. A great attention has been paid to global warming (green house effects) including some in underwater ATOC (Acoustical thermometry of ccean climates) (Munk *et al*. 1994).

Less attention has been paid to anthropogenic heat inputs that may affect the environment at smaller scales of observation. On one hand, sound production (intended or not) is always accompanied by some thermal effects for example:

- An active transmitter always possesses a given efficiency and most of the power that is not transformed to acoustics is transformed in heat.
- An air gun is compressing air onboard the ship (heating) and decompressing in the water (cooling effect).
- A piling system bringing an object into the sediment is facing a friction problem and most of the energy produced by the piling hammer is aimed to overcome the friction during sediment penetration in the sediment.

On another hand many other sources are bringing directly heat energy in the sea, such as:

- Underwater power cables transfer high currents up to 1500 amperes and the heat dissipation is a problem both in relation to the economy and ecology (OSPAR 2008).
- Coastal power plants using water to for cooling will heat up the surrounding waters.
- Sewage releases, pipeline passages.

The input of thermal energy into the marine environment differs widely between the various human activities. For example, if 4.000 strikes with an 800 KJ piling hammer are needed to drive a pile into the sea bottom and hammering energy is totally converted into heat – what certainly is not the case – the amount of heat emitted reaches 0.89 MWh per pile. Heat dissipation of power cables is calculated to be up to 100 W/m (Worzyk 2009) and – if buried - its operation will continuously heat the sediment by 10 MW per 100 km cable. A 1.600 MW power plant recently planned at the German coast of the Baltic Sea is predicted to release every hour 250.000 m^3 cooling water containing more than 2.000 MWh thermal energy (Burchard *et al*. 2008).

Whereas the input of heat due to activities such as piling, airguns etc. is very localised and temporary heat dissipation by power cables may lead to a long-term increase of the sea bottom at least in the close vicinity of the cable route and potentially having an impact on the local biota. Power plants releasing their cooling water act as a point source but may cause a long-lasting increase of the ambient temperature of both the water and the sediment on a larger spatial scale. Sensitive coastal areas such as e.g. spawning grounds may be affected.

Many works have shown that an increase of only 1°C may be of importance for the ecosystem balance (Newell 1997; Drinkwater 2004; Greve *et al.* 2004). Considering the high number of power cable and their permanent nature, it is relevant to monitor the effect on local flora and fauna in these areas. Temperature observations must be part of global one (acoustics, in particular). It has to cover both the water column and the sediment layer.

Both laboratory experiments and in situ measurements should be carried out in conjunction with modelling effort that could be used for future predictions. Such a prediction is essential for providing a relevant indicator to decision makers either to regulate existing systems or to mitigate the adverse effects (e.g. avoid heating sensitive areas, burial of power cables) of future ones.

5. Research needs

Some obvious research needs can be derived from the concepts considered above. The Task Group noted that the Terms of Reference referred to existing methods, but felt that these failed to account for all of the possible reasons why inputs of energy could lead to states less than "Good Environmental Status". If indicators are required in these areas, research and development was required. Priority topics are listed below.

5.1 Research using the proposed indicators

The proposed indicators have been established for three typical scenarios where the available information could lead to a unique and simple definition (and measurement):

- Low and mid-frequency impulsive sounds
- High frequency impulsive sounds
- Low frequency continuous sound

They have been chosen for their relative simplicity and for their easy and uniform measurement by non-specialists.

The Task Group recommends that their use be monitored, and that they be reviewed regularly. It is likely that insights will be gained (and aspects clarified) through usage.

There have been a number of reviews of research needs by other groups (e.g. MMC, 2007; Boyd et al. 2008); here we focus on research needs for better understanding of Good Environmental Status. As explained earlier, the effects of noise on receiving organisms is not known well, neither across the breadth of individual marine biota, or on the population consequences of effects known to occur at the individual level. Research in these areas is both challenging and costly, but is necessary if regulation is to be fully appropriate to the risks posed by an activity.

5.2 Effects of underwater noise

The more important research needs are on

A) Biology

- Seasonal presence and abundance of marine life;
- Use of sound of marine organisms;
- Species-specific communication maximum ranges;
- Basic information on hearing, especially for low frequency and high frequency species;
- Modelling of the auditory system to reduce dose response experimental exposure to sound;

B) Sound in the ocean

- Measurements of ambient noise trends and budgets;
- Acoustic mapping of areas of interest;

C) Effects of noise

- Avoidance or abandonment of preferred habitat;
- Behavioural response studies during real-time activities;
- Masking effects, including overlap between passive perception (orientation) and communication (see Clark *et al.* 2009 for background);
- Temporal and permanent hearing threshold shifts: e.g. growth, recovery rates and variability among different sources, species and individuals;
- Impacts on non-auditory systems;
- Impacts on benthic communities;
- Population level impacts;
- Spatial measurements of noise interference and cumulative effects on behaviour and/or physiology within and between trophic levels;
- Impacts of noise due to particle motion;
- Mitigation effectiveness while evaluating current measures and providing guidance on further measures to mitigate emissions and the environmental impacts.

