Future Science Brief

Nº 7 October 2021

Addressing underwater noise in Europe

Current state of knowledge and future priorities

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This Future Science Brief is a result of the work of the European Marine Board Expert Working Group on Underwater Noise. See Annex 1 for the list and affiliations of the Working Group members.

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First edition, October 2021

Foreword

With all due respect to Commander Cousteau, the Ocean is not “Le monde du silence” (the silent world). Actually, sound propagates particularly well underwater and the deep world of the Ocean is traversed by a multitude of natural and anthropogenic sounds. Underwater noise has been a topic of interest and concern within research circles for several decades. However, it has gained less traction in policy and public awareness compared to more tangible and visible pollutants such as plastics. Marine organisms rely on sound to understand the world around them, and the potential effect of external sources of noise is therefore significant. However, some external sources of noise are unavoidable if we want to develop our Blue Economy and for research activities that advance our understanding of marine environments and ecosystems. It is therefore important that we further develop our understanding of this topic, including its complexities and subsequent compromises. It can then be applied to the development of appropriate and proportionate mitigation and regulation of underwater noise.

In 2008, the European Marine Board published its first Position Paper on underwater noise, specifically in relation to marine mammals. Since then, research in and regulation of underwater noise has advanced and expanded significantly. For this reason, in 2019 the EMB approved the establishment of a new Working Group tasked with revisiting underwater noise and providing an update on this topic. They were also asked to highlight priority areas for further research and development to ensure that we can achieve the requirements of the EU Marine Strategy Framework Directive and its noise-related Descriptor of Good Environmental Status. The Working Group kicked off in June 2020 in the midst of the first COVID-19 pandemic lockdown, and despite never having met in person, they have delivered an informative document which addresses these requirements.

With the Horizon Europe Mission ‘Restore our Ocean and Waters by 2030’ and the UN Decade of Ocean Science for Sustainable Development (2021-2030) both highlighting underwater noise as a topic of interest, this publication and its recommendations are particularly timely and relevant.

On behalf of the EMB members, I would like to thank the members of the EMB Working Group on Underwater Noise (Annex I) for their hard work and dedication in producing this Future Science Brief. I would also like to thank the external reviewers for their valuable input. I thank the EMB Secretariat for their work in supporting the working group and coordinating the production of this document, namely Paula Kellett, Rebecca van den Brand, Britt Alexander, Ángel Muñiz Piniella, Ana Rodriguez, Sheila Heymans and Jana Van Elslander. Finally, I would like to thank Amy Dozier, Kathrin Kopke, and the JONAS and SATURN projects for their support in designing and producing the infographics that are included in this document.

Gilles Lericolais
Chair, European Marine Board
October 2021

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Executive summary

Anthropogenic underwater noise impacts have become a hot topic for environmental managers and regulators in Europe and beyond. Sounds from human activity at sea include shipping and other marine craft, construction and installations, sonar and seismic surveys. This Future Science Brief presents an update on the previous EMB publication on underwater noise, Position Paper N° 13 on "The effects of anthropogenic sound on marine mammals: A draft research strategy". This Future Science Brief expands the scope of the discussion beyond marine mammals to fishes and invertebrates, and outlines key developments that have taken place since the Position Paper's publication. The main chapters of the document focus on: the advances in our knowledge on anthropogenic underwater sound in the Ocean; the new knowledge that has been developed on the effects of noise on marine organisms; and the measures that have been taken to address the issue of underwater noise.

While significant progress has been made, knowledge gaps still remain. The document therefore presents these outstanding issues and highlights priority actions for addressing them. This Future Science Brief states that the most urgent priority actions/questions are to:

1. Develop collaborative international standards applicable to all steps of the risk framework;
2. Conduct comprehensive monitoring combined with spatial ecological modelling of marine species' dynamic habitat use, movements, behaviour and distribution to establish baselines;
3. Foster comprehensive monitoring and data collection of current soundscapes / ambient noise, including via joint monitoring programmes in existing and new areas;
4. Shortlist high priority (and biologically relevant) sound sources and perform standardized source characterization studies;
5. Undertake hearing studies on baleen whales and on selected fish and invertebrate species;
6. Conduct field and modelling studies on changes in acoustic habitats to identify masking risks to communication in fishes and marine mammals;
7. Conduct further studies on behavioural response of marine mammals and fishes due to exposure to high intensity impulsive sounds to assess population consequences;
8. Conduct taxa-relevant studies on hearing impairment and physiological stress to address existing knowledge gaps in invertebrates, fishes and marine mammals;
9. Conduct dedicated studies including multi-species investigations, predator-prey interactions, and interaction with other food web levels, addressing the question of how noise impacts combine with other stressors;
10. Develop frameworks and conduct studies to allow population-level assessment of effects from cumulative impact of noise and other pressures;
11. Conduct dedicated modelling and field studies to improve understanding on effectiveness, safety and cost-effectiveness of noise mitigation devices, mitigation measures and management options;
12. Develop regional action plans and guidelines for Environmental Impact Assessment and policies; and
13. Initiate international collaborative transdisciplinary projects to develop stakeholder and societal capacity in understanding and addressing underwater noise.

1 Introduction and scope

Background

Anthropogenic underwater noise impacts have become a hot topic for environmental managers and regulators in Europe and beyond. From a topic undertaken by a few devoted academics in the 1970s, the effects of noise on marine organisms such as mortality, hearing impairment, communication masking and behaviour disturbance have in the last couple of decades received increasing attention worldwide, resulting in numerous reviews including a United Nations report (see Richardson *et al.*, 1995; Southall *et al.*, 2007; Hawkins & Popper, 2016; UN, 2018a). A research strategy for the effect of underwater noise on marine mammals was published as Position Paper N° 13 by the European Marine Board 13 years ago (Boyd *et al.*, 2008). This report defined a strategic framework for future research; provided guidance about prioritisation; and proposed a process of implementation. A stepwise analytical risk assessment framework (see Figure 1) was developed as a systematic process to assess gaps in knowledge and identify priority research topics in underwater noise and has been influential in informing research on this topic over the past decade.

A lot has happened in the past thirteen years. Further attention has been brought to the impacts of underwater noise on fishes and invertebrates, which are not only more abundant and diverse than marine mammals, but also represent important components of the marine food web on which higher trophic levels such as marine mammals and humans feed. New technologies have allowed us to follow animals and observe their reactions while being exposed to noise. Frameworks and models for assessing the population-level consequences of noise exposure on mammals and fishes have been further conceptualized and tested. Methods to mitigate noise effects have been developed and implemented. Crucially, international and national policies have been drawn up to address underwater noise pollution. In the European Union, the 11th Good Environmental Status (GES) descriptor of the European Marine Strategy Framework Directive (MSFD) requires that "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment" and includes two indicators, considering both impulsive and continuous sound.

The above mentioned work led the EMB to convene a new expert Working Group who were tasked to follow up on the work of Boyd *et al.*, (2008). Our objectives were to:

- Update on progress related to this topic since the 2008 EMB Position Paper;
- Raise awareness of the current knowledge and research gaps;
- Broaden the scope from marine mammals to all marine organisms; and
- Highlight the conflicts and solutions that exist relative to underwater noise.

The risk assessment framework revisited

One of the novelties of EMB Position Paper N° 13 was that it applied an explicit risk assessment framework that can be used to structure research and impact assessments in the field of underwater noise. This ensures that all of the information identified for environmental protection is addressed. This risk framework involves a stepwise procedure, including: (i) risk identification (referred to as 'hazard identification' in Boyd *et al.*, 2008); (ii) exposure assessment; (iii) dose–response assessment; (iv) overall characterization of risk, all of which leads to (v) risk management and the selection of appropriate mitigation measures (Figure 1).

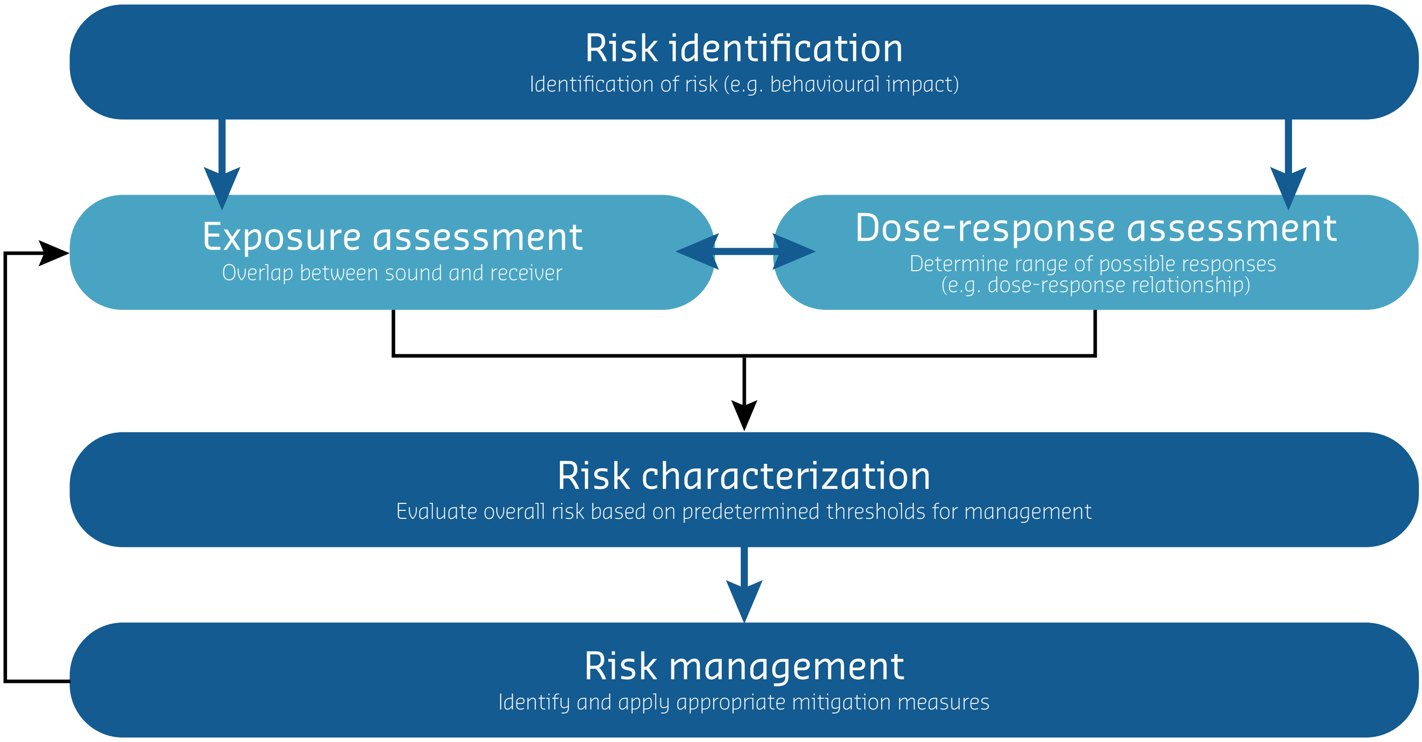


Figure 1. Overview of the risk-based approach (World Organization of Dredging Associations, WODA 2013; after Boyd *et al.*, 2008)

Building on Boyd *et al.*, (2008), the World Organization of Dredging Associations (WODA (2013)) emphasized the use of the risk-based approach in impact assessments of underwater noise. There is now a broad appreciation among regulators and scientists that the fundamental way to investigate the potential effects of noise is the risk-based approach developed in EMB Position Paper N° 13 (McQueen *et al.*, 2020; Popper *et al.*, 2020).

A second important framework is based on the "zones of noise influence" described in Richardson *et al.*, (1995), which has been further revised since 2008 by Hawkins & Popper (2016). The revised framework suggests that underwater noise can have a variety of effects on marine organisms (Figure 2), which can be conceptualised as overlapping zones of influence relative to a sound source. This simplified model assumes that effects are related to the received sound level. The received sound level in turn is dependent on the distance between a sound source and the marine organism potentially affected. Thus, different effects may extend to varying distances from the source. This basic model has been used in many studies and impact assessments (see Hawkins & Popper, 2016), but it also has limitations which are outlined in Chapter 3 in more detail. The key features of the model include:

- **The zone of masking:** the area where noise interferes with the detection of biologically relevant signals or cues used for communication and navigation, meaning that these sounds cannot be heard, or are less clear;
- **The zone of behavioural response:** the area within which a marine animal changes its behaviour in response to noise, e.g. by swimming away or diving deeper;
- **The zone of impaired hearing:** delineates the areas in which noise can lead to changes in hearing sensitivity. These changes can be temporary (temporary threshold shift, TTS) or permanent (permanent threshold shift, PTS). In most cases, TTS and PTS relate to changed sensitivity to certain frequencies. For an animal to detect a certain frequency, it will need to be louder. Generally, it does not mean that there has been a complete loss of hearing ability;
- **The zone of physical[1] and/or physiological[2] effects:** the zone where tissue damage and physiological effects other than those associated with hearing can occur. In extreme cases, the damage can lead to the death of the marine organism. It should be noted that death can also result, albeit indirectly, from any of the other effects listed above.

[1] Physical effects of noise can include damage to internal tissue and/or to the auditory system

[2] Physiological effects of noise can include stress and the release of stress hormones and/or increases in blood pressure

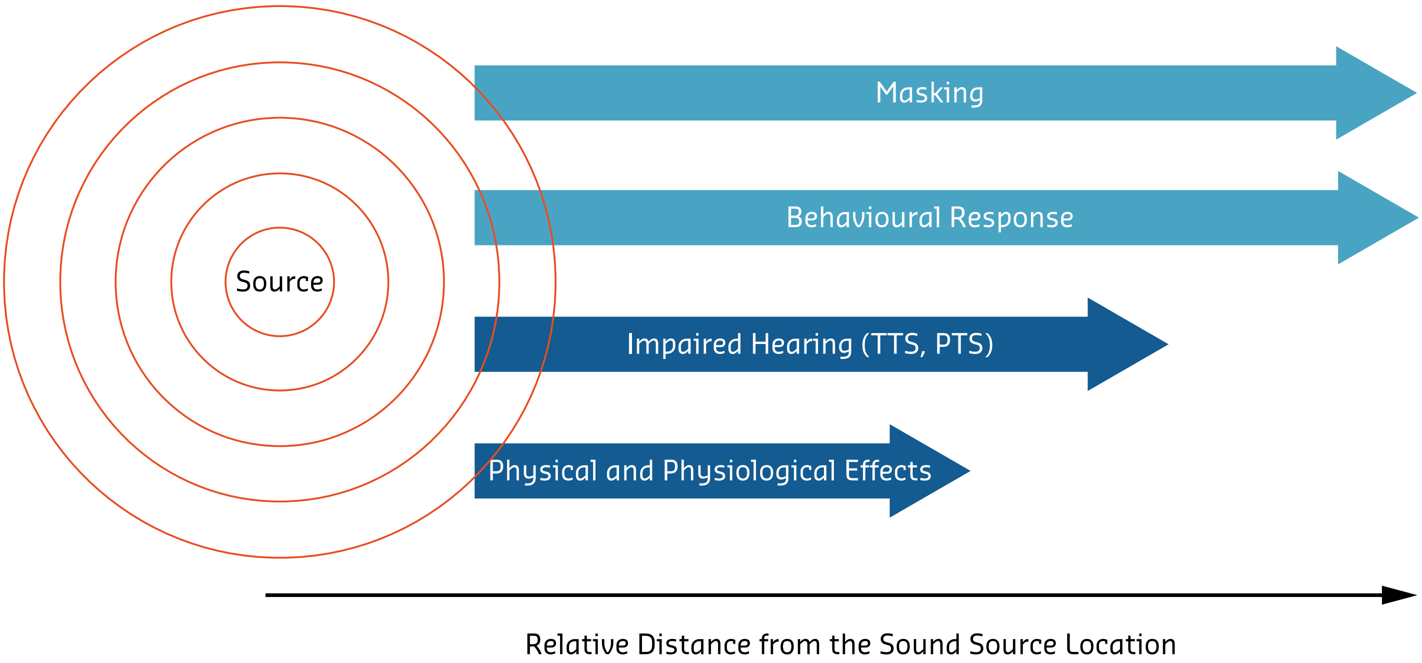
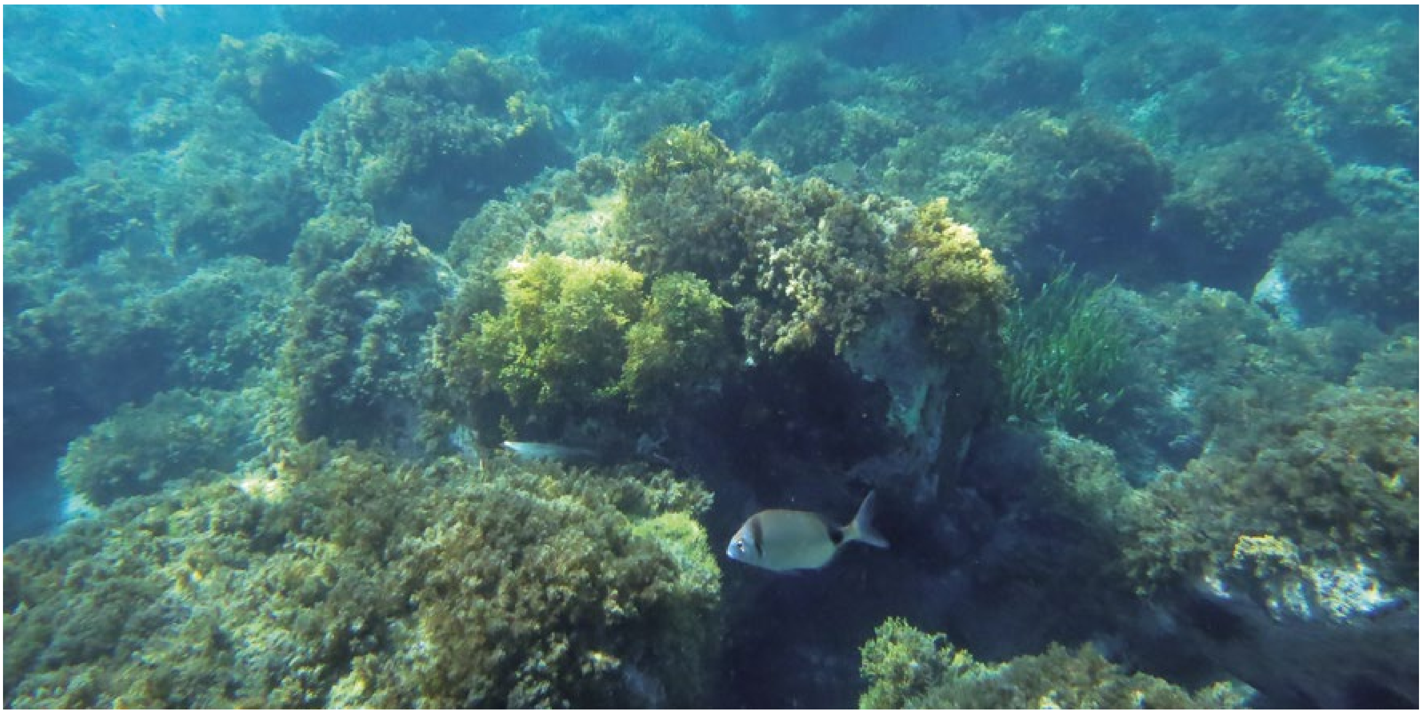


