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Impacts of noise and use of propagation models to predict the recipient side of noise

Final Report

Authors: J.F. Borsani, R. Faulkner, N.D. Merchant

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Head office

Centre for Environment, Fisheries & Aquaculture Science

Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK

Tel +44 (0) 1502 56 2244 Fax +44 (0) 1502 51 3865

www.cefas.defra.gov.uk

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Executive Summary

Underwater noise from human activities may have significant negative impacts on marine ecosystems through a variety of direct and indirect effects on marine organisms. To address the risk of such impacts in European waters, a number of legislative instruments are being developed and implemented, including Descriptor 11 of the Marine Strategy Framework Directive (MSFD), which addresses underwater noise directly at the European level. Although scientific understanding of the effects of noise has advanced rapidly in recent years, further research is needed to develop the tools and knowledge necessary to inform effective management decisions. To this end, the European Commission (EC) supported the present Cefas-led project with the aim of developing a roadmap towards defining thresholds for Good Environmental Status (GES), and evaluating the use of sound maps for GES assessment. This report presents a high-level summary of the project findings.

A number of key knowledge gaps were identified through a review of recent literature and as outcomes of a specially convened workshop of international experts held in Brussels in April 2014. These include, but are not limited to:

- Long-term effects of elevated ambient noise levels on marine fauna at the population and ecosystem scales
- Assessment of the particle motion component of noise with respect to fish and invertebrates
- Understanding of how and whether laboratory studies can be extrapolated to wild animals
- Effects of noise exposure at key life stages

Projects which target these areas will help to reduce uncertainty in the evidence base for GES assessment.

One tool which may be useful in assessing levels of manmade noise in the marine environment is sound mapping, by which sound levels are modelled based on known distributions of sound sources. As part of the project, preliminary sound maps were produced for the Netherlands Exclusive Economic Zone and for an Atlantic region near Madeira, each using a different modelling approach. Such techniques show promise as a supplementary tool to support GES assessment, as they enable extrapolation from field measurements which may have limited spatial coverage. However, it is important that GES assessment does not depend on the particular modelling approach employed by a Member State, and that model predictions have a high level of confidence. For these reasons, further research is needed to ensure that sound maps are standardised and extensively validated before they will be suitable for application in a policy context.

The major task of the project was to develop a roadmap towards defining operational sound level thresholds for GES. Based on the outcomes of the workshop and other components of the project, several concrete steps (Actions) were proposed. It was noted that there are instructive precedents for applying expert judgement to derive noise exposure thresholds: such thresholds have been successfully developed for marine mammals and fish in the context of environmental impact assessment, despite considerable uncertainties in the evidence base. Although it is important that

knowledge gaps are addressed through further research, this need not preclude the definition of operational targets for GES that are proportionate to the risks and uncertainties involved.

The roadmap consists of the following four Actions:

1. **Agree standards for underwater noise monitoring**. It is important that noise levels for GES assessment are measured consistently by Member States. No suitable international standard exists for noise monitoring, and a general standard may in any case be incompatible with the particular requirements of the MSFD. Monitoring standards specific to the MSFD have been developed by the EC-funded BIAS project, and could be ratified or adapted by the Technical Group on Underwater Noise (TG Noise) for use by all Member States.
2. **Commission studies to address knowledge gaps**. Targeted studies are needed to reduce the uncertainties that constrain management decisions relating to underwater noise. There are several suitable EU funding mechanisms (e.g. Horizon 2020, Life+, INTERREG) which could be used to address the knowledge gaps outlined above.
3. **Agree common standards for noise monitoring instruments**. There are a range of commercially available devices for monitoring underwater sound, and not all may be adequate to meet monitoring requirements for the MSFD. Efforts to establish standards for monitoring devices could fall under Action 1. Another option is to develop bespoke monitoring equipment to ensure standardised results for GES assessment, as has been piloted in the EC-funded Common Sense project.
4. **Define operational GES criteria**. For Descriptor 11 to become operational, quantitative criteria for attainment of GES assessment must first be defined. There are a number of unresolved questions to be addressed in addition to the particular formulation of the targets, including the metrics and spatial resolution to be used. A GES target for ambient noise need not be a 'hard threshold' above which GES is not attained, but could be expressed as a maximum proportion of time that noise levels can exceed a certain threshold. Expert judgement will be required to resolve these issues. Sufficient consensus could be reached through a series of workshops drawing on international expertise, particularly those with experience of formulating noise exposure thresholds. Agenda items should not consider research needs, but be tightly focused on defining operational targets based on the available evidence and expert judgement.

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1 Introduction

Underwater noise pollution can have a range of adverse effects on marine biota. To address the risk of negative ecological consequences, regulators and legislatures are beginning to take management actions which will lead to evidence-based assessment of whether current levels of noise pollution are harmful to the ecosystem and particular species. In 2010, the European Commission (EC) adopted two Indicators for underwater noise (EC Decision 2010/477/EU) under Descriptor 11 of the Marine Strategy Framework Directive (MSFD), which states that to attain Good Environmental Status (GES), underwater noise should be "at levels that do not adversely affect the marine environment" (MSFD 2008/56/EC). These two Indicators are:

- **Indicator 11.1.1** for low- and mid-frequency impulsive sounds. These noise sources, such as pile driving, seismic surveys, and explosions, have been associated with injury, displacement, and behavioural disturbance of marine fauna.
- **Indicator 11.2.1** for continuous low frequency sound (ambient noise). Rising levels of ambient noise, particularly from shipping, have been linked to masking of bioacoustic signals, chronic stress, and developmental and behavioural effects.