It is plainly important to understand the amount of variance there is in all of the above issues – this will probably necessitate multiple studies. Topics A and B above are both necessary background in understanding the effects (C). If potential adverse effects are found, then plainly (in relation to the topic of the current report) research on suitable indicators would be needed.

In parallel, temperature and electromagnetic fields (whose effects are insufficiently known) could usefully be measured in sensitive areas in order to have better understanding of their interaction and relative importance in causing effects. Two or three of these physical phenomena may happen simultaneously in some cases. For examples:

- Pile driving: noise and heat
- Undersea cables: heat and electromagnetic field
- Sonar: noise + heat + electromagnetic field

5.2. Effects of electromagnetic fields

There are gaps in knowledge on the effects of submarine cables. In-situ measurements of the electromagnetic fields (including induced fields) emitted by operating cables of different types are not well known, including the consequences of operational and environmental variables, including burial depth.

Understanding of the specific sensitivities of many marine organisms to electromagnetic fields is poor and could be improved. In particular field studies on behavioural changes and on potential disturbance of migration routes of species that are sensitive to electromagnetic fields would be most useful.

5.3. Effects of heat input

Several studies have shown that an increase of temperature of just 1°C can affect ecosystem balance (Newell 1997; Drinkwater 2004; Greve *et al.* 2004). It would be particularly useful to understand the effects of relatively permanent sources of heat input, such as some power cables, on local flora and fauna. Observations should cover both the water column and the seabed. Such studies could give important insights into suitable indicators of Good Environmental Status.

5.4. Effects of ADDs and AHDs

Little is known about the long-term effect of acoustic deterrent and harassment devices on marine animals. Research focusing on habitat exclusion, stress and reduced fitness on both individual and population level is needed to assess the effect and develop indicators on this issue.

5.5. Effects of high frequency sonar

Little is known about the effect of high frequency boat sonars on marine animals. Research focusing on short and long term behavioural changes and habitat exclusion in areas with high boat activity is needed. The results of such research together with distribution information on species should be included in a spatial model for use in future marine spatial planning.

5.6. Effects of shipping

Shipping is the main contributor to the rise in background noise in European waters. It is therefore highly relevant to get more information on the effect of elevated background noise and specifically shipping lanes on marine animals. At the same time it is relevant to reduce the background noise by developing more silent ships, which will have multiple benefits like lowering noise pollution, reduce friction heating, reduce global warning (from CO_2) and reduce oil expenses.

5.7. Cumulative effects

Good Environmental Status is an objective of the Marine Strategy Framework Directive. Plainly GES can be affected by individual effects of human activities, but is just as likely to be affected by in combination and synergistic effects. Any indicators of the status of biota (see reports of other Task Groups) will be affected by the total effects of human activity, including the input of anthropogenic energy.

From the point of view of noise exposure, regional noise maps or charts might be a useful management tool, though it is difficult to see how these could be easily used for an indicator to address the Energy Descriptor. Such noise maps should contain information on variance (as well as e.g. peak noise).

A systematic inventory of acoustic conditions in regional seas would help in documenting the extent of current noise exposure, and estimating the pristine historical or desired future conditions for the resources. This would help in understanding the impacts of different noise sources in different areas and show differences between regional seas. This comparison will help making objective decisions of a good or bad environmental status. In contrast to chemical pollution noise stays only as long in the environment as it is actively produced.

6. Acknowledgements

The Task Group benefitted from the help of many of their colleagues through discussion and reflection on concepts. We would particularly like to acknowledge the help of Paul Keizer, Claus Hagebro and Almuth Janisch of the ICES Secretariat and the colleagues of Michel Andre for their help and for facilitating the two meetings of the group.

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Annex 1. Further information for Indicator 1

Indicator 1 is based on noise exposure criteria proposed for cetaceans by Southall *et al.* (2007). Table A1.1 provides a general overview of noise exposure criteria for marine mammals and fish.

Table A1.1. Overview of noise exposure criteria (for more detailed values by Carlson *et al.* 2007, see Table 3).
Note: the levels in this table correspond to the level received by the animal and not the source levels used in Indicator 1.