Figure 2. Potential effects of noise at different distances from a sound source (based on Richardson *et al.*, (1995) and adapted from Hawkins & Popper (2016)) where TTS = Temporary Threshold Shift and PTS = Permanent Threshold Shift. For further explanation see Chapter 3.

In this Future Science Brief, we follow the risk-based approach (Figure 1) and the 'zone of noise influence' model (Figure 2). In Chapter 2, we outline the advances in knowledge of anthropogenic underwater sound in the Ocean (sources, distribution, propagation and trends) corresponding to risk identification (step 1 of the risk-based approach) and exposure assessment (step 2). In Chapter 3 we then review the advances in knowledge of the effects of noise on marine organisms, following the definitions in Figure 2, including examples of state-of-the-art projects and corresponding to dose-response assessment (step 3). This is followed in Chapter 4 by a summary of what is being done to address the issue of underwater noise, particularly in a European context, providing examples of successful initiatives. This Chapter corresponds to risk management (step 4). Chapter 5 reflects on the current key knowledge gaps, barriers and actions needed for the proportionate management of underwater noise. Concluding this Future Science Brief is a list of the key priority actions/projects that could be conducted to address the identified knowledge gaps and barriers (Chapter 6).



Flora and fauna (including brown algae, different species of seabream) off the coast of the Cabo de Gata-Níjar Natural Park, Spain.

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

This Future Science Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development (Ocean Decade) in a number of ways.

The Future Science Brief highlights knowledge to support Societal Outcome 1 *(A clean Ocean where sources of pollution are identified and reduced or removed).* It also provides input to Outcome 2 *(A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed)* by providing recommendations that focus on developing our understanding of the interaction between marine organisms and underwater noise.

Regarding the Ocean Decade Challenges, this document addresses Challenge 1 *(Understand and map land and sea-based sources of pollutants and contaminants and their potential impacts on human health and Ocean ecosystems, and develop solutions to remove or mitigate them)* by presenting an overview of existing European efforts to map underwater noise pollution, and providing recommendations for their further development. It also provides recommendations relating to less-understood marine species and noise mitigation measures and how our understanding of these topics could be expanded, and eventually applied. This document also addresses challenge 2 *(Understand the effects of multiple stressors on Ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social and climate conditions*) by discussing the importance of considering underwater noise within the context of other stressors. Finally, to address Challenge 7 *(Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users*), this document makes recommendations on the expansion of monitoring and observations in Europe, specifically for underwater noise.

Credit: tkremmel / Pixabay

It is important to understand how underwater noise interacts and combines with other stressors which are also impacting on marine organisms.

2 Advances in knowledge of anthropogenic underwater sound in the Ocean

- Progress has been made in the past decade on the characterization of both impulsive and continuous sound sources such as airguns, pile-driving, shipping, and dredging;
- Some sources have still not been sufficiently characterized, which is essential for impact assessments;
- A substantial increase in activities producing impulsive sounds has been observed over the last decade in European waters due to offshore construction, e.g. pile-driving;
- Recent projects have provided new information on ambient noise levels in parts of Europe, but there are still large gaps in some regions such as the Black Sea and the Mediterranean Sea; and
- The on-going growth in the number of commercial ships might, without countermeasures, substantially increase ambient noise levels.

In this chapter, we define some basic terms such as 'sound' and 'noise'. We then provide a summary of knowledge built over the past decade on the different anthropogenic sound sources that contribute to the soundscape today. Further, we highlight the knowledge gained on spatial distribution of noise in Europe (e.g. noise hotspots), followed by what we know about the latest trends in ambient sound. To make it more easily accessible we do not provide formulas and/or (in most cases) numbers. Detailed reviews on the acoustics of underwater sound already exist elsewhere (e.g. OSPAR Commission, 2009b; Ainslie, 2010).

2.1 Background on sound

Sound or noise?

Boyd *et al.,* (2008) did not define the terms 'sound' or 'noise' and consequently, the terms were used interchangeably, which is also often the case in other work and can lead to confusion.

Within this Future Science Brief, we apply the definitions used in both US and EU regulatory contexts. Accordingly, the term 'sound' is used to refer to the acoustic energy radiated from a vibrating object, with no reference to its function or potential effect. 'Noise' is sound that is not a useful signal or cue, i.e. it has no adaptive value or biological meaning for the receiver, and may either be neutral or may have adverse effects (Van der Graaf *et al.,* 2012; Southhall, 2018; see also ISO, 2017). The term 'soundscape' is defined as 'ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field' (ISO, 2017).

What is sound?

Sound is a variation in pressure which propagates through a compressible medium (e.g. water). Sound pressure levels (SPL) are referred to in decibels (dB) with 1 µPa (one microPascal) as a reference unit. A decibel is a unit for measuring the relative loudness of sounds. SPLs are useful when analysing sounds of relatively long duration, such as the noise of a ship. The received levels from shorter duration sound sources such as pile-driving strikes, are often denoted in peak or peak-to peak SPLs, and Sound Exposure Level (SEL, 1 µPa2.s), which is a measure of the energy of the emitted sound (ISO, 2017).

Besides decibels, another important metric is frequency, which is the number of sound wave cycles per second. It is given in hertz (Hz): 1 hertz = one cycle per second, 1 kHz = 1000 cycles per second. Different marine animals use and are affected by different frequencies (see Chapter 3).

With the scope of this Future Science Brief reaching beyond marine mammals, it is important to understand that, in addition to pressure, sound also manifests itself in a particle motion component. Particle motion includes the movements of the particles in the sound wave (as acceleration, velocity and displacement). Acoustic waves can propagate within the substrate (e.g. the seabed) or at the substrate water interface, generating high levels of particle motion. Fishes and invertebrates are principally sensitive to particle motion. Marine mammals are sensitive to sound pressure, and some fishes are sensitive to both sound pressure and particle motion (Fay & Wilber, 1989; Nummela, 2009).

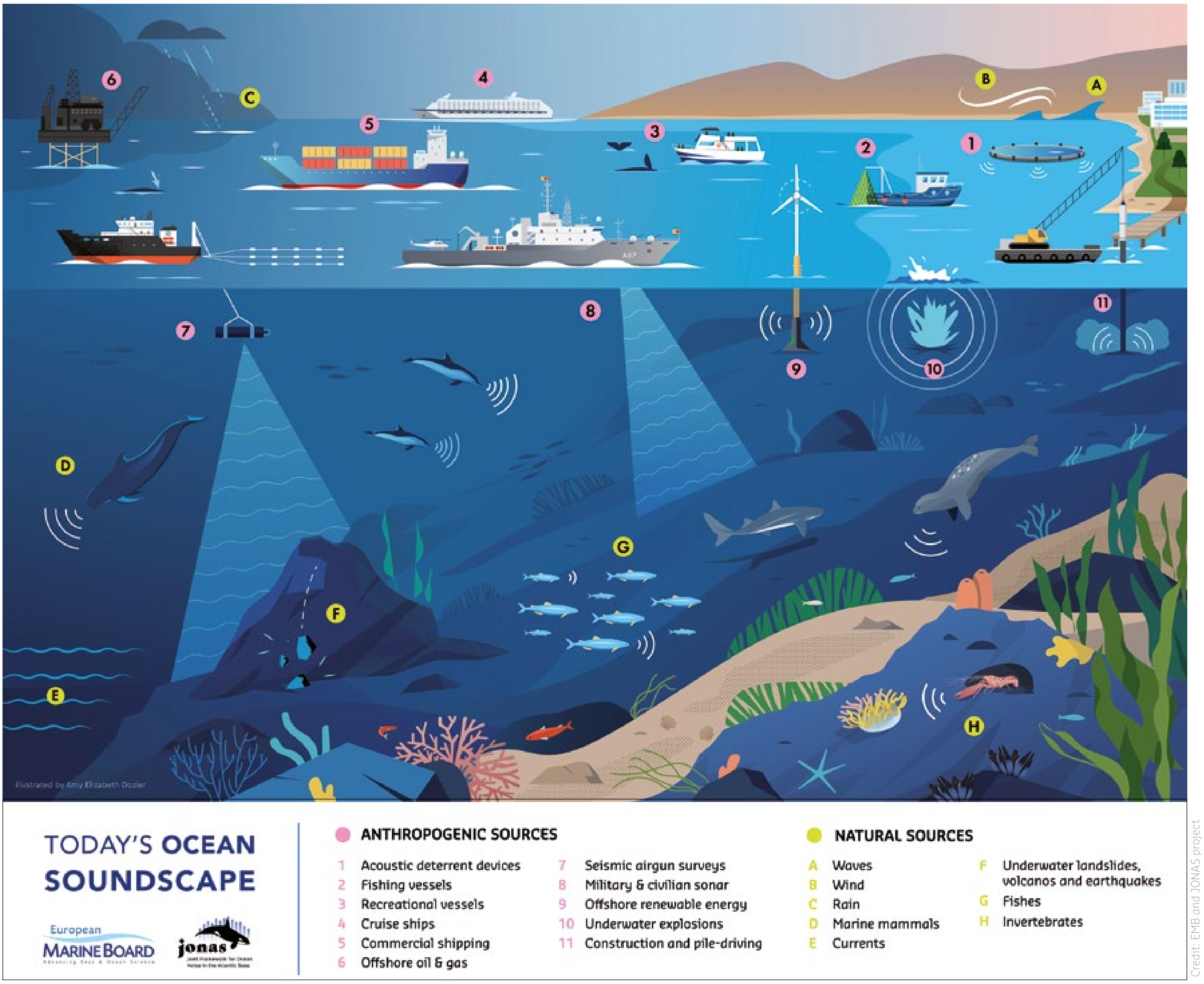


Figure 3. Today's Ocean soundscape including anthropogenic and natural sound sources, labelled anti-clockwise.

2.2 Today's Ocean soundscape

Today's Ocean soundscape comprises many different sound sources of both natural and anthropogenic origin. Natural sources include geophysical events such as wind-generated waves, wave breaking, earthquakes, rainfall, thermal agitation of the seawater and cracking ice, as well as biological phenomena such as shrimp snapping, whale song, dolphin clicks and fish vocalizations. Anthropogenic sources are also diverse and range from small recreational crafts to supertankers, and from acoustic deterrent devices to seismic surveys (see Figure 3). Most human activities in the marine environment generate sound, either intentionally for a specific purpose (e.g. seismic airgun surveys for mapping of deep geological structures, sonar for detection and localization of objects, acoustic deterrent devices), or unintentionally as a by-product of their activities (e.g. shipping, offshore construction).

A description of sound sources is a very important part of the risk assessment framework. Underwater sounds are commonly classified into 'impulsive' if they are of short duration or 'continuous' if they occur without a pause. Impulsive sounds can occur individually, irregularly or as part of a repeating pattern. In many cases impulsive sounds (e.g. seismic airgun pulses) have higher intensity than continuous sounds, such as those recorded from shipping. However, these definitions are not unambiguous and are contingent on circumstances. For example, pulses from an airgun can merge at larger distances from the source and thus become continuous. On the other hand, some continuous sources can be very powerful e.g. supertankers (Hildebrand, 2005; Southall *et al.,* 2007; Southall *et al.,* 2019). Figure 4 presents an overview of the respective frequency ranges for sound sources, which are split into natural and anthropogenic, with the latter split further into continuous and impulsive.