It was considered that defining quantitative criteria for GES was difficult based on the current knowledge of noise impacts on marine biota, and so initial Indicators were chosen to reflect the environmental *pressures*, rather than the absolute *status* with respect to noise (Dekeling *et al.*, 2014). This difficulty is particularly the case for Indicator 11.2.1, where there are currently insufficient data to assess whether absolute levels of background noise may have negative consequences for individual species. Nevertheless, if long-term trends in noise levels are known then it may be possible to draw some conclusions about changes in environmental pressures. The Technical Group on Underwater Noise (TG Noise) has suggested that trends alone are not sufficient to describe GES, since trends do not indicate whether absolute levels of noise are harmful. However, in the absence of an evidence-based threshold and as a precautionary approach, a downward trend could be adopted as an interim target until further work is completed (Dekeling *et al.*, 2014).

In the context of this uncertainty in the relationship between noise levels and environmental status, the EC supported the present project, *Impacts of noise and use of propagation models to predict the recipient side of noise*, with the following objectives:

1. To evaluate the current knowledge of the impacts of noise on marine biota at all levels (individuals, populations, and ecosystems) and methods to assess these impacts.
2. To develop modelling techniques to predict the recipient side of noise, i.e. as it is received by marine fauna.

Key elements of this work were to convene a workshop of international experts aimed at addressing the current knowledge gaps, and to prepare a roadmap towards defining noise limits for GES.

This report summarises the outcomes of the project in non-technical language, drawing on the six task-specific reports which are provided in the Supplementary Annexes for further information. Chapter 2 presents an assessment of knowledge gaps in the effects of noise on marine biota, while Chapter 3 briefly reviews current legislation and regulation relating to marine noise pollution. The following two chapters address acoustic modelling: in Chapter 4, the main outcomes of a review of acoustic propagation models are discussed, and Chapter 5 presents sound maps which were developed for the project. The main conclusions of the workshop are presented in Chapter 6, and the roadmap towards defining GES for noise is outlined in Chapter 7.

2 Current knowledge gaps

In recent years, it has become increasingly clear that anthropogenic (i.e. manmade) noise can affect marine life in numerous ways, with the potential for detrimental consequences. These effects can be broadly categorised as:

- acoustic masking of biologically important signals;
- behavioural responses;
- temporary or permanent auditory impairment, known as Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS);
- physiological responses and non-auditory injury, including developmental effects;
- in extreme cases, mortality.

It is also evident that there remain significant gaps in our understanding of these effects and of their consequences. These areas are summarised below, and further details are provided in Annex B.

Themes relevant to all taxa

A broad gap in our current knowledge is how and whether effects on individual animals have consequences at the population and ecosystem scales. This is the case for all taxonomic groups. To date, research has largely focused on investigating the effects listed above in individuals or small groups of animals. However, there is growing recognition of the need to assess how exposure to noise may ultimately affect population growth rates and ecosystem dynamics, through its effects on individual fitness and fecundity. A framework for assessing such consequences has been developed for marine mammals, known as the Population Consequences of Acoustic Disturbance (PCAD) model (National Research Council, 2005). This framework has also been generalised to include other forms of disturbance, within the so-called Population Consequences of Disturbance (PCoD) framework. Further empirical data is needed to derive parameters for this modelling approach for particular marine mammal species (e.g. New *et al.*, 2013, 2014; Pirotta *et al.*, 2015). It remains to be seen whether the PCAD/PCoD frameworks are appropriate for other taxa (e.g. fish), and the extent to which indirect consequences of noise (e.g. on predator or prey species) can be accounted for within them.

Adopting a population consequences perspective leads to a greater focus on the less acute effects of noise exposure. Shipping noise, a relatively low-level noise source, is the most pervasive in the marine environment (Hildebrand, 2009), and consequently has the greatest potential to impact populations and ecosystems through the widespread and chronic effects of acoustic masking, behavioural responses, physiological stress, and developmental effects (Slabbekoorn *et al.*, 2010). It is therefore important to highlight that the most severe effects of noise exposure, such as permanent hearing loss or mortality, are likely to be far less significant than the repeated and widespread low-level effects listed above when considering population-based and ecosystem-based management of underwater noise pollution.

A related and emerging strand of investigation concerns *cumulative* effects related to noise exposure. Effects may be regarded as cumulative in three ways:

1. Accumulation of deleterious responses over time, i.e. the cumulative effects of repeated or chronic exposure to noise (Wright *et al.*, 2007; Kight and Swaddle, 2011).
2. The exposure of individuals and ecosystems to multiple noise sources, distributed in space and time. Much previous research has adopted a reductive approach and considered the effect of only one noise source or type, and studies are needed which consider how multiple sources of noise pollution could impinge on a study system (e.g. Pine *et al.*, 2014).
3. The effects of noise exposure when combined with non-acoustic stressors. Noise may not be the only anthropogenic stressor affecting a population or ecosystem (Science Communication Unit, 2013), and considering noise in isolation from other factors such as habitat loss or effects on prey may lead to errors in predicting the consequences of noise disturbance on a system.

To facilitate effective management of underwater noise, a priority area is to better understand how noise might disrupt individuals and populations at key life stages, such as spawning, nursing, mating or migration. One of the mitigation tools available to regulators of noise-generating activities is to impose spatiotemporal restrictions based on the behaviour patterns of at-risk species. More information on the risks of disturbance at key life stages and the possible benefits of mitigation measures is needed to support these decisions.

There is increasing recognition that animals which do not avoid artificially noisy environments are not necessarily unaffected by the presence of anthropogenic noise (Bejder *et al.*, 2009). Animals may make trade-offs between noise exposure and foraging or mating opportunities, for instance, resulting in harmful effects without overt behavioural responses. One example is offshore wind farms, which can act as artificial reefs, creating foraging opportunities for predators (Inger *et al.*, 2009) while also generating relatively low levels of noise when in operation (Tougaard *et al.*, 2009b). A recent study reported that harbour seals were foraging around these structures for sustained periods, potentially leading to harmful levels of noise exposure (Russell *et al.*, 2014). Further work is needed to investigate whether such tolerance of anthropogenic noise exposure may belie detrimental consequences for exposed animals.