Source	**Effect**	**Taxa**	**Sound type**	**Sound pressure level /SEL**
NMFS 2003	Physical injury	Cetaceans	Airgun pulses	180 dB re 1µPa received level
	Physical injury	Pinnipeds	Airgun pulses	190 dB re 1µPa received level
Nedwell *et al.* 2003	Mild behavioural reactions	Marine mammals and fish	All sound types	75 dB_{ht}
Nedwell *et al.* 2003	Strong behavioural reactions	Marine mammals and fish	All sound types	90 dB_{ht}
Popper *et al.* 2006	Injury	Fish	Pile driving single pulse	208 dB re 1µPa peak
Popper *et al.* 2006	Injury	Fish	Pile driving single pulse	187 dB re $1\mu Pa^2$-s SEL
Southall *et al.* 2007	PTS	Cetaceans (3 hearing classes)	Single - multiple pulse	230 dB re 1µPa peak
Southall *et al.* 2007	PTS	Cetaceans (3 hearing classes)	Single - multiple pulse	SEL 198 dB re $1\mu Pa^2$-s
Southall *et al.* 2007	PTS	Pinnipeds (in water)	Single pulse - multiple pulse	218 dB re 1µPa peak
Southall *et al.* 2007	PTS	Pinnipeds (in water)	Single pulse - multiple pulse	SEL 186 dB re $1\mu Pa^2$-s
Southall *et al.* 2007	TTS / behavioural disturbance	Cetaceans (3 hearing groups)	Single pulses	224 dB re 1µPa peak
Southall *et al.* 2007	TTS / behavioural disturbance	Cetaceans (3 hearing groups)	Single pulses	183 dB re $1\mu Pa^2$-s SEL
Southall *et al.* 2007	TTS / behavioural disturbance	Pinnipeds (in water)	Single pulses	212 dB re 1µPa peak
Southall *et al.* 2007	TTS / behavioural disturbance	Pinnipeds (in water)	Single pulses	171 dB re $1\mu Pa^2$-s SEL

Source	Effect	Taxa	Sound type	Sound pressure level /SEL
Carlson *et al.* 2007	TTS	Fish / hearing specialist	Single pulse	205 dB re 1µPa peak
Carlson *et al.* 2007	TTS	Fish / hearing generalist	Single pulse	207 dB re 1µPa peak
Carlson *et al.* 2007	TTS	Fish / hearing specialist	Multiple pulses (cumulative SEL	183 dB re 1µPa^2-s SEL
Carlson *et al.* 2007	TTS	Fish / hearing generalist	Multiple pulses (cumulative SEL	185 dB re 1µPa^2-s SEL
Carlson *et al.* 2007	Auditory tissue damage (hair cells)	Fish / hearing generalist	Single pulse	> 207 dB re 1µPa peak
Carlson *et al.* 2007	Auditory tissue damage (hair cells)	Fish / hearing specialist	Single pulse	> 205 dB re 1µPa peak
Carlson *et al.* 2007	Auditory tissue damage (hair cells)	Fish / hearing generalist	Multiple pulses (cumulative SEL	> 189 dB re 1µPa^2-s SEL
Carlson *et al.* 2007	Auditory tissue damage (hair cells)	Fish / hearing specialist	Multiple pulses (cumulative SEL	> 185 dB re 1µPa^2-s SEL

The U.S. (NMFS 2003; NOAA 2005) used a 'generic' exposure criterion of 180 dB re 1 µPa rms for cetaceans (both baleen and toothed whales) and 190 dB re 1 µPa rms for. Nedwell *et al.* (2003) proposed dBht (ht = hearing threshold) values for 'mild' and 'strong' behavioural reactions in fish and marine mammals. Their values indicate received levels above hearing threshold of the receiver and are thus identical to sensation levels (dBA). Yet, there is no empirical evidence for the values put forward by Nedwell *et al.* (2003) and the underlying assumption of an absolute auditory threshold function (the audiogram) as a frequency weighting function for marine animals exposed to underwater noise has been challenged (see Southall *et al.* 2007). Therefore, the dBht approach has found very little support outside the group that has proposed it.

Very recently, Southall *et al.* (2007) proposed sound exposure criteria for cetaceans and pinnipeds composed both of unweighted peak pressures and M-weighted sound exposure levels (similar to human weighting functions [i.e., dBA] but reflecting the frequencies that marine mammals hear) which are an expression for the total energy of a sound wave (for details, see Southall *et al.* 2007). Values both for injury and temporary threshold shift, are given for three hearing classes of cetaceans in water and for pinnipeds in air and underwater (see Table A1). Even if they are based on limited data and are therefore discussed critically within the scientific community, the values by Southall *et al.* (2007) might represent a step forward as they are perhaps based on more realistic assumptions on hearing and extrapolations from actual data. Yet there are many gaps remaining in our understanding of onsets for TTS and injury and recent research indicate that for some species, for example harbour porpoises, TTS values proposed by Southall *et al.* (2007) might be too high (Lucke *et al.* 2008). There have been similar attempts to define exposure criteria for fish (Table A1.1), but none have yet been published in the peer reviewed literature.