Boyd *et al.,* (2008) concluded that the uncertainty around characteristics of natural and anthropogenic sound sources was 'moderate', which reflected the relatively good level of understanding of the characteristics of natural and anthropogenic sound sources, which was summarized in EMB Position Paper N° 13. However, with increased research in the past decade, particularly with respect to 'new' sound sources such as offshore wind farm construction and operation, it is useful to summarize the current state of knowledge, noting in particular where progress has been made since EMB Position Paper N° 13. The consensus in the scientific literature is that

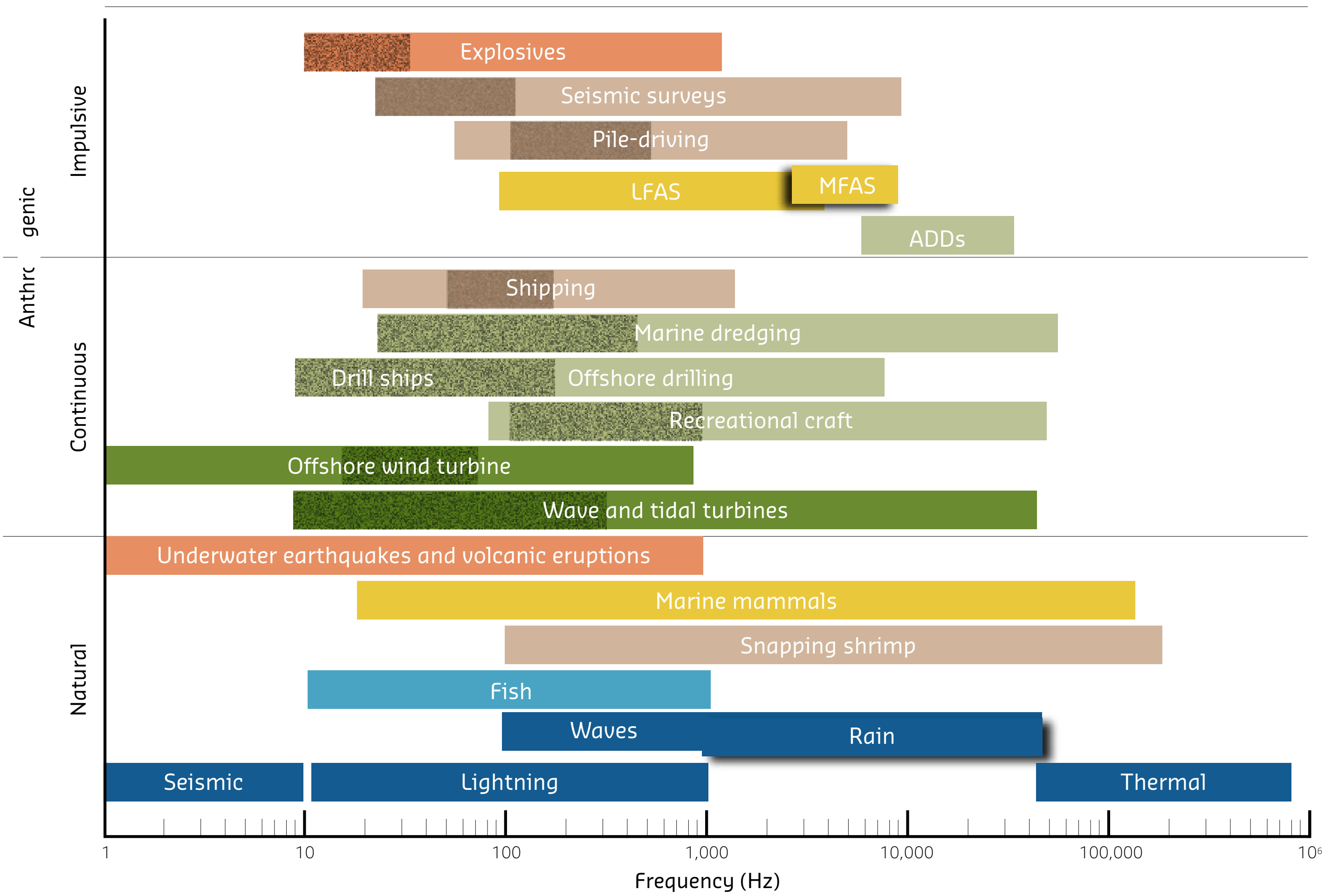


Figure 4. Comparing sound sources, where the order shows the relative sound pressure levels (dB) of the noise sources and the colour code allows comparison of the levels between categories (orange being highest dB level to dark blue being lowest). The areas with hatching indicate the frequency range with most energy. MFAS = Medium Frequency Active Sonar, LFAS = Low Frequency Active Sonar, ADD = Acoustic Deterrent Device

impulsive sound emitters of high relevance are explosions, airgun arrays and navy sonar. Pile-driving could be regionally important, for example in Northern Europe. The main and most important emitter of continuous sound is commercial shipping. These sources of anthropogenic sound are described in more detail below. For easy reading, we avoid in most cases any reference to specific units such as decibel levels and frequency. For frequency, 'low' refers to 1 Hz – 500 Hz, 'mid' means >500 Hz – 10 kHz and 'high' refers to >10 kHz – 200 kHz (and more, see Figure 4; see Tasker et al., 2010). Concerning decibel levels, 'high' and 'low' are always referred to as relative terms, i.e. in comparison to other sources. Due to the different physical properties of impulsive vs continuous sounds, these comparisons have to be viewed with caution.

Anthropogenic impulsive sounds

Explosions are caused by the use of explosives e.g. for the removal of structures from the seabed, in military operations or when clearing unexploded ordnance such as those deposited in the North Sea after World War II. Across all the impulsive sound sources, explosions produce the highest peak levels of noise. This is why there is serious risk of direct injury to marine organisms, which depends on the weight of the charge and the depth of the detonation (Hildebrand, 2005; OSPAR Commission, 2009b).

Seismic surveys are conducted to map geological structures beneath the seabed, both for the oil and gas industries and research purposes, using arrays of airguns towed from seismic vessels. An airgun is a compressed-air-filled cylinder and when the air is suddenly released, it causes a transient high-pressure peak that can create a sound with very high sound pressure levels (>230 dB re 1 µPa m). The sound is reflected by the seabed and is detected, providing information about the sub-sea properties. The main energy content is at low frequencies (see Figure 4), with some mid- and high frequency content, although the extent of the high frequency component is still uncertain (OSPAR Commission, 2009b; Genesis Oil and Gas Consultants, 2011). **Sub-bottom profilers** are also used to survey the seabed and are highly directional sound sources. Sound levels can be relatively high and there is a wide variety of profilers operating across a range of frequencies (from low to high). Given their prevalent use in some areas, more measurements are needed to fully characterize these sources and assess their potential impact.

Much research has been done since 2008 on **pile-driving**, where piles are driven into the seabed to provide foundation support for offshore structures. This activity is undertaken in the construction of offshore platforms, including those for wind farms. Pile-driving emits short pulses of intense sound with a relatively high SPL in the low frequency range but extending to higher frequencies as well. Propagated sound levels depend on a number of factors including the maximum energy rating of the hammers and the fact that the sound is not only transferred into the water column but also to some extent into the substrate (Bellmann *et al.*, 2020; Jiménez-Arranz *et al.*, 2020).

Sound emitted from **active military sonars** (Low- and Medium Frequency Active Sonar, **LFAS** and **MFAS**) depends on the operational purpose, which determines the frequency range and the source strength. Most active military sonar used for submarine detection operate in the low to medium frequency range, however possible higher frequency sound content of the sonar is often not specified and may still be significant (OSPAR Commission, 2009b). **High-frequency sonars**, used for civilian purposes such as fisheries, surveying and research, generally produce signals directed towards the seabed. This category includes **Single-beam** and **Multibeam Echosounders** and **Side Scan Sonars**.

Acoustic Deterrent Devices (ADD) or **pingers** are used to deter marine mammals away from human activities such as fishing vessels and aquaculture farms. They operate in the medium-high frequency range with source levels reaching from relatively low to high levels. Acoustically, there is significant variation in pingers. Concerning their acoustical characteristics, ADDs are not easily categorized as impulsive or continuous. They are considered impulsive if they operate with a low duty cycle, i.e. where the duration for which the sound is active is short compared to the duration for which the sound is inactive. If they operate continuously, or with a high duty cycle (i.e. the duration for which the sound is active is long compared to the duration for which the sound is inactive), they are not considered impulsive (see Dekeling *et al.,* 2014).

Anthropogenic continuous sounds

Sounds from **shipping** have been researched intensively in the last decade. The sounds from ships cover a wide range of frequencies from low to high. There is also significant variation in emitted sound levels (OSPAR Commission, 2009a; Erbe *et al.,* 2019). The exact characteristics of the sound emissions depend on variables such as vessel type, size and operational mode. In general, the larger the ship is, the more intense the sound levels and the lower the frequency. A notable exception are modern military vessels which use technology to suppress the radiated noise.

Large commercial vessels produce relatively intense and predominately low frequency sounds, with the most energy concentrated below 100 Hz (OSPAR Commission, 2009a). Large vessels dominate low-frequency background noise on a global scale and, due to the steady increase in shipping over the past decades (estimated to continue at 4% per year globally between 2018-2023), pressure on the marine environment will potentially also increase (Erbe *et al.,* 2019). Sound from **recreational craft**, while relatively less powerful than commercial vessels, can vary significantly between vessels (Erbe *et al.,* 2016) and is concentrated in coastal areas.

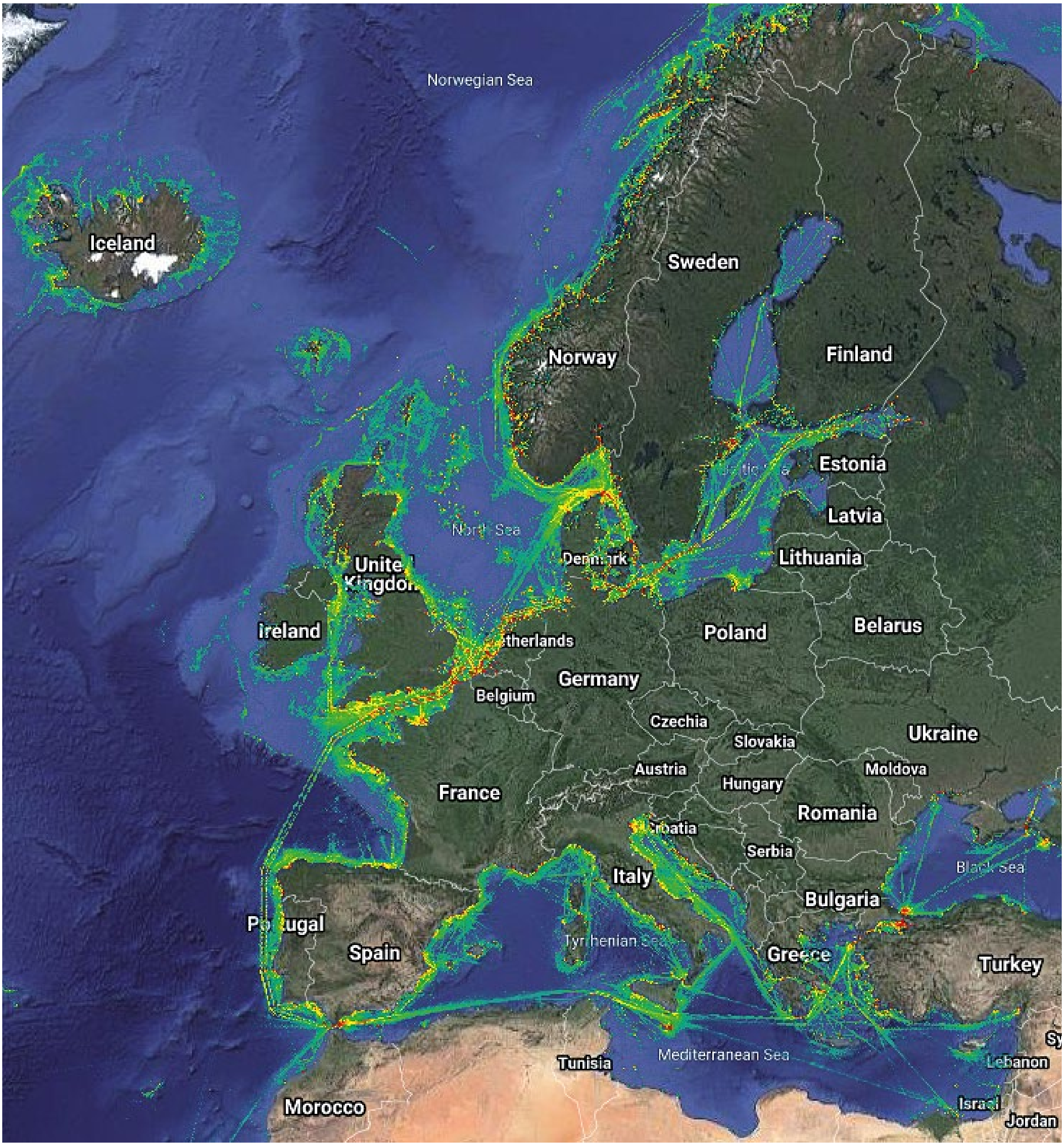
Offshore drilling and **especially marine dredging** produce sound levels in the range of small – medium sized vessels, which are below the emissions of large commercial vessels. They can contribute locally to the soundscape (CEDA, 2011; WODA, 2013; Prideaux, 2017). Due to more dedicated measurements in the past decade, the sound output of operating **offshore wind turbines** is better understood. Source levels are low compared to other continuous sound sources discussed here. However, in low ambient noise conditions, noise from individual turbines can overlap and lead to higher noise levels at least within the wind farm area and its immediate vicinity. It should thus not be overlooked in impact assessments. This is especially important when considering the development of larger and potentially more noisy turbines in the future (Tougaard *et al.,* 2020; Stöber & Thomsen, 2021). **Wave and tidal turbines** have only been investigated in the past decade and studies show moderate sound levels with maximum energy below 400 Hz (Thomsen *et al.,* 2015).

Credit: European Marine Board

Dredger off Ostend beach in Belgium.

2.3 Monitoring spatial distribution of anthropogenic noise

The acoustic environment of the Ocean is highly variable. At a given time and place, a broad range of sources may be combined into a complex soundscape. In addition, different components of anthropogenic sound attenuate at rates that depend on the frequency involved and environmental conditions (e.g. temperature, salinity, pressure, water depth, bathymetry, characteristics of the seabed). Globally, shipping is the main contributor to chronic underwater anthropogenic noise, and there are clear indications that an increase in shipping has led to an increase in ambient noise in some regions (Erbe *et al.,* 2019). Figure 5 gives an indication of the density of shipping in European waters in 2019, highlighting the major shipping lanes. As this map is based on Automatic Identification System (AIS) data, smaller vessels (those under 300 gross tons) which are not legally required to have this system are likely to be underrepresented. AIS data does not provide sufficient information about a vessel to be able to accurately predict the noise it makes, so shipping density can only give an indication of relative sound levels, and is sometimes used as a proxy for sound. Figure 5 therefore represents a large-vessel density map rather than a sound map.

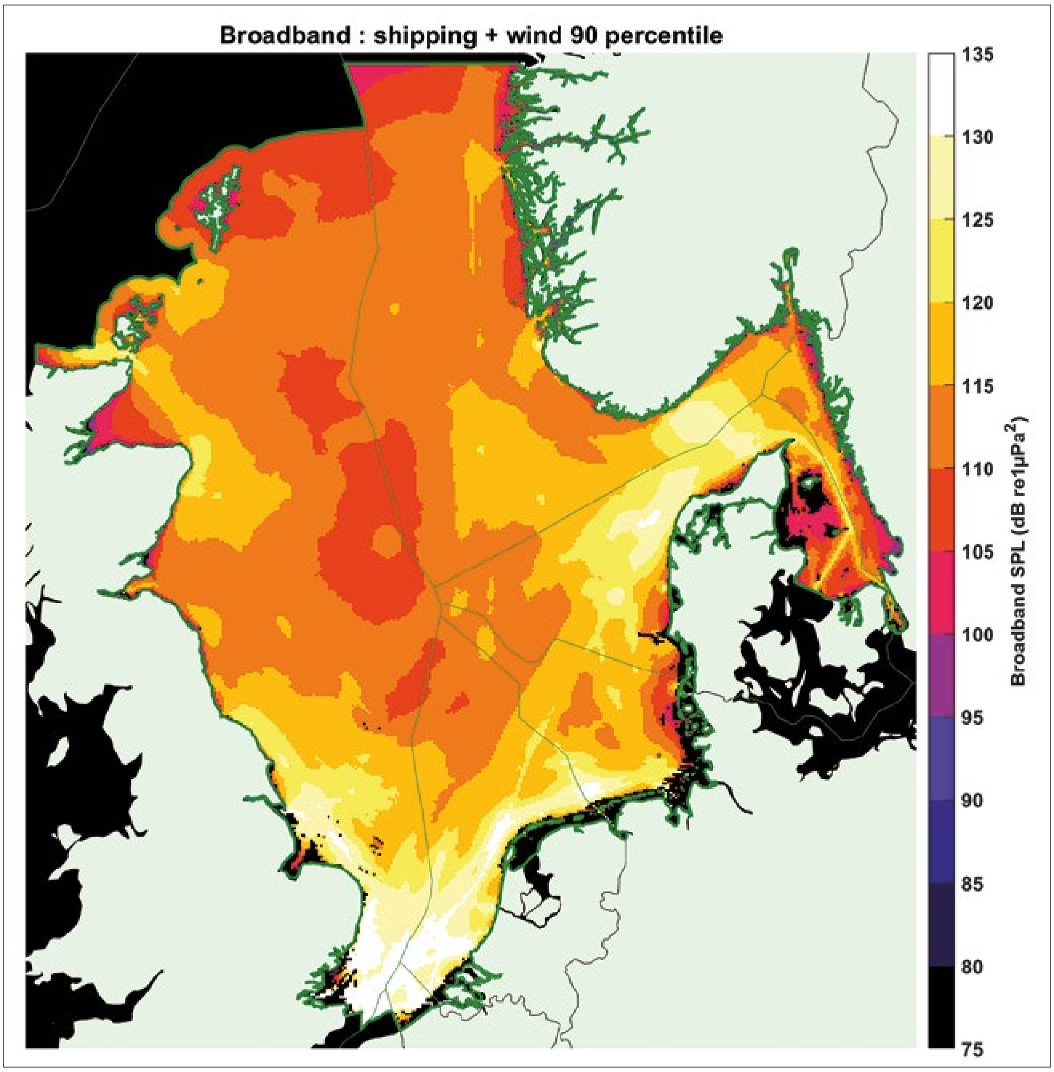


Credit: EMODnet Human Activities

Figure 5. Shipping density using AIS for all AIS-enabled ship types for 2019.