A final theme applicable to all taxonomic groups is the extent to which the results of laboratory experiments can be extrapolated to freely moving animals in their natural environment. Lab-based studies have the advantage of a controlled environment, enabling repeated measurements and control of contextual factors that may otherwise affect responses. However, these conditions are unrepresentative of the natural environment where the behavioural context may play a key role in animal responses to noise (Ellison *et al.*, 2012), and the sound fields generated in tank experiments are likely to be unrepresentative of field conditions (Parvulescu, 1967). On the other hand, in field studies, it is much more challenging to control experimental variables, and there may be factors other than noise exposure that elicit responses, leading to misinterpretation of results or the obfuscation of significant effects. For these reasons, studies are needed which address the linkage between laboratory and field experiments, such as by scaling up controlled experiments into the field (e.g. using mesocosms or large, contained water bodies) to provide an intermediate scale of assessment, or by developing methods to corroborate the findings of lab-based studies in the field.

Themes specific to marine mammals

Many of the key themes relevant to marine mammals have already been outlined above. Topics specific to marine mammals include large-scale displacement from impulsive noise (e.g. pile driving). Recent studies of harbour porpoise displacement from pile driving for offshore wind farm construction have shown short-term displacement effects at up to and exceeding 20 km (Tougaard *et al.*, 2009a; Dähne *et al.*, 2013), though there is evidence that short-term effects from impulsive sources may not lead to long-term displacement (Thompson *et al.*, 2013). Several studies have observed an increase in harbour porpoise abundance within offshore wind farms after construction (Scheidat *et al.*, 2011; Teilmann and Carstensen, 2012), possibly due to an artificial reef effect or the absence of shipping, suggesting that offshore wind farms may have longer term benefits for small cetaceans (though note the potential risks of noise tolerance described above). Longitudinal studies could investigate the overall 'impact budget' of these developments, in the context of population scale effects.

Themes specific to fish and invertebrates

Over the last two decades, much of the research into the effects of noise on marine life has concentrated on marine mammals. However, in recent years, the number of studies on fish and invertebrates has grown rapidly (Williams *et al.*, 2015), leading to greater understanding of the effects of noise on lower trophic levels and possible consequences for ecosystem dynamics. A key constraint on acoustic studies of fish and invertebrates is that these taxa primarily sense sound through the particle motion component of the sound field (Popper and Fay, 2011; Morley *et al.*, 2014). The conventional means of measuring sound underwater is by measuring sound pressure (another component of the sound field) using hydrophones, but for most environments it is not possible to use this to derive the particle motion. Commercial devices to measure particle motion are becoming available, but research into applying these in field measurements is still in its infancy (Merchant *et al.*, 2015). Field studies are needed to quantify particle motion from sound sources and to examine associated responses of fish and invertebrates to this component of the sound field.

A greater understanding of the hearing sensitivities of fish and invertebrates is also required, particularly in relation to particle motion (Popper and Fay, 2011). This will require the development of devices and protocols to make such measurements for particle motion (Popper *et al.*, 2014).

On the whole, little is known about the impacts of anthropogenic underwater sound exposure on marine invertebrates (Normandeau Associates, 2012), though several studies have reported adverse behavioural and physiological effects (e.g. Wale *et al.*, 2013a, 2013b; Filiciotto *et al.*, 2014). 'Invertebrates' covers a wide range of organisms and the range of responses to noise in this group may be correspondingly diverse. To prioritise research needs, it may be beneficial to focus on species with high ecological, social, or economic importance.

With regard to eggs and larvae of fish and invertebrates, information on sound levels at which lethal and sub-lethal effects occur is very limited (but see, e.g. Bolle *et al.*, 2012; de Soto *et al.*, 2013; Nedelec *et al.*, 2014). Further research is needed into these effects, including behavioural responses and developmental consequences.

3 Legislation review

Regulation and enforcement vary greatly among jurisdictions, and a range of national and international laws and guidelines are currently in place. Before summarising these noise management instruments, it is worth briefly considering the available means of mitigating the effects of underwater noise pollution. These measures can be divided into four broad categories:

1. **Location and timing**. Spatiotemporal management of noise-generating activities to avoid habitats and periods where animals have a greater vulnerability to noise pollution.
2. **Mitigation equipment**. Physical barriers to reduce noise radiated from activities (e.g. bubble curtains for pile driving operations) and devices to displace marine fauna to reduce risk of high noise exposures (e.g. acoustic deterrent devices (ADDs) or use of 'ramp-up' at onset of operation).
3. **Source quieting**. Use of alternative methods with lower noise emission (e.g. vibration piling rather than impact piling) or modifications to existing noise sources to reduce noise output (e.g. ship quieting technologies).
4. **Real-time mitigation**. Delay or interruption of noise generating activities based on observations of at-risk species in the vicinity (e.g. marine mammal sightings or passive acoustic detections).

Effective management of underwater noise pollution will require a combination of these measures spanning local, national, regional, and global jurisdictions to address the range of scales at which noise generating activities are regulated. For example, shipping routinely traverses international boundaries and so will require a coordinated international approach. Offshore construction projects may introduce significant levels of noise across national boundaries and so demand a bilateral or regional approach to managing cumulative effects. Some activities may be sufficiently localised that they can be managed at a local or national level. In the following summary, existing management instruments to address noise pollution are briefly reviewed; further details are provided in Annex A.

At a global level, the United Nations Convention on the Law of the Sea (UNCLOS) defines pollution as "the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life..." (UNCLOS, 1982). This can be interpreted as encompassing noise, but this view has not officially been adopted by UNCLOS. In 2014, another UN body - the International Maritime Organization (IMO) - adopted non-mandatory guidelines in relation to shipping noise (MEPC

66/17). These guidelines set out a ten-point work plan to address current knowledge gaps in ocean noise (see Annex A), although these proposals are non-binding.