Following points have to be considered when looking at noise exposure criteria:

- The criteria are concerned with sound pressure levels at the receiver and not at the source and are therefore very difficult to regulate as received sound pressure level depend on many variables (see chapter 4).
- As of yet, all criteria are provisional as they are based on extrapolations from very limited sets of data.
- Most of the criteria - for example the ones for fish (see Table A1) are only addressing one sound type (in this case pile driving).
- All criteria are given in sound pressure levels (peak or SEL or rms), yet, for some taxa -such as some fish - particle motion might be the more relevant stimulus (see for example Popper *et al.* 2003).
- Most of the values are given for exposure to single sounds. Yet, in the real world, an animal is very likely to be exposed to a series of acoustic signals, sometimes many simultaneously operating sounds sources spread over large areas, and it is perhaps reasonable to assume that effects will accumulate over time. In fact, both Southall *et al.* (2007) and Carlson *et al.* (2007) discuss a cumulative noise exposure SEL criteria which can be estimated (for pile driving strikes) as:
  Cumulative SEL = SEL (single strike) + 10 log (number of pile strikes).

That means that the SEL (cum) increases by 10 dB with every tenfold increase of the number of strikes (see Carlson *et al.* 2007).

If we apply the exposure criteria put forward for fish by Carlson *et al.* 2007 and estimate the distance from the source at which these criteria are reached, we derive the potential impact zones for single and multiple strikes (n = 500) that are shown in Table 3. It can be seen that impact zones for single strikes are relatively small. For multiple strikes, zones are much larger.

Table 3 Exposure criteria after Carlson *et al.*, 2007 and estimated impact zones (Broadband source sound pressure = 216 dB re 1 µPa²-s SEL; TL = 15 log (r); multiple strikes n = 500)

Effect	Group	Cumulative SEL	Single strike Impact zone (m)	Multiple strikes impact zone (m)
Non-auditory tissue damage	Mass of fish < 0.5 g	183 dB	158	7,943
	Mass of fish > 200 g	> 213 dB	< 1.58	< 79
Auditory tissue damage	Hearing generalist	> 213 dB	< 1.58	< 79
	Hearing generalist	> 189 dB	< 63	< 3,162
	Hearing specialist	> 185 dB	< 115	< 6,309
TTS	Hearing generalist	185 dB	115	6,309
	Hearing specialist	183 dB	158	7,943

It has to be noted that, again, this value is very provisional as it assumes no recovery between acoustic events (see Southall *et al.* 2007 for more details). We also have to consider that fish would perhaps move out of an area after receiving an undefined number of pile driving sounds, so the estimated radii should be viewed as provisional exercise providing very rough indicators of the expansion of injury zones due to multiple strikes.

There is very little data to allow setting out exposure criteria for behavioural disturbance. Behavioural reaction to underwater sound varies enormously across as well as within species and is depending on a large variety of internal and external factors (see Figure A1.1)

Some studies indicate that individuals might avoid sound sources at considerable distances which in some cases might ultimately lead to effects that are at least as severe as in the case of injury (see Janik 2005, OSPAR 2009c).

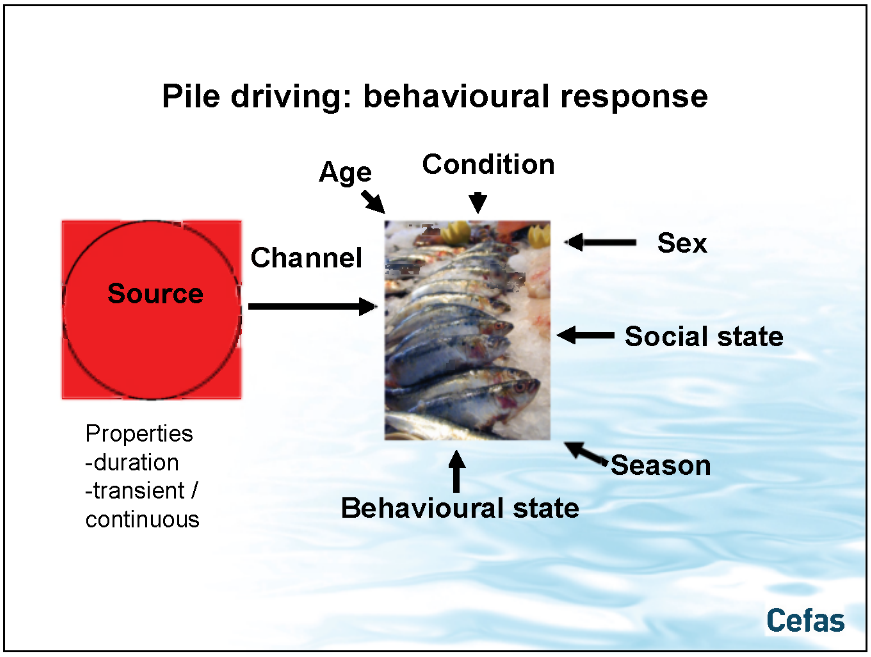

Figure A1.1 Factors affecting behavioural response to underwater sound (note: in transient signals, repetition rate might be an additional factor to consider)

Annex 2. Further information for Indicator 2

Depth-sounding sonar systems in small vessels typically use frequency bands from 10 to above 200 kHz (Table A2.1). Many systems are dual/multiple frequency (e.g. 50 kHz and 200 kHz) allowing the operator to choose between lower frequency (deeper range, coarser resolution) and higher frequency (shallower range, finer resolution) or offering fused/split screen presentations with both frequencies operating simultaneously.