In 2008, the uncertainty around the distribution and abundance of sound sources was 'high' (Boyd *et al.,* 2008). At that time, very little research had been done on the topic, partly due to a lack of resources but also due to a lack of appropriate methods to record and map sound over large spatial scales (such as AIS, sound (propagation) modelling, and mapping). In 2009, a first assessment of the environmental impact of underwater noise in the Northeast Atlantic was provided by OSPAR, the Convention for the Protection of the Marine Environment of the North-East Atlantic[3] (OSPAR Commission, 2009a). The available data indicated that pressures due to underwater noise emissions might be relatively high in the Greater North Sea and Celtic Seas. This is attributed to the comparably high level of human activities in those areas. OSPAR also concluded that this trend might increase with the development of maritime activities in Europe such as wind farm deployment, construction of harbour infrastructures, ongoing seismic surveys, etc. Since then, the European Commission's Marine Strategy Framework Directive (MSFD; European Parliament and the Council of the European Union, 2008) has triggered a variety of projects aimed at systematically monitoring both impulsive and continuous sources of underwater noise.

Continuous noise monitoring projects have been, or are being, conducted in the Baltic Sea (BIAS project[4]; Baltic Sea Information on the Acoustic Soundscape), the wider North Sea (JOMOPANS[5]; Joint Monitoring Programme for Ambient Noise North Sea), the Atlantic (JONAS[6]; Joint Framework for Ocean Noise in the Atlantic Seas), the Mediterranean Sea (QuietMed[7] and QuietMed2[8]), and the newly started Quiet Seas[9] in the Mediterranean and Black Sea. These programs have deployed sound monitoring stations in their respective study areas to document baseline sound levels (and trends over time) and contributed to the development of standards both for the measurement and analysis of underwater ambient noise. An important step forward is the development of sound maps, as proposed in Dekeling *et al.,* (2014), making use of numerical modelling, AIS data, and the use of source models (e.g. MacGillivray & de Jong, 2021). These sound maps provide insight into spatial and temporal distribution of sound that individual measurements cannot provide, and they can be used as the basis for assessments. Sound maps can also be used for other purposes, such as predicting the effect of noise mitigation measures. Figure 6 is an example of a sound map for the North Sea showing sound levels from shipping and background sound (wind, waves etc.), based on modelling underwater sound from these sources, and supported by a year of measurements at 15 locations.



Credit: Jomopans / TNO

Figure 6. Estimated sound from shipping and wind in the North Sea, presented using a colour-blind accessible colour scale where white is the highest level and black is the lowest.

[3] https://www.ospar.org/
[4] https://biasproject.wordpress.com/
[5] https://northsearegion.eu/jomopans/
[6] https://www.jonasproject.eu/
[7] http://www.quietmed-project.eu/
[8] https://quietmed2.eu/
[9] https://quietseas.eu/

Impulsive noise monitoring has also been in place in the last few years. In the Mediterranean Sea, the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS; see Maglio *et al.,* 2016) produced an inventory of noise-producing human activities over ten years (2005-2015), including marine traffic, coastal and offshore construction, seismic surveys and military operations. This inventory was used to map areas where such activities were carried out and to identify noise hotspots. More recently, Merchant *et al.,* (2020) reported impulsive noise events between 2015 and 2017 in the North Atlantic, Irish Sea and North Sea, showing high concentrations of events over time in some areas. Seismic airguns were the dominant (impulsive) sound source in these areas over these three years. The Convention on the Protection of the Marine Environment of the Baltic Sea Area[10] (HELCOM) and OSPAR Commission have also created impulsive noise registers which can be accessed online[11].

These investigations are very valuable to improve our understanding of the spatial and temporal distribution of noise and to identify trends, which is covered in more detail in the next section.

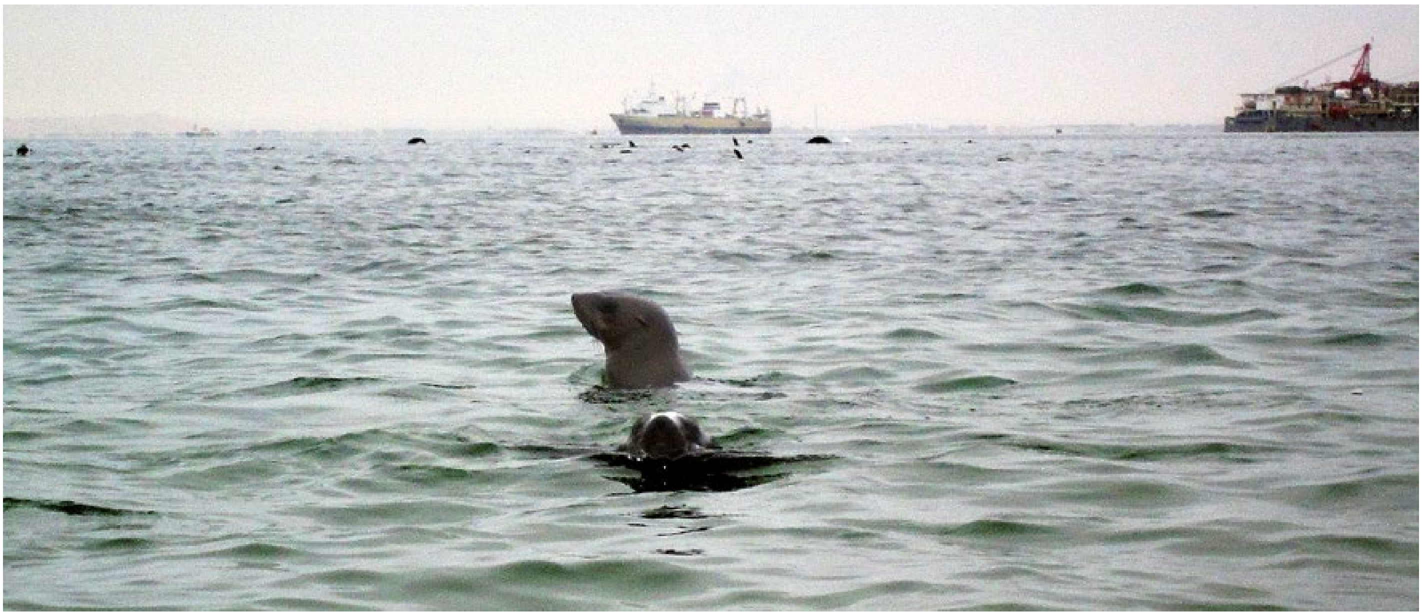
2.4 Trends in Ocean noise

Boyd *et al.,* (2008) concluded that studies looking at trends in Ocean ambient noise would be highly influential in the management of underwater noise. In the context of the MSFD, the European Commission refers to anthropogenic continuous low-frequency sound in water in one of the two indicators for 'good environmental status' (see European Commission, 2017). We know that human activities generating this type of underwater noise have been increasing over the past decades and that this could raise Ocean noise levels (Frisk, 2012; Kaplan & Solomon, 2016; Duarte *et al.,* 2021). Yet even with the strong policy incentive, our understanding of trends in the Ocean soundscape remains very limited.

Long-term data on low-frequency shipping noise is only available for the Northeast Pacific Ocean (Andrew *et al.,* 2002; McDonald *et al.,* 2006; Andrew *et al.,* 2011; Chapman & Price, 2011) and shows a gradual increase in noise levels of approximately 3 dB per decade. Recently, follow-up investigations covering the time period between 1964 - 1998 showed a 5 dB increase in noise levels at frequencies between 63 and 125 Hz related to shipping and a 10 dB increase in the 16-32 Hz band, which is dominated by baleen whale vocalisations rather than anthropogenic sources (Ainslie *et al.,* 2021). Ship traffic has been proposed as responsible for the steady rise in ambient noise at low frequencies (10–100 Hz) in some Ocean regions (Erbe *et al.,* 2019). However, deciphering trends is extremely challenging due to our lack of baseline information and the need to monitor over extremely long periods in order to document change (Merchant *et al.,* 2016). It is important to emphasize that the understanding of temporal trends of underwater noise in Europe and beyond requires internationally agreed monitoring standards.

Looking at tomorrow's Ocean soundscape, we can anticipate that some noise-generating activities will increase e.g. offshore construction, decommissioning of oil and gas infrastructure, and shipping. In addition, new noise-generating activities will or may emerge, e.g. deep-sea mining, widespread use of autonomous vehicles, and new acoustic communication systems (e.g. underwater Wi-Fi) (see Duarte *et al.,* 2021). These need to be assessed and managed in the context of the risk assessment framework outlined in Figure 1. The 2nd World Ocean Assessment report (Chapter 20, United Nations, 2021) discusses future trends in anthropogenic noise in the marine environment. It concluded that increases in noise are expected in areas such as the Arctic, due to the area opening up to shipping, and the Ocean around Africa, as investment expands in the region. Finally, global warming will change the chemical composition of the Ocean, which might impact sound transmission. Although impacts are suspected to be low, this issue may need further research (Reeder & Chiu, 2010)..

The 2020 outbreak of the COVID-19 pandemic and the subsequent worldwide lockdowns created a unique scenario for underwater noise research. Whilst studies have found that there was a reduction in some categories of vessel traffic (March *et al.,* 2021), the impacts on underwater soundscapes were less clear (e.g. Leon-Lopez *et al.,* 2021; Sertlek, 2021).



Credit: Sheila Heymans

Sea lions and vessels off the coast of Namibia.

[10] https://helcom.fi/

[11] hhttps://www.ices.dk/data/data-portals/Pages/underwater-noise.aspx

3 Advances in knowledge of the effects of noise on marine animals

- Despite significant research effort in the past decade, there remain considerable gaps in knowledge about hearing abilities and sound usage, especially for fishes and invertebrate species;
- Given the many factors at play, and the high variability in marine species and scenarios, it is challenging to assess the effects of noise, particularly the consequences of behavioural and physiological responses;
- Most studies have focused on individuals, and population-level consequences are challenging to observe and assess;
- Most studies have focused on single sound source impacts, so cumulative and combined impacts are not clearly understood;
- High-priority effects from underwater noise needing further study are displacement due to behavioural response, masking and stress;
- Focus should be on population consequences and cumulative effects, and efforts to fill some of the gaps in modelling frameworks.

As sound transmission from water to air is weak, humans are typically unaware of the acoustic energy that we introduce into the marine environment, and we are not directly affected by it. It is the marine organisms sensitive to underwater sound that are most affected, in ways that we are only now beginning to understand. Light cannot travel far in water, so sound is very important to marine organisms. They inhabit a primarily acoustic environment that provides them with information about their surroundings: including biotic, abiotic, and anthropogenic activities. Since sound transmission is so effective underwater, this information transfer can be far-ranging. Consequently, sound is used for a wide range of purposes. This includes communication with conspecifics, which occurs in a variety of contexts such as mating and group coordination. These behaviours are well described both for marine mammals and fishes. However, sound is also used for foraging and navigation, e.g. when marine mammals use echolocation for prey detection and hunting. Marine animals also eavesdrop on the communication and echolocation signals emitted by individuals of the same or other species. Evidence suggests that animals also perform an analysis of the 'acoustic scene' (or 'soundscape') when using the surrounding sound field for orientation and navigation, or predator detection (Popper & Hawkins, 2019). There is increasing knowledge about sound usage in marine mammals, less so in fishes and very little in invertebrates (see Tyack & Clark, 2000; Popper *et al.,* 2001; Dudzinski *et al.,* 2002; Ladich, 2015; Weilgart, 2018; Hawkins & Picciulin, 2019).

In this chapter, we first review progress in knowledge on hearing in marine animals since 2008. We then describe the advances in knowledge about noise effects[12] and impacts[13] and then outline the key known noise impacts. In order to provide a wider overview and to aid in the identification of trends, the chapter has been organised in topics (e.g. 'hearing' and 'effects' such as masking and behavioural response) rather than taxonomically.

3.1 Hearing in marine animals

Boyd *et al.,* (2008) focussed on marine mammals (cetaceans (e.g. whales and dolphins), pinnipeds (e.g. seals and sea lions) and sirenians (e.g. manatees)) due to the importance of sound to them for various purposes. However, in the past decade, the equal importance of sound for fishes and invertebrates has been increasingly recognized (Popper *et al.,* 2020).

The sensory systems that receive and perceive sounds are very diverse in marine organisms, resulting in a wide variety of sensitivities and hearing ranges (concerning the bandwidth of frequencies over which sounds can be perceived). Sound pressure changes and particle motion (or displacement) both occur when sound is produced and transmitted, but hearing systems evolved to detect one or the other. Due to the anatomy and physiology of their hearing systems, marine mammals are sensitive to sound pressure, whereas fishes and invertebrates are primarily sensitive to particle motion. The acknowledgement of the importance of particle motion has been consolidated among the scientific community since 2008 (see Popper & Hawkins., 2019). However, some fish species, such as herring and cod are also sensitive to sound pressure. Finally, the assumption that the frequency range of animal vocalisations is strictly related to the frequency bandwidth of their hearing might not be fully applicable. For example, some fishes listen to the sound field and use it as a cue for orientation and navigation even if the frequencies are different from those produced by the animals themselves, and it has been suggested that this is also true for other vertebrates (Fay, 2009).

[12] Effects are changes caused by sound exposure that are a departure from a prior state, condition, or situation, which is called the 'baseline' condition (Popper *et al.,* 2020)

[13] Impacts are biologically significant effects (see definition above) that reflect a change whose direction, magnitude, and/or duration is sufficient to have consequences for the fitness of individual fish or populations of fishes (Popper *et al.,* 2020)

Bottlenose dolphins off the Spanish coast.

In general, marine mammals hear in a relatively wide bandwidth, much beyond what humans can hear, which is between 20 Hz and 20 kHz. Whales can likely hear infrasound (below 20 Hz) and dolphins and other toothed whales can hear ultrasound up to around 200 kHz. In 2008, the degree of uncertainty on marine mammal hearing was 'moderate' (Boyd *et al.,* 2008), presumably because several studies had been undertaken with captive animals. Hearing tests had been conducted on toothed whales (e.g. porpoises, dolphins) and as well as sea lions and seals, but not on baleen whales such as blue, fin or humpback whales, due to their size and the associated challenge of keeping them in captivity or experimental settings. Recently, anatomical studies using CT scans have been used to predict hearing sensitivities in baleen whales (Cranford & Krysl, 2015). Numerous hearing studies have been carried out since 2008 on toothed whales and pinnipeds, including new species and by increased sample sizes in species already studied (Erbe *et al.,* 2016; Southall *et al.,* 2019). One important finding was that some toothed whales have the ability to adjust their hearing sensitivity depending on incoming sounds; a phenomenon known as 'auditory gain control' (Nachtigall & Supin, 2014; Southall *et al.,* 2019).

Hearing in fishes has continued to be studied during the past ten years, however substantial gaps remain. This is partly because much of the data focuses on sound pressure and not particle motion, which as we have pointed out already is more important for most fishes. Another source of uncertainty is that most audiogram[14] studies use electrophysiological approaches to measure the response of the ear to lower levels of the central auditory system, whilst behavioural studies are thought to be the more valid measures of hearing sensitivity in fishes. Thus, our understanding of fish hearing is still limited (Popper *et al.,* 2014; Popper & Hawkins, 2021). One field of progress was that anatomical 'hearing types' were better specified in the past 10 years. Accordingly, fish hearing types can be arranged on a graded scale depending on anatomical adaptations. Fish species such as flatfish or elasmobranchs (e.g. sharks and rays) that lack a swim bladder are only sensitive to particle motion over a small bandwidth of a few hundred Hz. Species with a swim bladder, such as cod, that are sensitive to sound pressure in addition to particle motion, still exhibit a rather limited bandwidth of hearing. Finally, some fishes have special anatomical adaptations connecting the swim bladder with the inner ear. Herring, for example, can hear sound pressure over a wide bandwidth and are relatively sensitive to sound. Compared to marine mammals, fishes hear over a much smaller bandwidth and are more or less restricted to hearing sounds with frequencies of up to a few kHz at most (i.e. in the lower frequencies; see Popper & Fay, 2011; Popper *et al.,* 2014).