Within Europe, a range of multinational and EU-wide agreements are in place. The Marine Strategy Framework Directive (MSFD) addresses underwater noise directly under Descriptor 11. Two Indicators within this Descriptor describe impulsive sound (11.1.1) and ambient sound (11.2.1). The MSFD aims to achieve GES (Good Environmental Status) for European seas, with a recurring six-year assessment cycle. Targets for these Indicators have yet to be developed, and the definition of GES with respect to noise remains qualitative: "input of energy, including underwater noise, is at levels that do not adversely affect the marine environment." Prior to the MSFD, a number of other Directives (e.g. Environmental Impact Assessment, Strategic Environmental Assessment, Habitats and Species) were used to address underwater noise issues, and remain relevant in their respective areas.

A number of European bodies (e.g. OSPAR, HELCOM) provide fora for regional cooperation among nations with shared seas, including with regard to MSFD Descriptor 11 implementation. Two non-binding multilateral agreements to promote the conservation of cetacean species have also addressed underwater noise issues. The Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) was signed by 23 countries bordering these waters, while the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) is a similar coordination tool for the named region. These Agreements call on participating countries to address underwater noise pollution with regard to cetacean conservation, although there is no provision for the legal enforcement of these recommendations.

At a national level, several countries have introduced mandatory requirements in relation to underwater noise pollution. One example is Germany, where a threshold for pile driving noise has been implemented: the peak-to-peak sound pressure level from piling must not exceed 190 dB re 1 µPa outside a 750 m perimeter from the pile. In other countries, legislation to protect certain species has been used to impose restrictions on noise generating activities. For example, in the United States marine mammals are given protection from injury and behavioural disturbance under the Endangered Species Act and the Marine Mammal Protection Act. The requirements of these statutes have formed the basis for developing sound exposure thresholds for these species.

Finally, a number of countries have adopted guidelines for mitigating the effects of certain noise generating activities. In the United Kingdom, the Joint Nature Conservation Committee (JNCC) has developed marine mammal mitigation guidelines for seismic surveys, marine explosives, and marine piling (e.g. JNCC, 2010). In each case, a mitigation zone to be surveyed by marine mammal observers (MMOs) is defined (within a specified distance from the activity), and procedures for beginning operations with a soft start (ramp-up) are outlined. Another example is New Zealand, where a code of conduct has been developed for seismic surveys to mitigate the potential effects on marine mammals (New Zealand Department of Conservation, 2013). Similarly to the JNCC guidelines, these specify mitigation zones and soft start procedures for seismic operations.

4 Review of underwater acoustic propagation models

A number of 'off-the-shelf' acoustic propagation modelling solutions have been developed, and are widely used in the underwater acoustics community. These models apply particular solutions to the wave equation, and can be downloaded from open sources (e.g. http://oalib.hlsresearch.com/). No single model provides an efficient and applicable solution to all scenarios: each has advantages and disadvantages in relation to their suitable frequency range, water depth, computational requirements and ability to account for spatial variability in the environment (Jensen *et al.*, 2011). Table 1 summarises some of these factors for five commonly used models; further details are provided in Annex E.

Table 1. Suitability of five commonly used propagation models for different water depths and frequencies (see Annex E for details).

Shallow water - low frequency	**Shallow water - high frequency**	**Deep water - low frequency**	**Deep water - high frequency**
Ray theory (Red)	*Ray theory* (Green)	*Ray theory* (Amber)	*Ray theory* (Green)
Normal mode (Green)	*Normal mode* (Amber)	*Normal mode* (Amber)	*Normal mode* (Red)
Wave number integration (Green)	*Wave number integration* (Green)	*Wave number integration* (Green)	*Wave number integration* (Amber)
Parabolic equation (Green)	*Parabolic equation* (Amber)	*Parabolic equation* (Green)	*Parabolic equation* (Red)
Energy flux (Green)	*Energy flux* (Green)	*Energy flux* (Amber)	*Energy flux* (Amber)

Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable

It is critical to select an appropriate model for a particular scenario, yet even a suitable model can only be predictive if the input data are accurate and of a sufficient spatial and temporal resolution. Indeed, the quality of input data is typically the key constraining factor in underwater propagation modelling, since gathering marine environmental data is costly and existing datasets (typically collected for other purposes, e.g. geophysical surveys) may not be adequate. The relevant parameters can include, for example, bathymetry, seabed data, sound speed profile, and sea surface roughness. The seabed properties in particular are a key factor in modelling propagation in the shallow, continental shelf waters that are typical of several European seas. For large-scale applications such as sound maps, small changes or errors in these input parameters could have a considerable effect on model predictions, and so it is important that field measurements are undertaken to validate results and to help to identify sources of uncertainty. Such corroboration is the only reliable way to verify that model predictions are accurate. The more a model has been benchmarked in this way, the more confidence there can be in extrapolations into similar environments where detailed measurements are lacking.

5 Use of sound maps for assessing Indicator 11.2.1

It has been suggested that a combination of measurements and modelling will be required to evaluate Indicator 11.2.1 of the MSFD (Dekeling *et al.*, 2014). Deploying acoustic monitoring equipment at sea is costly, and providing comprehensive spatial coverage across EU waters using only measurements would be prohibitively expensive and logistically challenging. Whether a limited number of indicative measurement locations would be adequate to assess GES is a matter of debate. One solution could be to use acoustic propagation models, which extrapolate from measurements based on environmental parameters and sound source characteristics as described in the previous chapter. Models based on the spatial distribution of sound sources can be used to produce maps of sound levels at large spatial scales (e.g. Erbe *et al.*, 2012; Heaney, 2014). Such sound maps need to be ground-truthed and optimised using calibrated measurements of sound levels if they are to produce valid results (Merchant *et al.*, 2015).