One important aspect of sonar use is safety, where it can be argued that a deep probing sonar system is important to avoid running aground. However, even 200+ kHz sonar systems are operational to several hundred meters' depth, provided that the output power is enough and the beam width is sufficiently narrow; this should be considered sufficient for safe navigation. Higher frequencies may also be more vulnerable to clutter, e.g. from thermo clines, air bubbles, or sediments in the water column, which would reduce the operating depth. However, modern advanced signal processing techniques mostly makes it possible to cope with this problem.

Table A2.1 Sonar frequencies emitted by some common leisure boat sonar systems

Model	Single frequency kHz	Dual frequency kHz	Multi-frequency kHz
Humminbird	200	83/200	83/200/455
Eagle	200	50/200 83/200	
Lowrance	200	50/200	
Gamrin		50/200 80/200	

Another important feature in the context of this indicator is the beam width. This is given as a standardized measure at the -3dB or -10 dB level relative to the centre amplitude. Lower frequencies tend to give broader beams than higher frequencies (Figure A2.1). This means that there is still acoustic energy radiated outside the specified width. The beam width is also determined by the transducer size; the smaller the transducer, the wider the beam (e.g. a 2.54 cm spherical transducer typically emits a 20 degree beam, whereas a 5cm diameter transducer emits 8 degrees). Hence lower frequency sonar pulses and smaller transducers will "leak" more to the surrounding. This is an advantage as well as a disadvantage: a broader beam would map a larger portion of the bottom, but also result in a larger area being "noise polluted". However, even high frequency, narrow beam sonar systems may cover a wide bottom profile, and affect a large area, either by having multiple beams or operating a narrow beam sweeping from side to side (fig X1).