Recent research on crustaceans and cephalopods shows that they can sense particle motion (and perhaps also pressure) via sensory hairs (inside small sack-like structures called statocysts) on their body and in body cavities. Their hearing is limited to relatively low frequencies (i.e. up to a few kHz; see Popper *et al.,* 2001; Solé *et al.,* 2013; Hughes *et al.,* 2014; Radford *et al.,* 2016). Jellyfish are also able to detect low-frequency sound (Solé *et al.,* 2016).

[14] *An audiogram is a graph which shows the results of a hearing test.*

Little cuttlefish caught during scientific campaign of FishConnect on *RV Simon Stevin*.

To summarise, despite much progress in the past decade, our knowledge of patterns in hearing across taxa is still incomplete as hearing has been investigated for only a few fish and invertebrate species. Knowledge has improved for marine mammals but there are gaps too, especially concerning the hearing abilities of baleen whales.

3.2 Effects of noise

As we have mentioned in the introduction, the 'zones of noise influence' (masking, behavioural response, impaired hearing, and physical and physiological effects) in Figure 2 provide a conceptual framework for the possible effects of underwater noise on marine organisms. While this simplified 2D framework has proven useful for a systematic approach when assessing the effects of noise and describing its spatial reach, it also has considerable limitations because the reality is a lot more complex. For example, sound propagates from the source in all directions, both horizontally and vertically through 3D space. Also, factors such as depth or bottom type etc. affect sound transmission and will influence the extent and magnitude of effects. In addition, physiological effects and hearing damage are related to the dose of exposure, which is defined by both the received sound pressure level and the duration of exposure (Southall *et al.,* 2019). Exposure over a long period can lead to physical and physiological effects even if sound levels are low and would not trigger a behavioural reaction. This may lead to a larger zone of influence for hearing impairment than behavioural effects. Physiological effects can also arise from behavioural responses to noise, such as in the case of beaked whale strandings, where rapid surfacing may have led to various decompression sickness manifestations (see review in Bernaldo de Quirós *et al.,* 2019). Thus, the zone of behavioural response can become the zone of physiological and physical effects, and even death. Finally, there is no clear-cut answer as to whether masking or behavioural response zones are larger. However, despite these limitations, the 'zones of noise influence' is a practical model when defining and broadly categorizing noise impacts.

According to Boyd *et al.,* (2008) the degree of uncertainty on noise impacts on marine mammal individuals was 'high' for all effects except hearing impairment (TTS, PTS). Subsequent research has improved our knowledge on mammals and fish especially on TTS (Popper *et al.,* 2014; Finneran *et al.,* 2015; Southall *et al.,* 2019), although many open questions remain.

Masking

Broadly speaking, **masking** can affect communication, navigation and predator detection in marine animals. Masking potentially has an important impact on marine taxa because, (i) it can be long-lasting (chronic), and (ii) it affects the 'acoustic habitat' of an animal which can impair both the active and passive usage of sound over considerable ranges (Clark *et al.,* 2009; Slabbekoorn *et al.,* 2010). Focussing on marine mammals, Erbe *et al.,* (2016) review a variety of studies from the past decade which have improved our understanding of masking. These relate to the sources of underwater noise (see Chapter 2) and the role of the acoustic environment in


Credit: Pieter Jan Verhelst

Implanting an acoustic tag in a European silver eel.

masking, as well as hearing characteristics and strategies to reduce masking effects. The models to understand the range and exact physical impact of masking have also improved (see Erbe *et al.*, 2016). Compared to mammals, there is less information on masking in fishes (Popper & Hawkins, 2019). One problem with understanding masking with respect to communication is that, in most cases, we do not know over which ranges marine mammals or fishes effectively communicate with each other. We can thus only speculate about the severity of the loss of communication space due to noise.

One increasingly documented behavioural effect of masking, shown in both marine mammals and fishes, is the 'Lombard effect', when animals raise the amplitude and/or pitch of signals as a response to masking noise (see reviews by Erbe *et al.*, 2016; Hawkins *et al.*, 2016). The concern here is mainly in relation to the energetic costs of compensating for the noise.

Studies have shown that noise affects the soundscape surrounding an individual which can impair navigation, e.g. in fish and coral larvae (Simpson *et al.*, 2005; Lecchini *et al.*, 2018). Furthermore, increased background noise may prevent marine animals from detecting sounds produced by predators and prey, impacting their escape response and foraging behaviour (Ferrari *et al.*, 2018).

Behavioural response

Behavioural response to noise has been widely studied mostly in marine mammals and less in fishes and even, to a lesser extent in invertebrates. Since EMB Position Paper N° 13, huge progress has been made in designing and conducting Controlled Exposure Experiments (CEE) in very large field efforts, which are required to collect these data. Such studies were really only beginning in 2008. In particular, there have been advances in passive acoustic monitoring (PAM) and especially automatically detecting and recording the behaviour of marine mammals and fishes underwater, and also in measuring the received sound levels on the animal (see Chapter 4 - new technologies).

Acoustic tagging has allowed the expansion from studies mostly carried out in a lab setting to those carried out in the field (e.g. Thomsen *et al.*, 2012; Miller *et al.*, 2014; Southall *et al.*, 2014; Sivle *et al.*, 2015; Russell *et al.*, 2016; Harris *et al.*, 2018). In both marine mammals and fish, documented behavioural responses include startle reactions, the aforementioned Lombard effect, and short- and long-term avoidance of ensonified areas (i.e. areas where the sound is present). These effect ranges can have various sizes, ranging from small zones to many hundreds of square kilometres in some cases concerning mammals. In addition, marine mammals have been observed to change surfacing patterns and diving behaviour. Fishes reacted with 'herding' (school tightening). There is little information on response to noise in marine invertebrates, but a recent meta-analysis concluded that at least shipping noise can affect their behaviour (Murchy *et al.*, 2020). It is worth pointing out that some studies also found no observable reactions of marine animals to anthropogenic noise at all (see reviews by Slabbekoorn *et al.*, 2010; Hawkins *et al.*, 2016; Erbe *et al.*, 2018).

There are some general messages emerging from the multiple investigations on behavioural response undertaken since 2008:

- The likelihood and intensity of the response depends on the physical properties of the received sound. Sound pressure level, frequency and duration (i.e. acoustic dose) are important factors that influence responses, but there are other properties that may be influential too (Southall *et al.,* 2007; Hawkins *et al.,* 2015);
- Reactions to the same sound input can be extremely variable within and across species, as well as within and between individuals, and seem to depend on additional contextual variables such as behavioural and physiological state, food availability, prior exposure, age, sex, season, time of day and many more (Ellison *et al.,* 2011; Hawkins *et al.,* 2015; Harris *et al.,*2018);
- Both fishes and marine mammals react to certain impulsive and continuous sound sources such as pile-driving, airguns, sonar and acoustic deterrent devices at relatively long distances of several kilometres (Morton & Symonds, 2002; Brandt *et al.,* 2011; Thomsen *et al.,* 2012; Hawkins *et al.,* 2014; Miller *et al.,* 2014; Dunlop *et al.,* 2018). Most of these effects are of short duration, but there have been cases where displacement was long-term (e.g. Morton & Symonds 2002). Studying such long-term changes in distribution due to noise is challenging due to the lack of adequate long-term species and noise monitoring programmes (Thomsen *et al.,* 2011) but also due to potentially confounding factors such as habitat changes as a function of other human activities.

The US National Research Council (NRC) developed a framework for investigating the Population Consequences of Acoustic Disturbance (PCAD; NRC, 2005), later defined as PCoD, i.e. Population Consequences of Disturbance (Pirotta *et al.,* 2018). Originally the work on PCAD focused on marine mammals, but recently PCAD / PCoD studies have also included fishes. The PCAD / PCoD model involves several steps describing how behavioural effects could cause further effects on life functions (e.g. feeding) which in turn can affect vital rates (e.g. survival and reproduction). Ultimately, this cascade can lead to effects at the population-level. One of the challenges with PCoD is that the understanding of how disturbance can affect life functions and vital rates is extremely limited and more empirical data are needed (Pirotta *et al.,* 2018). In Europe, a limited number of studies have been able to apply the PCoD framework. These include for example, investigations on the effects of offshore wind farm construction in the North Sea on harbour porpoises (King *et al.,* 2015) and population consequences of acoustic exposure in cod (Mortensen *et al.,* 2021).

Hearing impairment

In the past decade there have been advances in our understanding of **hearing impairment** in marine mammals (e.g. sea lions and bottlenose dolphins; for a review, see Finneran, 2015) and to a lesser extent in fishes (see Popper *et al.,* 2014). For both marine mammals and fishes, the nature and intensity of the effects depend on the sensitivity of the animal in question and the received dose of noise. In principle, multiple pulses (e.g. from pile-driving) have a larger effect than a single pulse as they increase the dose (Finneran *et al.,* 2015; Popper *et al.,* 2014, 2019). The recovery time from Temporary Threshold Shift (TTS) is a function of its severity. The larger the TTS, the longer it takes for the hearing to recover (Finneran, 2015; Breitzler *et al.,* 2020). There is uncertainty about recovery from TTS for multiple pulses. This is yet to be considered in standard impact assessments. As pointed out before, there is now evidence that some marine mammals may also have evolved mechanisms of self-mitigation when exposed to potentially injurious noise. These include behavioural reactions that indicate anticipation and avoidance (Finneran, 2015) and reduction in hearing sensitivity when a loud sound was preceded by a faint warning sound (Nachtigall *et al.,* 2014). The many unknowns in the field of impaired hearing in mammals arise partly because Permanent Threshold Shift (PTS) is always extrapolated and never intentionally tested for reasons of animal welfare. In the case of fishes, there is no evidence for PTS. Indeed PTS might not occur since hearing cells can regrow (Popper *et al.,* 2019).

Physical and physiological effects

Physical and physiological effects have also become better understood in the last 13 years. In Boyd *et al.,* (2008), studies on strandings of cetaceans due to military mid-frequency sonar were a high priority, reflecting the significant discussions within the scientific community at that time. Since 2008, much effort has been made to further understand the physiological causes and especially the behavioural mechanisms behind the stranding events, and our understanding is much improved. The most widely accepted explanation for the cause of strandings is that the received sonar pulses trigger an extreme behavioural reaction resulting in rapid dives and surfacing which lead to decompression sickness effects, similar to what happens to humans when getting ‘the bends’, which in case of the affected whales can lead to fatal stranding (see Bernaldo de Quirós *et al.,* 2019). Several controlled exposure experiments have shown that responses vary greatly between individuals and with behavioural state (Southall *et al.,* 2016). Strandings of marine mammals have also been reported concurrent with other activities, such as hydrographic surveys using multibeam echosounders (Southall *et al.,* 2014).

Concerning fishes, studies show that Barotrauma (= the physical damage to tissue caused by noise) and even mortality was found in response to high intensity impulsive sounds such as from pile-driving and explosions. As in the case of hearing impairment, the magnitude of injury was dependent on the received dose (Popper *et al.,* 2014, 2019).

For invertebrates, very few studies have been undertaken. Injury of tissue due to exposure to noise was found in molluscs in experiments in tanks (André *et al.,* 2011) and subsequently also in the wild (Solé *et al.,* 2017). There is also evidence that noise from airguns causes mortality in zooplankton (McCauley *et al.,* 2017). Wale *et al.,* (2019) found evidence of shipping noise induced changes at multiple levels

Zostera marina seagrass meadow in the Dzharylhach Bay in the Black Sea.

of biological organization on a reef-building mussel, for example at the level of the DNA. Finally, in a first in the field of aquatic plant pathology, a recent laboratory investigation documented that seagrass morphology and ultrastructure can be affected by noise, with potential implications for the ecology of seagrass meadows (Solé *et al.,* 2021).

Human studies have clearly shown the health consequences of chronic exposure to noise, principally stress-related (World Health Organization, 2011). Despite its potential importance, only very few studies have been undertaken on stress in marine organisms, due to exposure to underwater noise. Those that have been conducted have indicated a stress response (e.g. increased heart rate, changes in levels of stress-related hormones) to exposure of both impulsive and continuous noise both in marine mammals and fishes (see Miksis *et al.,* 2001; Wysocki *et al.,* 2006; Rolland *et al.,* 2012; Debusschere *et al.,* 2016; Yang *et al.,* 2021). Although most investigations on this topic have been performed in captivity, one field study on North Atlantic right whales found some evidence for a reduction in stress when ambient noise levels were reduced, due to a decrease in shipping activity after the events of 11 September 2001 (Rolland *et al.,* 2012).

4 Addressing the issue of underwater noise

- The last decade has seen the issue of underwater noise acknowledged in a series of international agreements. In Europe, the most significant driver in tackling this pressure is the Marine Strategy Framework Directive adopted in 2008;
- International standards for measuring and reporting underwater noise have been published, facilitating international collaboration on the issue;
- In the last decade there has been some progress towards the reduction of noise from shipping. Regional monitoring programmes in European waters started in the last decade will inform policy and regulation in years to come;
- As the plans for a Blue Economy have intensified in the past decade, so has the development of best practices for marine environmental impact assessment of noise-inducing activities;
- Regulation, management and mitigation measures have gradually been tailored to noise sources, such as pile-driving and military sonar, and to the species affected, but further research is needed to develop more cost-effective measures;
- New technologies such as drones, modelling approaches and more multi-disciplinary studies appear promising in terms of increasing our understanding of underwater noise and our ability to manage it.

Boyd *et al.,* (2008) did not go into detail on the risk management aspects of underwater noise. This was partly because up until that time there was very little international or regional regulation on the issue. In addition, although noise mitigation measures had been well-established for example in seismic surveys, only during the last decade did noise management really start to be more widely developed and applied for other noise producing activities. In this chapter, we discuss regulations and other policy drivers, environmental impact assessments and mitigation strategies. We also outline emerging technologies applicable for each step of the risk framework (Figure 1).

4.1 Regulations and other drivers

4.1.1 International

In 1982, the United Nations Convention on the Law of the Sea (UNCLOS) (United Nations, 1982) provided a definition of marine pollution and urged countries to act in a transboundary approach, taking measures to control it. However, it was not until three decades later that underwater noise was acknowledged as a pollutant and started to appear explicitly in international environmental conservation agreements, conventions and fora. In the last decade in particular, a series of resolutions have been agreed on the issue of anthropogenic underwater noise, recognising it as a threat to marine organisms that need to be understood and managed. This is the case for both the Convention for Biological Diversity[15] (CBD) and the Convention on the Conservation of Migratory Species of Wild Animals[16] (CMS). For example, in 2008, the CMS adopted a resolution on the adverse impacts of anthropogenic underwater noise on cetaceans and other biota, calling on Parties to undertake environmental assessments when introducing systems which may lead to noise-associated risks for marine mammals. In 2017, it reaffirmed the need for further internationally coordinated research on the impact of underwater noise on cetaceans and other migratory species. This resolution also proposed that environmental impact assessments take full account of the effects of all activities on cetaceans, and that the issue of underwater noise be integrated into the management plans of marine protected areas. At the CBD 12th Conference of Parties in 2014, Decision XII/23 included a section on the impacts of anthropogenic underwater noise on marine and coastal biodiversity, asking Parties to, among other measures, carry out further research on the remaining significant knowledge gaps and to combine acoustic and habitat mapping of sound-sensitive species in order to identify areas where those species may be exposed to noise impacts.

The 2017 United Nations (UN) declaration 'Our ocean, our future: call for action' included a specific reference to addressing underwater noise. This was followed in 2018 by the UN Informal Consultative Process on Oceans and the Law of the Sea, which focussed on the issue, with contributions from both governmental and non-governmental stakeholders, resulting in a Secretary-General report on 'Oceans and Law of the Sea' (UN, 2018a). In 2019, UN General Assembly resolution 74/19 also explicitly included underwater noise and encouraged the International Maritime Organization[17] (IMO) to take action on shipping noise, in particular by looking at energy efficiency and noise reduction measures in tandem (see below).

In 2018, the International Whaling Commission[18] (IWC) made a resolution to continue its work on exposure, impact assessment and management of underwater noise. Furthermore, it aimed to

[15] https://www.cbd.int/
[16] https://www.cms.int/
[17] https://www.imo.org/
[18] https://iwc.int/private/downloads/0ymu0VhMNO_3YlwSi-QTcw/RESOLUTION_2018_NOISE.pdf

Ship passing Terneuzen, the Netherlands.

review progress on mitigation and management measures, and to develop advice on priority actions to address noise impacts on cetaceans.