The validation of modelling to produce sound maps is an iterative process, as there are a variety of parameters which can affect the model predictions. These include the accuracy of the propagation modelling used (which in turn depends on the quality of environmental input data, such as seabed properties) and of the sound levels assumed to be generated by the noise sources. As part of the present project (see Annex F), a four-step framework was developed for producing validated sound maps:

1) **A priori modelling.** Before undertaking a noise monitoring programme, a priori modelling can be used to identify sites at which measurements will most reduce uncertainty in the model.
2) **Initial validation measurements**. Having identified suitable monitoring sites in Step 1, initial monitoring at these sites can be undertaken to quantify the degree of agreement between the a priori model and the initial measurements.
3) **Iterative optimisation.** To improve the model predictions, the next stage is then a feedback loop in which the greatest sources of error or uncertainty in the model are identified and reduced in each iteration. Reducing these errors will involve improving the quality of the model input parameters, and possibly altering the modelling approach itself. Better input data may be obtained by making targeted measurements, such as of ship source levels, environmental parameters, or propagation loss.
4) **Mature results for Indicator 11.2.1**. The validated output is then a two-dimensional depth-averaged map of the Indicator over the relevant marine region.

In practice, the site selection for field measurements will also be influenced by practical considerations such as the costs of deployment and whether pre-existing monitoring stations can be utilised.

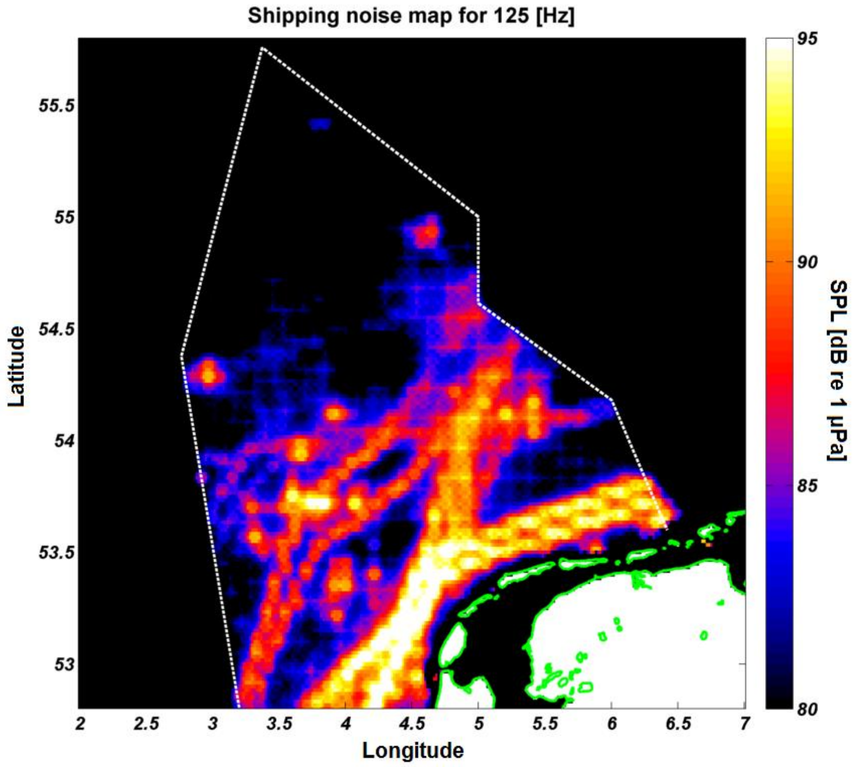

Figure 1: Shipping sound map of unweighted SPL [dB re 1 µPa] in the 1/3-octave band centred at 125 Hz (Annex F). Green border indicates the land boundary and white border the Exclusive Economic Zone (EEZ) of the Netherlands. X and Y axes indicate longitude and latitude, respectively.

Sound maps were produced for two areas in EU waters for the purposes of the present project: the Netherlands EEZ and a site between Madeira and the Canary Islands (see Annex F for details). Figure 1 shows an example for the Netherlands EEZ for the 125 Hz band based on AIS shipping data, and is an example of a priori modelling for Step 1 of the sound mapping framework. To produce validated sound maps, field measurements at comparable spatial and temporal scales are needed which will help to identify sources of error and refine the model parameters as outlined above.

A number of different developers and research groups are developing tools to create sound maps, and it will take time before these techniques are sufficiently mature and standardised to be implemented in a policy context. Variability in mapping predictions will result from differences in modelling approaches among Member States, and it is important that GES assessment is not dependent upon the particular modelling approach chosen. In addition to an agreed modelling benchmark for sound mapping, consistency is needed in the input data, including: AIS ship-tracking data; estimates of noise source levels; and environmental data (e.g. seabed properties, bathymetry, meteorological data, water column properties).

6 Outcomes of workshop on methodologies and guidelines

As part of the project, a workshop entitled *Propose methodologies and guidelines on how to evaluate impacts of noise on marine biota* was convened in Brussels on 10-11 April 2014 (see Annex C for full details). The workshop was co-chaired by Mark Tasker (JNCC) and Fabrizio Borsani (CEFAS), and was attended by 37 delegates from industry, academia, NGOs, and DG Environment. Five international experts provided insight into particular areas, specifically: the effects of noise on invertebrates (Michel André), fish (Michele Halvorsen), and marine mammals (Christine Erbe); the PCAD (Population Consequences of Acoustic Disturbance) framework (John Harwood); and noise modelling and mapping (Kevin Heaney).

The aims of the workshop were to:

a) Discuss and propose a roadmap towards defining Good Environmental Status (GES) for underwater noise;
b) Identify knowledge gaps and define research needs to address the impacts of underwater noise on marine biota;
c) Provide guidance for important features and considerations that a proposal related to the effects of underwater noise should have when submitted to the EC for funding.

The principal conclusion of the workshop was that there is currently insufficient knowledge to define GES in relation to underwater noise or to set quantitative and evidence-based targets. To make progress towards achieving these goals, key knowledge gaps should be addressed.