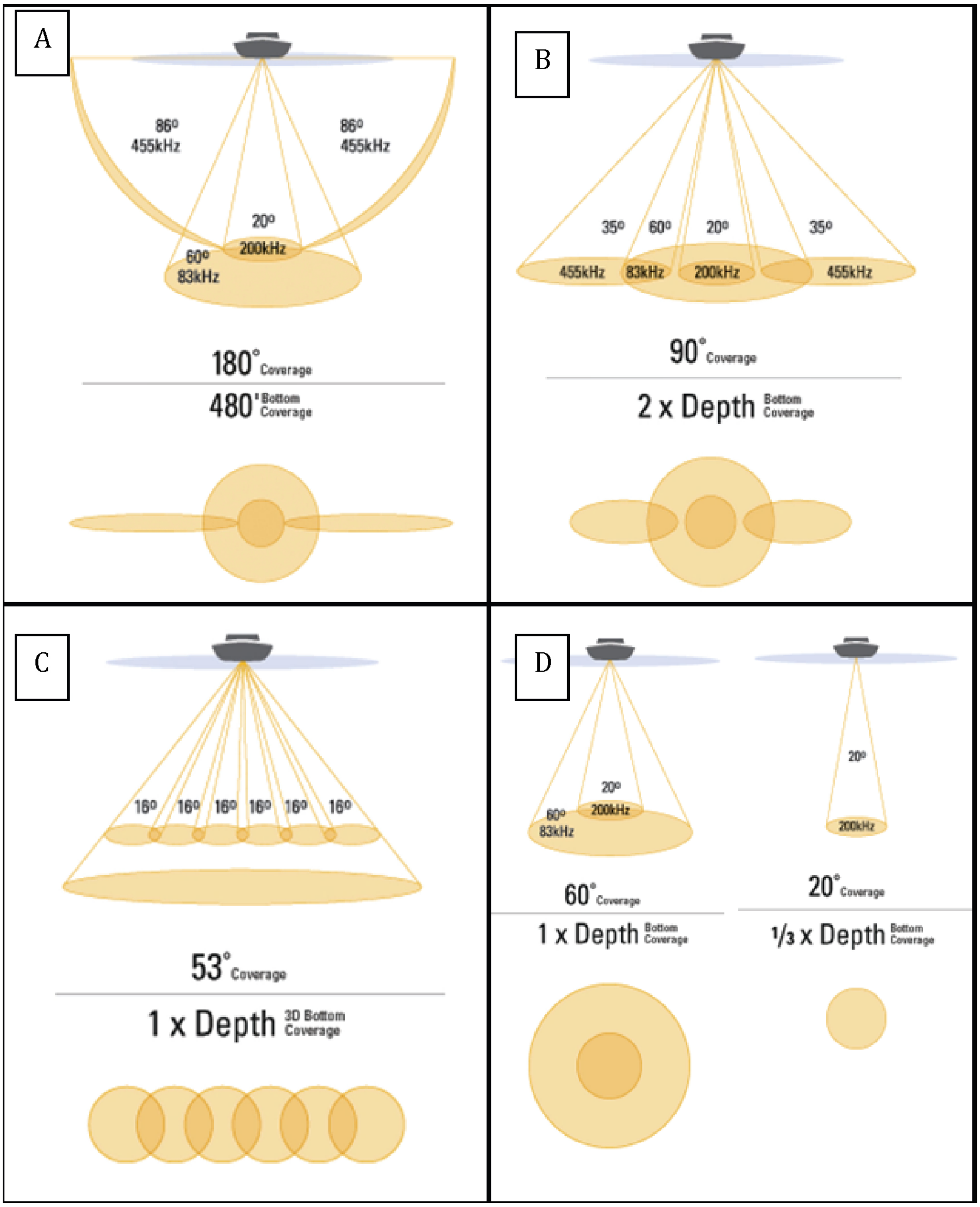

Figure A2.1. Schematic presentations of the distribution of acoustic energy of different sonar systems: dual beam/side imaging (A), quadruple beam (B), multiple beam (C), dual beam and single beam (D) (adapted from http://www.humminbird.com). It should be noted that as the boat is rocking from side to side in the waves, the sonar pulses are spread over a greater area.

Sonar systems transmit short (20-1000µs) pulses at varying repetition rates (ping speed). For deep ranging, ping speed is determined by depth, since the outgoing pulse has to return as an echo before the next pulse is transmitted. E.g. the Humminbird echosounders range from 10 pings per second used down to 240 feet (80m) to 10 pings/s used down to 60 feet (20m) (Humminbird customer service). For shallow waters, and at higher boat speed, ping speed is determined by 'information density', and is either set to a fixed rate (pings per second), or is manually or automatically adjustable (typically up to 50+ pings/s). The pulse repetition rate is an important factor when noise pollution is considered, since with higher repetition rates, this basically impulsive noise approaches the characteristics of continuous noise.

It is difficult to specify the source level of sonar from the typical sonar system technical specifications, since output power most often is only given in watts, which cannot be easily translated into sound pressure levels.

To facilitate impact assessment and monitoring, TG11 recommends that sonar system manufacturers are required, in addition to frequency and beam width, to declare sonar pulse source level (dB re 1µPa @1m peak-to-peak and energy flux density (dB re 1µPa^{2}s@1m), pulse duration/-s, and pulse repetition rate/-s (ping speed).

Many sonar and fish-finding systems are combined with a GPS navigation system, and often lack a differential switch off, allowing the boat operator to turn the sonar off e.g. when cruising in a ship lane or in safe, deep waters. Also many boat manufacturers install these combined system integrated with the boat engine, with no possibility to selectively switch off the sonar.

Combining GPS and sonar is an excellent and popular navigational tool being available to virtually all leisure boat owners, due to the recent advances in electronics and drop in price. To only provide a switch off option on the sonar part would probably not reduce its use to the necessary extent. Hence, the TG11 recommends that <180 kHz sonar systems are phased out. The use of >200 kHz sonar systems need not be controlled, since, even if they were to be used constantly on every boat, they would not, or at least only at a very limited degree, depending on the amount of lower harmonics, be disturbing the marine mammals concerned or any other parts of the marine environment.

Annex 3. Further information for Indicator 3

The relevant sections above outline some of the potential effects of chronic noise exposure, most notably interference with vital biological signals but also stress. Coming up with criteria assessing whether a given ambient noise level is indicative of a 'poor' environmental status and how to change ambient noise levels representing a 'good' environmental status was far from straightforward. Some of the remaining problems are outlined below:

- Active spaces for signals (=the perception distance of an acoustic signal) vary across species and taxa with fish having much less loud sounds and small active spaces compared to most marine mammals (see Richardson *et al.* 1995, Janik 2005 and Ladich *et al.* 2006 for overviews). A given ambient noise level might therefore only diminish active foraging / communication ranges in a marine mammal species but completely obstruct these functions in fishes. It will be therefore almost impossible to come up with single exposure criteria for ambient noise.

- Ambient noise levels will vary greatly across a variety of temporal (daytime, season, year) and spatial scales (near shipping lanes vs. 'quiet' bays), which will make a representative coverage for any monitoring effort quite difficult. We should also consider here that marine mammals and many fish are highly mobile and are likely to consistently move in and out of noisy areas.

- There are a variety of strategies to compensate for masking (see previous chapter). On the one hand, this might mitigate effects; on the other hand, adaptive measures might be costly and ultimately reduce individual fitness (see OSPAR 2009c).

- There is very little data on historic ambient noise levels to provide a baseline for 'good' environmental status. On the other hand the use of airguns and windmill pile driving are rather recent phenomena. In evolutionary scale all anthropogenic noise is very recent.