To translate all these non-binding recommendations and ambitions into concrete actions, international cooperation is paramount. Calls have also been made to incorporate technological noise mitigation and policy solutions into legally binding national and international commitments (Nowacek *et al.,* 2015; Merchant, 2019; Lewandowski & Staaterman, 2020; Duarte *et al.,* 2021), such as in the forthcoming treaty under the United Nations Convention on the Law of Sea on the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction (Duarte *et al.,* 2021).

In the last decade there has been some progress in international efforts to reduce noise from shipping (see Cruz *et al.,* 2021). In 2008, the International Maritime Organization (IMO) set up a group to develop non-mandatory technical guidelines on ship noise control strategies, resulting in the 'IMO Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life' (IMO, 2014). This guidance focussed on both technological and operational aspects. In 2019, the International Council for the Exploration of the Sea (ICES)[19] formed a working group to look at impacts in the marine environment from shipping, including impacts from noise. More recently, in 2021, a proposal from the Canadian delegation to IMO was approved, which recommended a review of the IMO Guidelines to identify barriers for their implementation, to promote the development of technological innovations, leveraging synergies with ship energy efficiency, requirements for decarbonization and greenhouse gas reduction, and to develop action plans.

Over the last 10 years, ship classification societies such as Det Norske Veritas[20], Bureau Veritas[21], RINA[22], American Bureau of Shipping[23] and Lloyd's Register[24] have developed specific class rules for underwater radiated noise from vessels, to encourage noise reduction. In 2017, the Port of Vancouver in Canada included underwater noise in their program to foster green shipping (Port of Vancouver, 2020). Ships that comply with certain class rules, including those for noise limits, are eligible for a port fee discount. Similarly, in 2013, the Port of Auckland introduced the Hauraki Gulf Transit Protocol[25], which includes a voluntary 10 knot speed limit. This was originally intended to reduce ship strikes on whales; however, it has also helped to reduce underwater noise levels in this ecologically important area (Putland *et al.,* 2018). More work is now needed to include different ship service profiles and operational conditions into the class rules, and encourage harbour authorities in Europe to follow these international examples.

Through enhanced international cooperation, the last decade also saw the publication of international standards for measuring and recording underwater sound. In 2016, the first internationally accepted standard from the International Standards Organization (ISO) for measurements of underwater sound from ships in deep water was published (ISO 17208-1:2016). One year later, ISO 18405:2017 defined terms and expressions used in the field of underwater acoustics, including natural, biological and anthropogenic sound and particle motion parameters, setting the foundation for future standards and facilitating communication among stakeholders. Norms were also published on the standardization of noise measurements from percussive pile-driving (ISO 18406:2017), and on noise mitigation systems for pile-driving activities (DIN-SPEC 45653:2017). A new ISO standard focusing on the quantities and procedures for description

[19] https://www.ices.dk/community/groups/Pages/WGSHIP.aspx
[20] https://www.dnv.com/services/class-notations-noise-and-vibration-4712
[21] https://marine-offshore.bureauveritas.com/nr614-underwater-radiated-noise-urn
[22] Formerly Registro Italiano Navale, https://www.rina.org/en/media/news/2019/05/16/rina-dolphin
[23] https://ww2.eagle.org/en/Products-and-Services/environmental-performance/ship-radiated-noise1.html
[24] https://www.lr.org/en/latest-news/new-underwater-noise-notation/
[25] https://www.poal.co.nz/sustain/Documents/150112-Transit%20Protocol.pdf

and measurement of underwater sound from ships was adopted in 2019 (ISO 17208-2:2019). TNO[26] (Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek) in the Netherlands, and BSH[27] (Bundesamt für Seeschifffahrt und Hydrographie) in Germany have also published standards for measuring noise in connection with offshore wind farm licensing (BSH, 2011; TNO, 2011). More recently, the ongoing multidisciplinary H2020 project on shipping noise – SATURN[28] – aims to, among other objectives, work with stakeholders to develop and validate standardized methods to cost-effectively measure underwater noise and facilitate the assessment of potential impacts from shipping by harmonized terminology, metrics, and methodology for measurements and modelling, including particle motion.

In 2018, 'Ocean Sound' was identified as an 'Essential Ocean Variable' by the Global Ocean Observing System[29] (GOOS); a programme executed by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), which aims to adopt common standards for data collection and dissemination to better understand the status and trends of the marine ecosystem. An inventory[30] of existing standards and guidelines relevant to marine bioacoustics has been published by the International Quiet Ocean Experiment[31] (IQOE) and their next step is to recommend which should be followed. Whilst much progress has been made in creating international standards, there are still gaps, mainly those relating to marine bioacoustics (see Chapter 5).

In 2020, both the European Commission (in the context of the Horizon Europe Mission 'Restore our Ocean and Waters by 2030'[32]) and JPI Oceans[33] explicitly included underwater noise within their planned future work programmes, and it was also highlighted as a topic of importance in the UN Ocean Decade Implementation Plan[34], indicating ongoing international support and appreciation of the importance of this topic.

Offshore wind turbine installation vessel in Ostend, Belgium.

26 https://www.tno.nl/en/
27 https://www.bsh.de/EN/Home/home_node.html
28 https://www.saturnh2020.eu/
29 https://www.goosocean.org/index.php?option=com_content&view=article&id=7&Itemid=101
30 https://scor-int.org/wp-content/uploads/2021/06/IQOE-Inventory-of-existing-standards-in-bioacoustics-20210625.pdf
31 https://www.iqoe.org/
32 https://ec.europa.eu/info/publications/mission-starfish-2030-restore-our-ocean-and-waters_en.
33 http://www.jpi-oceans.eu/underwater-noise-marine-environment
34 https://www.oceandecade.org/resource/108/Version-20-of-the-Ocean-Decade-Implementation-Plan-

Finally, industry has addressed the issue by forming working groups (CEDA, 2011; WODA, 2013) and providing funds for research on all aspects of the risk framework (see Figure 1). An example is the Joint Industry Programme for Sound and Marine Life[35]. This programme, which has been running for over a decade and has funded research on noise effects from the oil and gas industry. Another example is the UK Offshore Renewables Joint Industry Programme[36] which funds environmental research with the aim of reducing the risks linked to gaining consent for offshore wind and marine energy projects, and it has funded other noise related projects.

4.1.2 Regional

The adoption of the Directive on conservation of natural habitats and of wild fauna and flora (Habitats Directive) in 1992 (European Commission, 1992), the Environmental Impact Assessment (EIA) Directive (European Commission, 1985, updated in 2011) and the Strategic Environmental Impact Assessment Directive (European Parliament and the Council of the European Union, 2001), all aim at the protection of species and habitats from disturbance. Whilst they do not mention noise specifically, they include provisions for avoiding harm and disturbance, which includes noise. They provide the environmental impact assessment frameworks in which potential impacts from projects need to be assessed. However, it was not until 2008 with the adoption of the Marine Strategy Framework Directive (MSFD) that underwater noise appeared explicitly in European legislation. The MSFD requires EU Member States to achieve or maintain 'good environmental status' (GES) of their marine waters. It identifies 11 descriptors of GES, with the 11th aimed at ensuring that: 'the introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment'. An international expert group (Task Group 11 – Noise and later TG Noise) defined indicators for noise which were adopted by the European Commission. In 2010, the first Commission Decision on indicators of GES further described these indicators and the need to monitor underwater noise. This Decision focused on the 'distribution in time and space of loud, low- and mid-frequency impulsive sounds' and 'trends in continuous low frequency noise (as generated by shipping)' (European Commission, 2010). The MSFD broadened Europe's marine conservation commitments to a more ecosystem-based approach, reflected in the focus on the cumulative effects of noise and potential effect on all marine animals (not just protected species) and populations. Following a Commission Decision in 2017 (European Commission, 2017) Member States are now required to set threshold values for levels of underwater noise that do not adversely affect the marine environment.

Given that underwater noise can propagate across borders and affect populations of marine organisms with wide home ranges, the MSFD requires a regional, collaborative approach to monitoring, assessment and noise management through existing regional sea conventions such as OSPAR and HELCOM. This is currently being implemented and should be maintained. As mentioned in Chapter 2, the OSPAR/HELCOM impulsive noise registers were established in 2015[37] as the first of their kind, collating data on where and when impulsive noise events occur in order to inform one of the MSFD underwater noise indicators.

Two regional conservation agreements under the auspices of the CMS (The Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas[38] (ASCOBANS) and the Agreement on the Conservation of Cetaceans in the Mediterranean and Black Seas[39] (ACCOBAMS)), are specifically aimed at the protection of cetaceans. In the last decade, they have also acknowledged the potential threat caused by underwater noise. In addition, several initiatives have emerged, such as the Impulsive Noise Register for the Mediterranean (INR-MED) developed under the QUIETMED project, and continued under QUIETMED2. ACCOBAMS, through cooperation between industry, scientists and NGOs, also published guidance on underwater noise mitigation measures for impulsive and continuous noise (ACCOBAMS, 2019).

OSPAR and HELCOM are continuing work to develop an indicator of the risk of disturbance from impulsive noise, and the 'EU Harmonize' project, which started in 2021, aims to standardize and harmonize impulsive noise assessments in Europe. Continuous noise monitoring has also begun in several European sea regions (see Chapter 2). These monitoring programmes and associated indicators will inform policy and regulation in Europe.

In 2016, HELCOM adopted the Regional Baltic Underwater Noise Roadmap 2015-2017 (HELCOM, 2015), identifying steps to avoid harmful effects from noise on marine animals. Supporting the roadmap are the outputs of the BIAS[40] project that produced standards for noise measurements and signal processing and a tool to generate soundscape maps (see Chapter 2).

For a full review of the main European-funded projects and other relevant initiatives of the past decade see Ferreira & Dekeling (2019).

4.1.3 National

In Europe, regulations and national plans/strategies transpose the requirements set out in EU Directives. Prohibitions relating to killing, disturbing and injuring cetaceans are now embedded into the regulations of Member States. In addition to these prohibitions, important habitats for species such as bottlenose dolphins, harbour porpoises, and harbour and grey seals are protected by law from significant disturbance including from noise. Prevention and precaution lie at the heart of these regulations in line with guidance from the European Commission[41]. Certain activities can go ahead under licence even if they carry the risk of such impacts, as long as there are no satisfactory alternatives and there is no effect on a species' conservation status. In addition, mitigation measures are usually required for example to meet impulsive noise threshold levels, such as those adopted as statutory requirements in Germany, the Netherlands, Denmark and Belgium (see review in Thomsen *et al.,* 2015; Thomsen & Verfuss, 2019). There are nevertheless potential discrepancies between member states in how Directives are interpreted and transposed to national level, and also in the level of human resources and knowledge available to regulators, which can hinder effective and proportionate management.

A timeline of milestones in underwater noise regulations and management, publications and initiatives of relevance to Europe can be found in Figure 7 on page 28.

[35] http://www.soundandmarinelife.org/
[36] http://www.orjip.org.uk/
[37] https://www.ices.dk/data/data-portals/Pages/underwater-noise.aspx
[38] https://www.ascobans.org/
[39] https://accobams.org/
[40] https://biasproject.wordpress.com/
[41] https://ec.europa.eu/environment/nature/conservation/species/guidance/pdf/guidance_en.pdf

A BRIEF HISTORY OF UNDERWATER NOISE

LEGAL DEVELOPMENTS, PROJECTS, INITIATIVES AND KEY PUBLICATIONS IN UNDERWATER NOISE

1982
Adoption of **UNCLOS**

1985
Adoption of **EU Environmental Impact Assessment Directive**

1992
Adoption of **EU Habitats Directive**

2004
First **ACCOBAMS** resolution on noise

2006
E&P Sound and Marine Life Joint Industry Partnership starts

2007
Publication of **Southall** *et al.* Marine mammal noise exposure criteria: Initial scientific recommendations

2008
Adoption of EU **Marine Strategy Framework Directive**
CBD and **CMS** adopt resolutions on noise
First mandatory threshold in approvals for piling noise

2008
Publication of first **EMB position paper** on noise

2009
First **ASCOBANS** resolution on noise

2009
OSPAR overview of the impact of anthropogenic underwater sound

2010
Task Group 11 report on underwater noise (MSFD)

2011
TNO Standard for measurement and monitoring of underwater noise
BSH measuring instructions for noise from offshore wind farm

2012
EU TG Noise group established
SONIC, AQUO and **BIAS** projects start

2013
BSH measuring specification for effectiveness of noise control
HELCOM agreement on underwater noise

2014
IMO guidelines on ship noise
NPL good practice guide on underwater noise measurement

2014
BIAS standard for underwater noise measurement
HELCOM Baltic underwater noise roadmap 2015-2017 published
Publication of **Popper** *et al.* sound exposure guidelines for fishes and sea turtles

2015
International Quiet Ocean Experiment starts
OSPAR impulsive noise registry published
ACCOBAMS overview of noise hotspots project launched

2016
ISO standard for determination of source levels from deep water measurements published

2017
ISO standard for underwater acoustic terms published
ISO standard for measurement of pile driving noise published
DIN SPEC standard for offshore wind farm in situ determination

2017
QuietMED project starts
First **OSPAR** multi-year impulsive noise assessment published

2018
JOMOPANS project starts
UN Secretary-General report on underwater noise

2019
JONAS and **QuietMED2** projects start
ICES working group on shipping impacts in the marine environment starts
Publication of **Southall** *et al.* Marine mammal noise exposure criteria: Updated scientific recommendations

2020
Canadian proposal to review **IMO** guidelines
Ocean sound recognized as **Essential Ocean Variable**

2020
EMB working group on underwater noise starts
JPI Oceans approved activity on underwater noise
EC Horizon Europe Mission 'Restore our Ocean and Waters by 2030' document refers to underwater noise
UN Ocean Decade implementation plan refers to underwater noise

2021
SATURN, Quiet Seas and **Harmonize** projects start
Publication of **EMB Future Science Brief** on underwater noise

Figure 7. Timeline of European-centric legal developments, projects, publications and initiatives in underwater noise. The left-hand side presents key legal developments at international (green), regional (orange), European (light blue) and national (dark blue) level. The right-hand side presents important projects, publications and initiatives, with colours again referring to the same levels.

Port at Trieste in Italy.

4.2 Environmental impact assessments of underwater noise

Environmental Impact Assessment (EIA) lies at the heart of licensing human activities in Europe. EIA is a consultation process including planners, regulators, stakeholders and the public, culminating in an Environmental Impact Statement (EIS). The EIS generally involves descriptions of the local environment, including an inventory of species and other components that could be affected, a description of the development, a detailed assessment of its possible effects on the local environment, along with what mitigation is proposed. Regulators then examine the EIS and decide whether the residual effects are permissible. If consent is granted, it may come with conditions to ensure mitigation measures are employed.

As the plans for a Blue Economy have intensified in the past decade, so has the development of best practices for marine EISs. Noise risk assessments have been carried out for several years in association with permit applications for seismic surveys. However, the emergence of offshore wind farms has led to improved assessments for marine mammals, in particular for harbour porpoise. This coincided with the publication of a milestone paper on auditory injury thresholds and a disturbance assessment framework (Southall *et al.,* 2007), updated by Southall *et al.,* (2019), which have been used in Europe. Following a risk-based approach, the noise EIA should include the characterization of the source; the use of numerical sound propagation modelling to estimate sound levels at various distances away from the source; and some form of exposure assessment using knowledge on species' sensitivity to sounds of different frequencies, their risk of hearing damage and their distribution and abundance (Faulkner *et al.,* 2018). It may also, where data is available, include dose-response modelling for the risk of behavioural disturbance and sometimes population consequences modelling. A description of custom mitigation measures to be implemented and any residual risk should also be included. Guidelines[42] were published by the Convention on the Conservation of Migratory Species of Wild Animals on EIAs for noise generating activities and some countries have their own guidelines or general guidance. There have also been several industry-led international initiatives on standards for noise impact assessments that promote best practice amongst their companies, operating in multiple countries (CEDA, 2011; WODA, 2013). Thus, it is expected that the quality of assessments should continue to improve. However, it is key that the level of detail and complexity of EIAs be proportionate to the risk involved and to the level of uncertainty in each stage of the assessment.

[42] https://www.cms.int/en/guidelines/cms-family-guidelines-EIAs-marine-noise

4.3 Mitigating the effects of underwater noise

Unlike other forms of pollution, noise is temporary and once the sound generating operation stops, the pollution stops too. Although some of the effects on species may last longer than the duration of the sound (see Chapter 3), the temporary nature of noise renders this pressure potentially easier to manage than many others (e.g. chemical pollutants). In line with the precautionary principle, and given the uncertainties regarding the effects of noise, mitigation measures need to be employed when there is a risk of population- or ecosystem-level consequences or harm to individuals arising from anthropogenic noise (Thomsen *et al.,* 2019). Some examples of the latest developments in mitigation for shipping noise and other marine industrial activities, as well as a summary of potentially quieter alternatives to current marine operations in a European context are provided in this section.