The following were identified as priority knowledge gaps and/or needs for future action:

1. The current understanding of the adverse effects of sound on the marine ecosystem and marine fauna is limited. The main areas of concern are related to long-term effects of elevated ambient noise levels at the population and ecosystem scales. Assessment of these effects could be based on observations and modelling at the levels of populations, food webs and ecosystems. Another major gap is the lack of data on the particle motion component of underwater noise, which is the principal means by which fish and invertebrates detect sound. Primary research into the effects of noise on these groups in relation to particle motion will be critical to understanding potential risk. Finally, there is a need to better understand the limitations and opportunities in extrapolating the results of controlled lab-based experiments to populations in their natural environment. One way of evaluating the validity of such

extrapolations is to conduct controlled field experiments to provide an intermediate scale of assessment.

2. Underwater noise monitoring is needed to support the implementation of the Marine Strategy Framework Directive. While no international standards are available for underwater noise monitoring, standards developed by Member States such as those developed by the BIAS project in the Baltic Sea may be adopted or adapted for wider application to EU waters. It is important that monitoring is carried out in a standardized way, so that the results can be displayed, evaluated and compared consistently across Member States.
3. There is a need to identify or develop cost-efficient monitoring tools to monitor ambient sound at relevant frequencies to obtain the data needed to address Descriptor 11. A common EU-wide approach to the development of sensors and monitoring tools is desirable to avoid duplication and to harmonize approaches.
4. To better define GES for noise and its relations to other Descriptors, further work and guidance are needed. The introduction of thresholds or single-number levels appears questionable from an ecological standpoint, but is practicable and fits within the environmental monitoring paradigm of the MSFD. Indicators and targets should therefore be carefully evaluated, taking into consideration their practical implementation as management tools as well as advances in the available scientific evidence. There is also uncertainty over whether setting uniform thresholds for underwater noise across European seas is a reasonable approach, and whether noise should also be evaluated in concert with other major stressors to give an indication of the cumulative pressure that these ecosystems sustain.

The final aim of the workshop was to provide guidance on important features for funding proposals to the EC on the effects of underwater noise on marine biota. An extensive list of suggestions was put forward (see Annex C for details), including:

- Highlighting socioeconomic value, stakeholder engagement, impact on policy and/or enabling GES assessment.
- Providing publicly available datasets to allow open analysis of results for future work.
- Transparent assessment of uncertainties, errors, and biases in the methods and results.
- Clear documentation of environmental and contextual factors which may affect the results.
- Use of openly available, peer-reviewed techniques (e.g. in noise modelling) to ensure transparency and repeatability.

7 Roadmap

This final chapter considers the way forward to define GES for underwater noise. In previous chapters, key knowledge gaps were identified and the obstacles to defining GES were discussed. Here, a number of concrete steps are proposed to reduce uncertainty in the evidence base and to make progress towards defining effective GES criteria for underwater noise.

It is important to recognise at the outset that MSFD Descriptor 11 is the first legislative instrument to address ecosystem-based management of underwater noise pollution in a quantitative manner. The EU is leading the way in developing quantitative, practicable, evidence-based targets to ensure that underwater noise does not adversely affect the marine environment. This process of developing targets for Descriptor 11 remains a work in progress, and has involved extensive consultation with the scientific community, including through the Technical Group on Underwater Noise (TG Noise). Achieving this goal will mean aligning GES criteria with the best available scientific evidence while also ensuring that GES can be readily translated into operational targets for regulators of noise generating activities.

There follows a number of proposed Actions informed by the outcomes of the previous chapters. Indicative costs and timeframes have been associated with each Action. There are a range of organisations that could undertake the work described. In some cases, such as standard setting, certain international bodies may be appropriate. In others, where a number of groups could potentially undertake the work, it is recommended that an open public tender process be undertaken. To ensure that such calls for tender reach all parts of Europe, international bodies such as OSPAR, HELCOM, the Barcelona and Black Sea Conventions, and ICES should be asked to help in advertising the calls. Funding for some of these actions may be found within the current LIFE+ framework, as well as within future HORIZON 2020 calls. New INTERREG calls may be relevant to Action 3 at the regional level, since they involve small and medium-sized enterprises (SMEs) to provide a technical component and local regulatory bodies to put monitoring in place.

Action 1: Agree standards for underwater noise monitoring (2015-2016)

A variety of metrics and terminology are in use across the EU to describe underwater sound. Depending upon their technical background, scientists, developers, and military operators carry out measurements and analysis in different ways. To assess Descriptor 11 consistently across the EU, standards are needed for data acquisition, analysis, and modelling, that can be applied in all EU waters. While it would be convenient to adopt a suitable international standard (e.g. International

Organization for Standardization (ISO) standard), no such standards for ambient noise monitoring or mapping exist. International standards may be developed in the future, but the timescale is likely to be at least six years (see Annex F), and it is not clear that such standards will necessarily be aligned with the MSFD policy objective of attaining GES. For these reasons, it is incumbent upon Member States to agree EU-wide standards for MSFD implementation.

Considerable progress has already been made by the EC-funded BIAS project, which has developed standards for data handling and sensors (Verfuß *et al.*, 2014), and plans to publish standards for signal processing. These standards were developed for use in the Baltic Sea, but could be adopted or adapted for use throughout EU waters. In addition to measurement standards, standards for modelling and mapping of underwater sound for Indicator 11.2.1 are needed. Since sound maps are in a relatively early stage of development, and the key priority for Indicator 11.2.1 assessment is to begin monitoring (Dekeling *et al.*, 2014), the focus of standardisation initially should be to agree measurement and analysis standards. To this end, TG Noise should consider, in consultation with international experts, how the BIAS standards can be adapted for application throughout EU waters, leading to an operational standard for measurement and analysis endorsed by TG Noise. Subsequent workshops can then explore how sound maps can be validated and standardised as these techniques become more mature.