It might be feasible to discuss environmental status with regards to chronic noise exposure on a relative rather than absolute scale and define 'poor' as comprising an increase in ambient noise of 3 dB over a certain period in a given area. It will be very difficult to compare regions that have different 'starting' levels.

It is therefore perhaps most feasible to set absolute values. They can be provisionally be oriented along the values given by Wenz 1962. Note that these are given as spectrum levels in 1 Hz bands and have to be converted if 1/3 octave band levels are applied.

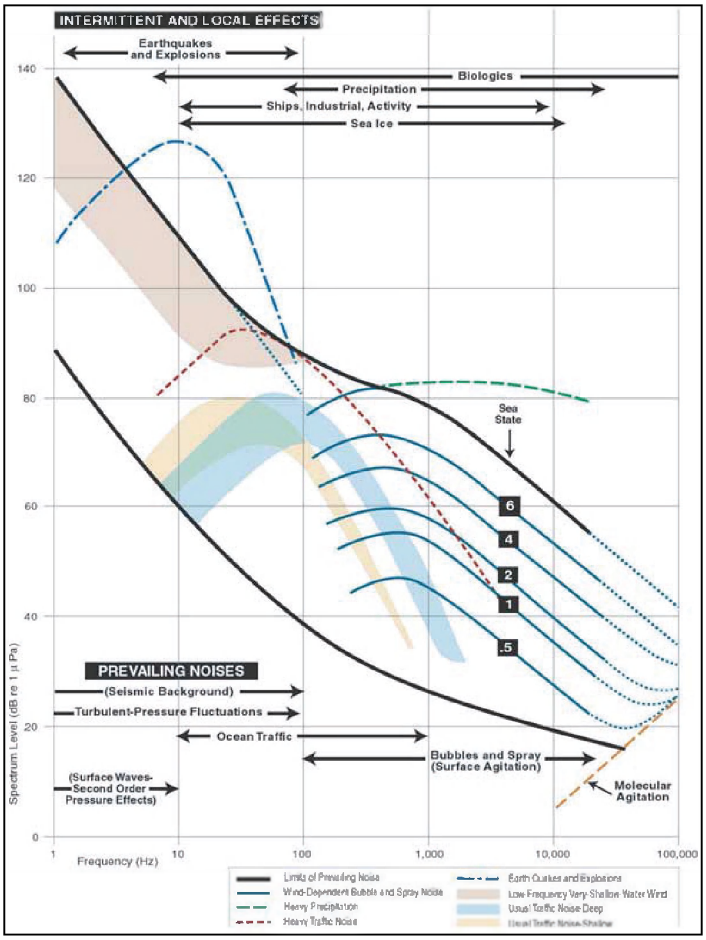

Figure A2.1. The typical sound levels of ocean background noises at different frequencies, as measured by Wenz (1962) (Note that corresponding levels in coastal / continental shelf waters might be higher).

Applying this model further, indicator for a 'poor' environmental status could then be defined as consistently (e.g. > 50 % of days in a year) above a certain level of the curves given by Wenz 1962 (e.g. the blue lines indicated in Figure A2.1).

Annex 4. Particle motion and its particular relevance to fish and invertebrates

Sound in water is a travelling wave in which particles of the medium are alternately forced together and then apart. The sound can be measured as a change in pressure within the medium, which acts in all directions, described as the sound pressure. However, in addition the sound also includes particle motion components, acting in particular directions (usually along the axis of propagation), described as the particle displacement, particle velocity or particle acceleration. The ratio between sound pressure and particle velocity is constant far from the source and is defined by the acoustic impedance of the medium. Close to a source or close to reflecting objects or surfaces (like the sea surface) this ratio changes and particle motions can reach higher (or lower) amplitudes.

Most terrestrial animals are sensitive to sound pressure (there may be exceptions in the case of some burrowing animals which are sensitive to ground vibrations). However, fish and many invertebrates are sensitive to particle motion. The fish ear itself consists of three dense bodies – the otoliths – in contact with sensory hair cells. As the density of the fish is almost the same as the surrounding water the passage of a sound moves the body of the fish back and forth relative to each otolith, stimulating the sensory hair cells. The otolith organs behave as nearly critically damped, mass loaded accelerometers and auditory sensitivity is most nearly related to the particle acceleration component of the sound.

In some fish where a gas-filled organ is present (for example, the swimbladder - which gives the fish neutral buoyancy) the gas expands and contracts in response to sound pressure, generating particle motions at the ear which are much greater than those in the absence of the gas. The gas-filled organ effectively transforms pressure into particle motion, rendering the fish more sensitive to sound. However, in many fish the swim-bladder is absent, or it is located well away from the ear. In these species the otolith organs are stimulated directly by particle motion in the incident sound wave.