Mitigation strategies for shipping noise

Beside the IMO guidelines mentioned in Section 4.1.1, the largest set of potential solutions for the mitigation of ship-generated noise can be found in the joint final report of the multidisciplinary EU-funded projects SONIC[43] and AQUO[44] (Baudin & Mumm, 2015). These include both long-term and temporary noise reduction solutions, whose effectiveness depends on energy efficiency, cost, and effect on marine organisms. **Long-term solutions** are focused on the reduction of the main noise source i.e. propeller noise, and other sources such as machinery vibrations transmitted by hull structures into the water (Huang *et al.,* 2016; Young *et al.,* 2016). However, these solutions can be expensive because of the high material and maintenance costs and are usually applicable for new construction only. A revolution in ship design is underway to reduce greenhouse gas emissions and move towards decarbonization, providing an opportunity within the next few years to include noise emissions as one of the variables in design optimisation. **Temporary solutions** can be achieved by adjusting vessel operational conditions (e.g. reducing ship speed), managing traffic, and better and regular vessel maintenance (see IMO, 2014). Traffic control strategies, such as prescribed shipping routes, avoiding marine life 'hot spots', and speed limits in vulnerable areas (Audoly *et al.,* 2017), can be customised to take into account ship traffic characteristics, ambient sound patterns and information on local marine organisms. The aforementioned SATURN[45] project will further assess the effectiveness and feasibility of mitigation measures to reduce shipping noise effects from a policy, legal and commercial perspective.

Credit EMB and JONAS project

Figure 8. Traffic control strategies such as prescribed shipping routes and speed limits can be used in vulnerable areas.

[43] www.sonic-project.eu

[44] www.aquo.eu

[45] https://www.saturnh2020.eu/

Mitigation strategies for impulsive noise

Mitigation measures have so far been well described for different impulsive noise sources like seismic surveys and construction work (Genesis Oil and Gas Consultants, 2011; OSPAR Commission, 2014; Feltham *et al.,* 2017; Long & Tenghamn, 2018; Thomsen *et al.,* 2019; Verfuss *et al.,* 2019; Bellmann *et al.,* 2020; Koschinski & Lüdemann, 2020). Several options are available depending on source, site of activity and species of concern.

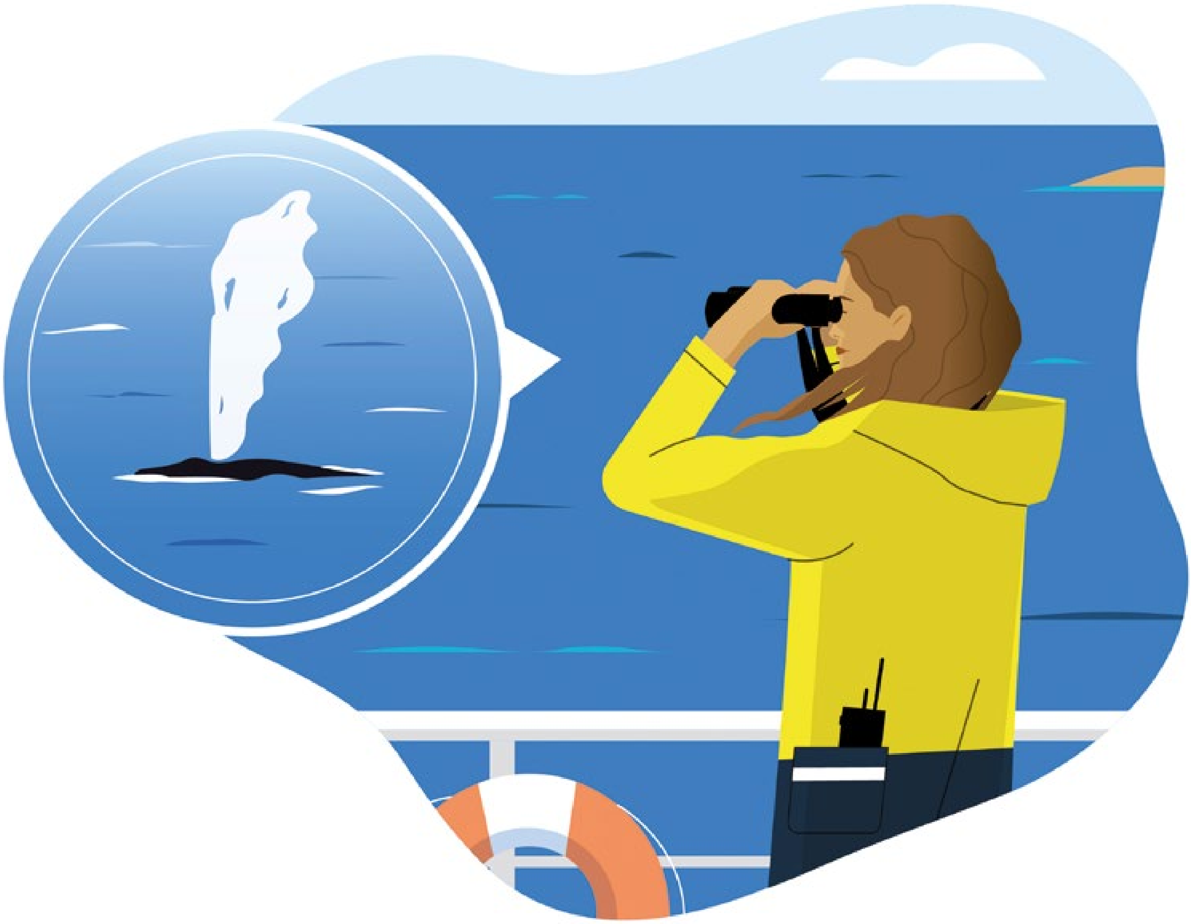
To avoid emissions of impulsive sound in the first place, **alternative methods** have been considered across many industries. In offshore construction, there are installation procedures that do not need to be carried out by impact hammer, including the use of quieter systems such as gravity foundations[46] and suction buckets[47] (Koschinski *et al.,* 2020). However, the installation choice will be driven primarily by cost, geology and logistical considerations. For some seismic explorations, techniques like vibroseis[48] (Feltham *et al.,* 2017; Long *et al.,* 2018) could provide an alternative, and industry has made significant progress in the last few years in developing fully commercial marine vibrators (Feltham *et al.,* 2017). However, more evidence is needed regarding the effects on marine organisms. Although these sources have a lower sound pressure and bandwidth compared to airgun arrays, they produce longer duration signals with short inter-signal periods and there are concerns regarding potential disturbance (Matthews *et al.,* 2021). For the clearance of unexploded ordnances (UXO) at sea, alternatives to high order detonation such as low order deflagration[49] (Cheong *et al.,* 2020) are likely to result in less noise and could be a game-changer in the clearance of several thousand UXOs littering the seabed in the North Sea in particular. Adoption of these by offshore operations is increasing, providing an opportunity to gather more evidence on their effectiveness and safety.

Temporal and spatial restrictions are used alone or as complements to other measures, and are particularly appropriate when source mitigation is more challenging and for areas/times that may be more sensitive to noise. Sensitive areas include fish spawning grounds, marine mammal calving/breeding grounds and areas of persistent high densities of marine mammals, while restrictions can be either year-round or seasonal (OSPAR Commission, 2009b). In the United Kingdom, for example, recent noise management advice for harbour porpoise marine protected areas is structured around the use of area and time limits to noisy operations (JNCC *et al.,* 2020).

Credit EMB and JONAS project

Figure 9. Temporal and spatial restrictions can be used to avoid areas/times that may be more sensitive to noise e.g. for spawning, calving/breeding or migration, with activities carried out outside those restrictions.

46 Gravity foundations are support structures that use their own weight to hold them in place.
47 Suction buckets use a pressure difference during installation, pumping water out of the bucket to force them to sink into the seabed.
48 Vibroseis is a seismic technique where a vibration source is used to generate controlled waves
49 Low order deflagration is where the explosive within the ordnance is burnt, resulting in its deactivation and avoiding detonation.



Credit EMB and JONAS project

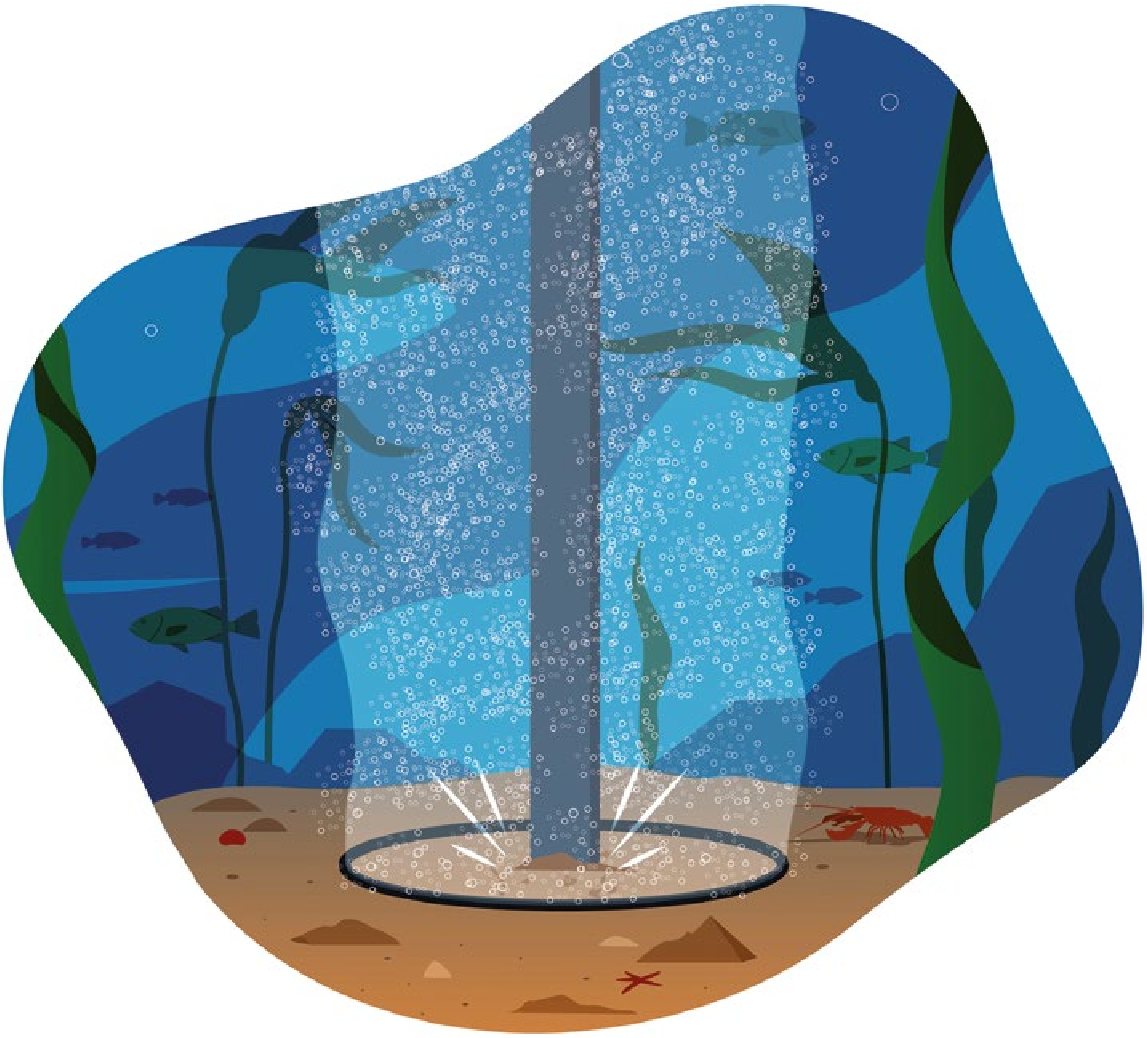
Figure 10. Marine Mammal Observers (MMO) can be used on board vessels to monitor the area for the presence of marine mammals,and call a halt to the noise generating activity when they are observed

The application of a **mitigation zone** around the sound source is a well-established strategy used across multiple industries. Here the aim is to ensure, as best as possible, that no animals of a certain species are present before starting or continuing the operations. Real-time monitoring of marine mammal presence using marine mammal observers (MMO), who survey the area and can halt to the operation if they are detected, is one way of doing that. There are, however, limitations to this, since marine mammals are difficult to detect, especially in poor conditions for visual or acoustic detection. Guidelines for minimising the risk of injury have been developed and are applied around the world (e.g. JNCC, 2017).

Acoustic deterrent devices (ADD), which emit noise either constantly or when approached, are another option to reduce the risk of injury by clearing the mitigation zone of certain species, especially for noise sources like explosions and pile-driving which can be particularly damaging. Originally developed for use in fish farms and fisheries, many new devices have come to market in the last 12 years (McGarry *et al.,* 2020). However, recent studies have highlighted concerns that in some cases the resulting spatial and temporal footprint of disturbance could be larger than needed (Brandt *et al.,* 2013), and therefore, ADD use should be optimized to achieve a defined deterrence range and avoid unnecessary far-field disturbance (Thompson *et al.,* 2020).

Operational measures to reduce sound at source can be used for most noise sources. For pile-driving for example, these include ramp-up procedures (or soft-start) of impact hammer energy where the hammer is operated at a lower energy initially, constraints on maximum impact hammer energy to the level required to achieve embedded depth, optimized pile-driving procedure, and duration for driving of single piles (OSPAR Commission, 2014). Real-time noise monitoring can be used in some instances to adjust parameters like hammer energy whilst operation is ongoing.

Ramp-up (or soft-start) procedures, are also widely used for seismic surveys, military sonar and some sub-bottom profilers, either by switching on different components one by one until full power, or gradually increasing the sound levels. However geophysical surveys in the future are likely to be increasingly undertaken from autonomous vehicles, and those that hover just above the seabed would reduce noise propagation in the water column (Duarte *et al.,* 2021) and hence address some of the challenges posed by current seismic surveys.



Credit EMB and JONAS project

Figure 11. A bubble curtain system produces air bubbles around a noise source such as pile-driving, and reduces the propagation of sound waves away from the source

Bubble curtains and casings have proven to be very effective at reducing broadband sound levels by up to 17 dB in water depths of 25-40 m. Higher frequencies are dampened more effectively compared to lower frequencies (e.g. >20 dB reduction at >1 kHz), which makes these methods effective at reducing impacts on marine mammals, but less so on fishes (Thomsen & Verfuss, 2019; Bellmann *et al.,* 2020). System configuration testing and developments are still needed to optimize each system to the environmental conditions and piling sound characteristics. The German-developed norm on noise mitigation systems for pile-driving activities (DIN-SPEC 45653: 2017; see also BSH, 2013) sets out rules for determining the reduction potential for a noise mitigation system, and thus enhances the further optimization of mitigation measures. In some instances, concerns have been raised regarding the cost and extended timelines for pile-driving operation relating to such mitigation (e.g. Thomsen & Verfuss, 2019; Merchant & Robinson, 2020). One area for further development is the fine-tuning of noise mitigation systems to achieve noise reduction in the frequencies that are of most concern for the relevant species needing protection.

Although many international conventions have a clause that exempt military activities, there is a requirement that Defence organisations should 'endeavour to ensure that such activities are conducted in a manner that is compatible, so far as reasonable and practicable, with the objectives of that convention or regulation' (see e.g. MSFD chapter 1, art. 2-2). Most national military organizations have mitigation measures in place to minimise risk to marine mammals when deploying military mid-frequency sonar. Several institutions and nations such as NATO (NATO, 2018), the UK, Norway, the Netherlands, Spain, Australia, Germany and Italy have also adopted other mitigation measures (Dekeling *et al.,* 2016). The main elements are risk assessment, avoidance of sensitive areas, considering the source level needed for a specific activity and soft-start / ramp-up (UN, 2018b).

4.4 Emerging technologies and methods

Since the last EMB Position Paper in 2008 there have been several technologies or approaches that have advanced understanding of the effects of noise on marine organisms and have helped with field studies, risk assessment and noise management. Some of these are listed here according to their relevance to the risk framework (see Figure 1).