This Action can be achieved through a series of workshops, under the aegis of the ongoing TG Noise work programme. These workshops would bring together international (i.e. including non-EU) specialists, so costs would comprise travel and subsistence for those specialists and some local venue costs. An estimated timeframe of 1-2 years would be required to agree and refine the measurement and analysis standards.

Sound mapping standards may be premature at this stage since these techniques have yet to be extensively validated and optimised with field measurements. Nevertheless, knowledge exchange and benchmarking of sound mapping methods is needed to promote consistency, and progress towards validated sound maps will accelerate as field data from MSFD noise monitoring programmes become available. A series of workshops should be convened to share the latest developments in sound mapping and to work towards standardisation among Member States.

Costs for these workshops are anticipated to be approximately €50,000 per year.

Action 2: Commission studies to address key knowledge gaps (2015-2018)

Targeted studies are needed to address key knowledge gaps in our understanding of the effects of noise on marine ecosystems. Uncertainties over the effects of underwater noise on marine fauna currently constrain management decisions and hinder progress towards defining GES for noise. A detailed summary of the key topics was provided in Chapter 2, and topics emerging from the workshop were outlined in Chapter 6. Common themes include (but are not limited to) the need for greater understanding of the population and ecosystem consequences of noise exposure, the need to assess the particle motion component of the sound field in relation to fish and invertebrates, and a need to more fully understand the limitations and opportunities in extrapolating experimental results to wild animals.

Research to address these issues can be commissioned under various EU funding mechanisms (e.g. HORIZON 2020, Life+, INTERREG), and will require a concerted and coordinated effort to direct funding at projects which will reduce uncertainty in environmental assessment. An indicative timeframe to achieve results from these projects is 4 years. Costs for the work may be in the region of €5-10 Million, and are high due to the anticipated need for extensive field work and novel instrumentation.

Action 3: Agree common standards for noise monitoring instruments (2015-2018)

Further to the standardisation in monitoring techniques identified in Action 1, there is also a need to standardise the sensor technology used to monitor underwater sound. A variety of devices are commercially available, and some may not be adequate to meet the requirements of noise monitoring for the MSFD. Work to establish standards and guidelines for suitable monitoring technologies could fall under Action 1. Another option is to develop appropriate and cost-effective monitoring equipment that could be deployed across EU waters to ensure standardised results for GES assessment. This coordinated approach would help to avoid duplication in sensor development, and could be achieved through collaboration between Member States and industry, academia, and researchers. Initial efforts are already underway within the EU-funded Common Sense project (http://www.commonsenseproject.eu/), and further development will be required to produce a fully operational system. The initial timeframe for this Action is estimated to be 4 years, with potential development costs of up to €6 Million.

Action 4: Define operational GES criteria (2016-2017)

It is clear that there is currently insufficient scientific evidence to support a comprehensive assessment of the levels at which anthropogenic noise may adversely affect the marine environment. Indeed, there will always be uncertainty over what levels of impulsive and ambient noise may lead to adverse effects. Nevertheless, this uncertainty need not preclude the development of Indicators and targets to attain GES based on the best available scientific evidence. A combination of scientific data and expert judgement will be required to define GES in a way that is proportionate to the risks and uncertainties involved and in a form that can be implemented as an operational management tool. It is important to note that this situation is not unprecedented. For example, in relation to the effects of noise on marine life, noise exposure thresholds have been developed for marine mammals (Southall *et al.*, 2007) and fish (Popper *et al.*, 2014) despite considerable knowledge gaps and uncertainties in the available scientific evidence. Making progress towards defining GES for noise will require an understanding from the scientific community that operational targets are needed that can be implemented as policy. If necessary, these targets can be refined in subsequent assessment cycles as more information becomes available.

The two Indicators within Descriptor 11 are complementary and address two aspects of the effects of underwater noise. In defining GES for noise, care should be taken to ensure that the Indicators and targets remain complementary and are relevant to the consequences of noise exposure for marine fauna. Indicator 11.1.1 addresses impulsive noise, which has been linked to injury, displacement, and disturbance. Indicator 11.2.1 addresses ambient noise: increasing ambient noise levels have the potential to mask acoustic cues, raise stress levels, and have developmental and behavioural effects. The noise sources that the Indicators address are similarly distinct and require different management strategies: the primary sources of impulsive noise are pile driving, seismic surveys, and explosions, which are all discrete events in space and time, while the main contributor to rising ambient noise is shipping, which is continuous and widespread throughout the marine environment.

Taking each Indicator in turn, the main challenges in defining GES will be outlined, and then an Action plan to resolve the remaining issues will be put forward.

Indicator 11.1.1 (low and mid-frequency impulsive sounds) is currently defined as (Dekeling *et al.*, 2014):

> *The proportion of days and their distribution within a calendar year, over geographical locations whose shape and area are to be determined, and their spatial distribution in which source level or suitable proxy of anthropogenic sound sources, measured over the frequency band 10 Hz to 10 kHz, exceeds a value that is likely to entail significant impact on marine animals.*

Source level thresholds for inclusion of particular noise sources in Indicator 11.1.1 (i.e. those that are likely to entail significant impact) have already been proposed by TG Noise (Dekeling *et al.*, 2014). The remaining questions to be resolved in defining GES with respect to impulsive noise can then be summarised as:

1. **What is an appropriate EU-wide spatial scale to evaluate Indicator 11.1.1?** In defining a spatial resolution, consideration should primarily be given to the relevance to potential effects on marine life, and secondarily to factors such as existing assessment areas (e.g. licensing blocks), which may differ between Member States.
2. **How can a target for GES be formulated based on this Indicator?** Indicator 11.1.1 has both spatial and temporal dimensions, and a GES target must similarly address both aspects; guidance could be sought from other areas of environmental science and policy which may have developed analogous targets.