There is great diversity in the structure of the ear and its connection with gas-filled bodies in fish. This is perhaps to be expected with more than 30,000 different species. Hearing ability also varies greatly between species. Some, like the anadromous herrings and menhadens are sensitive well into the ultrasound range. Other hearing specialists can hear sounds up to 3 – 5 kHz; the cod can detect sounds up to about 400 Hz. The sensitivity of fish where gas-filled organs are absent or placed well away from the ear is lower. Species like the plaice and salmon only detect sounds at frequencies up to 200 Hz.

Gas-filled organs are less effective in providing auditory gain at low frequencies. However, a number of fish have been shown to be very sensitive to particle accelerations at infrasonic frequencies (below 10 Hz).

Particle motion sensitivity has been shown to be important for fish responding to sounds from different directions. With the high speed of sound propagation in water, time differences between the two ears are very small. Moreover, for animals smaller than the wavelength of a sound any sound pressure differences between the two ears will be minimal. Indeed, with a single gas bladder attached to the ear there is effectively only one receiver. Nevertheless, fish are able to discriminate between spatially separated sources, both in the horizontal and vertical planes. They are also able to distinguish between sources at different distances. The ability to discriminate sounds from different directions is conveyed through the sensitivity of the otoliths to particle motion. The otolith organs are acting as vector detectors.

In analysing the impact of sounds generated by anthropogenic activities upon fish, the focus has usually been on propagated sound pressure, rather than particle motion. Detection of particle motion is, however, important to all fish, as it provides a basis for determining sound direction.

Most sounds generated in water by humans are characterised by very small particle motions except close to the source (in the so-called near-field, where the kinetic components dominate) or where the receiving animal is close to the sea surface (which releases pressure and generates high particle motion). There are important exceptions, however. During pile driving, and also during seismic surveys, sound propagates not only through the water but also through the sea-bed. Three types of wave are generated; compressive, shear and surface waves. Compressive waves, like sounds, produce particle motions parallel to the direction of propagation of the wave. Shear or distortional waves produce particle motions that are perpendicular to the direction of propagation. Surface waves, or Rayleigh waves, are transmitted along the interface between the substrate and the water (and also interfaces between different layers within the substrate) and can produce large particle motions in a vertical direction and also parallel to the direction of propagation.

The propagation velocities of compressive, shear and interface waves vary. The velocity is highest for compressive waves, intermediate for shear waves, and lowest for interface waves. As the waves propagate away from the source they therefore begin to separate. In addition, the waves decay at different rates and this decay is frequency dependent. Interface waves dominate at long transmission distances, the lower frequencies showing the least attenuation. Shallow water bodies overlying a substrate where pile driving is taking place will experience especially high amplitude low frequency particle motion from interface waves propagating through the substrate.

At present, very little work has been carried out on the sensitivity of fish and other organisms, including marine invertebrates, to particle motion. Particle motion has rarely been measured during sound exposure experiments, or during source characterisation exercises. Where it is measured it must be described by a 3-component vector, which makes measurement especially difficult. In laboratory studies, complex, spatially-varying relationships exist between sound pressure and particle velocity and sound intensity cannot be estimated from pressure measurements alone (which assume that pressure and particle velocity are in-phase). Specific measurements of particle velocity are required. Because of these difficulties we do not know what levels particle motions reach, or what their effects upon fish are. Further research is necessary. The important message is that where impacts upon fish and invertebrates are of particular concern, then it is important to take into account the particle motions generated in the medium as well as the sound pressure.

European Commission

EUR 24341 EN – Joint Research Centre

Title: Marine Strategy Framework Directive – Task Group 11 Underwater noise and other forms of energy.

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Luxembourg: Office for Official Publications of the European Communities
2010 – 55 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-15654-0
DOI 10.2788/87079

Abstract

The Marine Strategy Framework Directive (2008/56/EC) (MSFD) requires that the European Commission (by 15 July 2010) should lay down criteria and methodological standards to allow consistency in approach in evaluating the extent to which Good Environmental Status (GES) is being achieved. ICES and JRC were contracted to provide scientific support for the Commission in meeting this obligation.

A total of 10 reports have been prepared relating to the descriptors of GES listed in Annex I of the Directive. Eight reports have been prepared by groups of independent experts coordinated by JRC and ICES in response to this contract. In addition, reports for two descriptors (Contaminants in fish and other seafood and Marine litter) were written by expert groups coordinated by DG SANCO and IFREMER respectively.

A Task Group was established for each of the qualitative Descriptors. Each Task Group consisted of selected experts providing experience related to the four marine regions (the Baltic Sea, the North-east Atlantic, the Mediterranean Sea and the Black Sea) and an appropriate scope of relevant scientific expertise. Observers from the Regional Seas Conventions were also invited to each Task Group to help ensure the inclusion of relevant work by those Conventions. This is the report of Task Group 1 Underwater noise and other forms of energy.

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LB-NA-24341-EN-N

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ISBN 978-92-79-15654-0

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