Indicator 11.2.1 (ambient noise) is currently defined as (Dekeling *et al.*, 2014):

> *Trends in the annual average of the squared sound pressure associated with ambient noise in each of two third octave bands, one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels, in units of dB re 1 µPa, either measured directly at observation stations, or inferred from a model used to interpolate between or extrapolate from measurements at observation stations.*

There are several outstanding questions to be resolved before this Indicator can be applied to GES assessment. These include:

1. **What is a suitable metric to track trends in ambient noise levels?** The current TG Noise guidance is to use the arithmetic mean (Dekeling *et al.*, 2014), but this metric is strongly dominated by the loudest noise levels (Merchant *et al.*, 2012). This means that in many areas impulsive noise may skew this Indicator away from the overall trend in background noise, confounding assessment of whether ambient noise levels overall are rising or falling, or have exceeded a certain threshold. To reflect general trends in ambient noise - which are linked to levels of acoustic masking and noise-induced stress - an Indicator based on percentiles of the ambient noise level distribution may be more representative and relevant, as has been applied in studies of acoustic masking (e.g. Clark *et al.*, 2009; Hatch *et al.*, 2012).
2. **What is an appropriate target for Indicator 11.2.1?** Similarly to Indicator 11.1.1, levels of ambient noise have both a spatial and temporal aspect. Spatial variation in ambient noise levels may be modelled using sound maps, but these techniques are still in development, and it is important that attainment of GES does not depend upon the particular modelling approach employed by a Member State. Until sound mapping methods are well established and validated, measurements should constitute the primary means of GES assessment. The question is then how to formulate a suitable ambient noise target. Setting an absolute

threshold above which GES is not attained may seem arbitrary given the uncertainty in the relationship between environmental pressure, status and impact. One alternative strategy could be to use expert judgement to derive a threshold above which ambient noise levels are probable to cause adverse effects, and then stipulate a minimum proportion of time that noise levels should fall below this threshold to attain GES.

Reaching sufficient consensus on these issues to enable an operational definition of GES will be challenging, but can be achieved if targeted efforts are made to resolve the aspects that depend on expert judgement. This work could progress through a series of workshops with agenda items focused on resolving the outstanding issues. These workshops should draw on a broad pool of international expertise, and should seek the involvement of experts with previous experience of formulating noise exposure thresholds, as well as those with experience of environmental management of anthropogenic noise. The timeframe would be set initially to two years, with a potential for reiteration at the end of each 6-year MSFD cycle. Costs may be in the range of €50,000-100,000 per year, depending upon how much overlap there is with planned TG Noise activities.

Glossary

Acronym	*Term*	*Definition*
	Acoustic masking	The effect of a noise source interfering with the detection of another acoustic signal in the environment, e.g. ship noise obscuring a cetacean communication call.
	Ambient noise	All sound except that resulting from the deployment, operation or recovery of the recording equipment, and its associated platform, where "all sound" includes both natural and anthropogenic sounds (Dekeling *et al.*, 2014).
	Cumulative effects	Effects caused by repeated exposures to noise, by exposure to multiple sources of noise, or by the combined effect of noise exposure with non-acoustic stressors.
	Developmental effects	Effects caused at early life stages which have subsequent repercussions, e.g. impairment of embryonic development.
EC	**European Commission**	The executive body of the European Union.
GES	**Good Environmental Status**	The main goal of the MSFD, where GES is defined as "The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive." (MSFD 2008/56/EC)
	Impulsive noise	Brief, discrete pulses of sound generated by human activities, such as from impact pile driving or seismic airguns.
MSFD	**Marine Strategy Framework Directive**	European Union legislation which came into force in 2008 with the aim of protecting the marine environment across Europe more effectively (MSFD 2008/56/EC).
	Particle motion	The physical component of sound to which fish and invertebrates are primarily sensitive. See also sound pressure.

PTS	**Permanent threshold shift**	Irrecoverable impairment of the auditory system due to noise exposure.
PCAD	**Population consequences of acoustic disturbance**	A modelling framework designed to predict how acoustic disturbance to individual animals may lead to changes in population growth rates.
PCoD	**Population consequences of disturbance**	Similar model to PCAD.
PL	**Propagation loss**	The reduction in sound level as an acoustic signal travels through the environment.
	Ramp up	A procedure whereby the energy applied in impact pile driving or seismic surveys is gradually increased at the start of the operation, with the intention of displacing marine fauna from the area before potentially harmful noise levels are generated.
	Sea surface roughness	A parameter used in acoustic propagation modelling which accounts for the scattering of sound at the sea surface due to wave action.
	Soft start	Another term for ramp up.
	Sound map	A spatial representation of modelled sound levels over an area, usually plotted in two dimensions.
	Sound pressure	The physical component of sound to which mammals are sensitive, and which can be detected indirectly by some fish species. See also particle motion.
	Sound speed profile	A measured or modelled vertical profile of sound speed variation in the water column, often inferred from CTD (conductivity, temperature, depth) measurements. Used in acoustic propagation modelling.
SL	**Source level**	The sound level of a sound source at a notional distance of 1 metre from the source.
TTS	**Temporary threshold shift**	Recoverable impairment of the auditory system due to noise exposure.
TL	**Transmission loss**	Another term for propagation loss.

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Cefas Document Control

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Final Report

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Report compiled by:	J. Fabrizio Borsani, Rebecca Faulkner, Nathan D. Merchant
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Head office

Centre for Environment, Fisheries & Aquaculture Science
Pakefield Road, Lowestoft
Suffolk NR33 0HT
UK

Tel +44 (0) 1502 56 2244
Fax +44 (0) 1502 51 3865

Web www.cefas.co.uk

Centre for Environment, Fisheries & Aquaculture Science
Barrack Road, The Nothe
Weymouth, DT4 8UB
UK

Tel +44 (0) 1305 206600
Fax +44 (0) 1305 206601