4.4.1 Exposure assessment

Just a decade ago, impact assessments commonly applied rather simplistic calculations for sound transmission to estimate impact ranges for different sources. Now **numerical modelling** which uses more advanced mathematical models and include environmental data such as bottom topography and sound speed vertical profiles, is common practice. Its application has much improved noise assessments but more is needed to apply the appropriate models to the specific circumstances (see review by Farcas *et al.,* 2016). The emergent uptake in the use of autonomous underwater vehicles offers a potential cost-effective way to make extensive sound recordings over large areas, and to further validate noise propagation models. In terms of quantifying the number of animals exposed, statistical modelling has increasingly been used in identification of animal hot-spots for the identification of risk areas. For example, using **dynamic habitat modelling**, animal distribution can be correlated to environmental variables (e.g. current speed) to identify those habitat variables that drive the distribution of marine fauna in space and time (Heinänen *et al.*, 2018). Furthermore, **agent-based model**s (ABM) simulate the movement of individual animals in response to habitat drivers and pressures such as noise, providing more realistic assessments of exposure to sound than those based on stationary animals

Credit: HYDROTECHNIK LÜBECK GMBH

Double Big Bubble Curtain in action, used to mitigation sound propagation from pile-driving.

(Donovan *et al.,* 2017; Thomsen *et al.,* 2019; Mortensen *et al.,* 2021). Whilst modelling can play a significant role in impact assessments, there is still uncertainty in some of the parameters. This can be addressed by identifying those key parameters in the models and undertaking field measurements, research and monitoring of species and noise.

Concerning monitoring of noise and marine animals, considerable progress has been made in **Passive Acoustic Monitoring (PAM)** device durability, frequency response and especially in the capability to transmit data online. This has led to a rapid increase in PAM around Europe and elsewhere. Elaborate tools have been further progressed that allow for automatic species recognition (e.g. PAMguard[50]). Other methods, e.g. **infrared cameras** and **satellite imagery**, used for surveying marine mammals have emerged and show potential for further development (Zitterbart *et al.,* 2020).

4.4.2 Dose-response assessment

There has been significant progress in advancing the methods for **controlled exposure experiments** (see Harris *et al.,* 2015; Dunlop *et al.,* 2018; Harris *et al.,* 2018; and see Chapter 3). This has been revolutionised by the further development and increased use of **digital and acoustic tags** to monitor marine mammal and fish behaviour in the wild in the past decade (Johnson & Tyack, 2003; Mueller-Blenkle *et al.,* 2010; van der Knaap *et al.,* 2021). Tags are placed on the body of marine mammals and record variables such as received sound, orientation and speed of the animal, dive depth and even some physiological measurements such as oxygen uptake. For fish, acoustic tags are placed inside the fish or on their body and emit an acoustic signal that can then be used to track their location (Hussey *et al.,* 2015). Other technologies such as PAM and **drone technology** are now allowing real time documentation of the behaviour of marine mammals during sound exposure and also of changing body condition and health (Moretti *et al.,* 2014; Torres *et al.,* 2018; Centelleghe *et al.,* 2020).

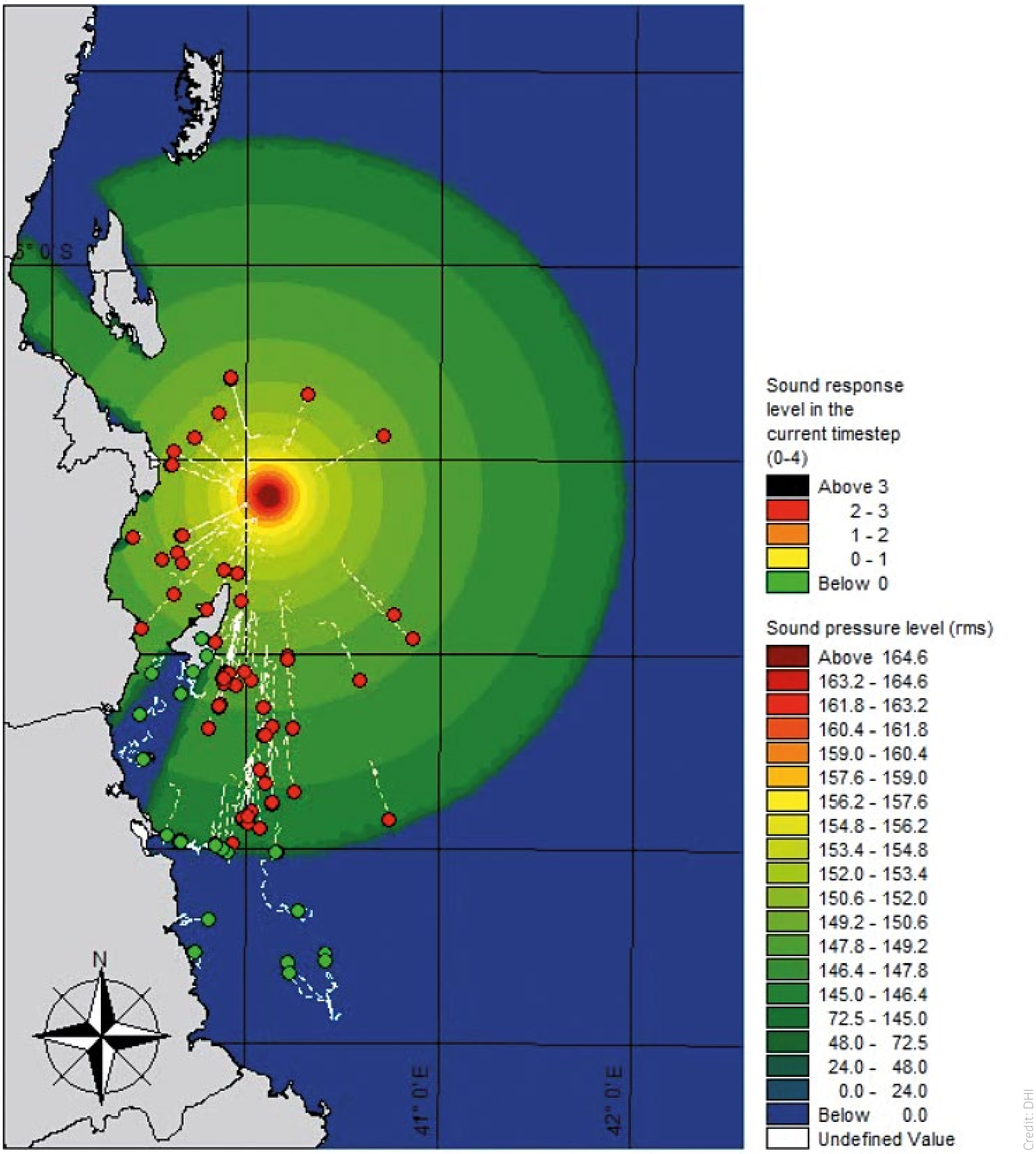


Figure 12. Snapshot of the predicted flight response behaviour of virtual whale agents due to anthropogenic noise from offshore pile driving activities.

[50] https://www.pamguard.org/

4.4.3 Overall risk characterization and management

The rapid increase in digitalisation has provided an incentive for the development of several **software tools for noise risk assessments**. These include noise mapping and the assessment of biological impacts such as masking, behaviour response and other effects (e.g. DHI's marine animal movement portal[51]). Population consequence models based on PCoD/PCAD, such as the interim PCoD[52] (iPCoD) and DEPONS[53] models which incorporate animal movement, are being developed and used in risk assessments in some European countries, and can provide an indication of the level of impact of different activity scenarios and improve understanding of the effects of noise disturbance.

In addition, the use of artificial intelligence to separate, identify and localize underwater sound sources shows some promise (Chen *et al.,* 2019; Gervaise *et al.,* 2021).

Credit: Josh Sorenson, Pexels

Drone technology will support research at sea.

[51] https://www.dhigroup.com/data-portals/marine-animal-movement-portal

[52] http://marine.gov.scot/information/interim-population-consequences-disturbance-model-ipcod

[53] https://depons.eu/

5 Key evidence gaps, barriers and actions to the management of underwater noise

Here we describe the key evidence gaps, as well as the barriers to desirable management of underwater noise, as highlighted in the previous chapters of this Future Science Brief.

To reflect back on progress made since the last EMB Position Paper, we categorized the present uncertainty using Table 2 from Boyd *et al.,* (2008; see Annex 2). Based on our judgement of prevailing uncertainties, and our expert opinion on importance, we identify some key priority items. By doing so, it is important to consider that although anthropogenic noise is a potential stressor for marine organisms, it is not the only stressor and also not necessarily the most important stressor in many cases. Fishing, by-catch, chemical pollution, global warming, and many other pressures impact on marine organisms, with potential cumulative effects (e.g. Thomsen *et al.,* 2011). We use the risk framework in Boyd *et al.,* (2008) (expanded upon in WODA, 2013; McQueen *et al.,* 2020) to identify and organize those gaps. We also provide suggested actions to address gaps and barriers. We focus on Europe, yet our conclusions may have relevance to other areas as well.

Key gaps that apply to all risk framework steps

Comprehensive monitoring of **marine species' habitat use, movements, behaviour and distribution** is fundamental to the assessment of noise exposure, dose-response, and the management of risk posed by noise. This has only been achieved for a handful of populations in the past but new technologies are now making such studies more feasible (see Chapter 4). Significant progress is expected in the next decade or so, providing adequate funding is available. It is also paramount to further **agree international standards in all steps of the risk framework**, including for measuring and modelling underwater ambient sound, and calculating source levels of specific sources such as ship noise in shallow water and operational wind farms. It is crucial that these standards have units relevant for the species of concern, such as sound pressure and particle motion. In order to gain the necessary scientific knowledge in a cost-effective manner, we also need standards to facilitate comparisons between studies (e.g. those looking at behaviour, Temporary Threshold Shift). Furthermore, we need standards to enable the evaluation of the effectiveness of mitigation measures, and to improve the quality of impact assessments. Standards will allow research projects, monitoring programmes, and environmental impact assessments to be comparable and, in some cases, combined. This will also help in the communication between biologists, acousticians, engineers, regulators and other stakeholders. It has to be emphasized that we do not yet have many of those standards (Popper *et al.,* 2019).

Risk identification / exposure assessment – Chapter 2

Considerable progress has been made since the last EMB Position Paper on the analysis of **sound source characteristics** and the **spatial distribution of sound** (e.g. sound mapping). Yet, there are gaps concerning some existing and especially new sound sources. We also have little knowledge about the baseline soundscape in many areas. The gaps and actions to address them are presented in detail below:

GAP / BARRIER	ACTIONS TO ADDRESS THE ISSUE
Current soundscape / ambient sound status in EU seas with emphasis on potential hotspots and less well understood areas e.g. the Mediterranean Sea, the Black Sea and, looking beyond the EU, off the coast of developing nations where noise generating activities are prevalent.	Continue existing joint monitoring programmes across regions, and expand data collection into uncovered areas, including the development of sound maps based on measurements and modelling.
Sound characteristics of data deficient sources such as some recreational craft, sub-bottom profilers, and new activities such as deep-sea mining, future acoustic communication systems (underwater Wi-Fi) and decommissioning.	Shortlist the high priority sources and perform standardized sound source characterization studies.
Cumulative acoustic footprint of increasing and scaled-up activities (more offshore projects e.g. pile-driving for and operation of wind farms, unexploded ordnance clearance, and shipping).	Dedicated scenario modelling studies concentrating on some areas where activity is high: North Sea, Baltic Sea, and Mediterranean Sea. Consider validation using targeted measurements.

Dose-response assessment – Chapter 3

Much knowledge has been gained in the past 13 years on noise effects, especially on **behavioural responses in marine mammals**, thanks to ground-breaking technology, large-scale and coordinated field efforts, and targeted funding. However, our understanding of **effects on fishes and especially invertebrates** is lagging behind. Important gaps remain in our knowledge on **health effects** of noise across all taxa. Finally, we have extremely limited understanding about the **population consequences of noise impacts**. In this context we need to refocus our attention to **ecosystem effects of noise**, i.e. how does noise affect the different components of the food web, such as invertebrates and fishes that can then in turn affect marine mammals? The list of gaps and actions is presented in detail below:

GAP / BARRIER	ACTIONS TO ADDRESS THE ISSUE
Effects of noise on fish and invertebrates.	Identify key species/groups for studies of effects of sound exposure on fishes and invertebrates, considering protection status, sensitivity to sound, commercial importance and methodological practicability (i.e. tagging of benthic species and echosounder investigations on pelagic taxa).
Understanding the hearing capabilities of baleen whales, fish and invertebrate species.	Studies on hearing sensitivity in baleen whales, and selected fish and invertebrate species, in units relevant for the study species (e.g. pressure, particle motion).
Masking	Dedicated field and modelling studies investigating how acoustic habitats change over time, and identification of the risk of masking to individuals and populations.
Physiological and physical effects of noise exposure and its impacts on the health of marine organisms.	Depending on taxa (see Annex 2), dedicated studies including PTS, TTS and other parameters such as physiological stress. Priorities for marine mammals are extrapolation of PTS and stress; priorities for fishes are stress; and priorities for invertebrates are a basic description of physiological impacts.
Ecosystem effects of noise / Cumulative impacts	Dedicated studies including multi-species investigations, predator-prey interactions and addressing the question of how noise impacts combine with other stressors.

Risk characterization – Chapter 3

Since the Position Paper by Boyd *et al.*, (2008), there has been an intense effort to further develop and apply practical frameworks to estimate the **biological consequences of noise exposure**. Cumulative impact assessments should be undertaken strategically with a long-term perspective and in collaboration with governments, industry and research laboratories. However, many questions remain open on this topic:

GAP / BARRIER	ACTIONS TO ADDRESS THE ISSUE
The mechanisms for, and biological consequences of, displacement/behavioural change in marine mammals and fishes due to exposure to high-intensity impulsive sound (e.g. pile-driving and airguns).	Further studies on behavioural response in fishes and marine mammals leading to displacement with associated population consequences (PCAD/PCoD). Priorities are effects on recruitment (e.g. disorientation of larvae, displacement of adult fishes from spawning areas and potential knock-on effects on fisheries), and displacement of marine mammals from vital habitats (feeding and breeding grounds). These studies should quantify dose-response relationships for behavioural response as a function of noise exposure. For these studies, it is important to have a good prior understanding of baseline movements, activity and energy budgets and any regional/environmental differences, feeding rates, and probability of response.
Cumulative impacts	Further development of frameworks and empirical studies to allow assessment of population-level effects from cumulative impacts of noise and other pressures. This includes the further refinement of population models and reducing assumptions by collecting field data on species' movements, energy budgets and responses to noise.

Risk management / mitigation – Chapter 4

Since EMB Position Paper N° 13, a series of resolutions by international environmental conservation agreements, conventions and fora have been established on the issue of anthropogenic underwater noise. In addition, most European countries now have regulatory frameworks to manage noise and the tools to integrate underwater noise into Marine Spatial Planning. However, more is needed to put some of these into practice and to fully test their effectiveness. Much progress has been made during the last decade in environmental impact assessments and mitigation, but to optimally use mitigation and management measures we need to gain better knowledge on their effectiveness. This includes further development of cost-effective noise mitigation methods and alternative quieter operations. Finally, there should be a high priority to make data and knowledge resulting from the various studies widely available to build capability, and to aid knowledge transfer.

GAP / BARRIER	ACTIONS TO ADDRESS THE ISSUE
Effectiveness of mitigation measures in protecting marine mammals, fishes, and invertebrates, e.g. noise mitigation.	Dedicated modelling and field studies including e.g. to improve understanding of how hydrographic conditions (currents) impact the effectiveness of noise mitigation devices. Investigation of the frequency dependencies of sound reduction for fish and marine mammal sensitivities. Previously identified constraints to the safe and cost-effective deployment of mitigation measures should be assessed. Emitted noise levels should be one of the design criteria for new ships. Mitigation measures could also include the further development of economic incentives (e.g. in shipbuilding and harbour regulation).
Effectiveness of current European regulations, policy, and guidance. Coordination of regulation across jurisdictions.	Regionally driven guidelines and action plans should be encouraged since noise travels beyond national jurisdiction. These can fill the gaps in national EIA processes and policies. Also, since many companies operate internationally, industries should themselves strive to always employ best practice, going beyond national protection measures for species and habitats where these measures are not robust enough.
Data management and knowledge transfer.	Concerted effort to share data from noise studies to make these globally and openly available. Dedicated capacity building, including development of technical guidance and workshops.

6 List of the most urgent priority actions/questions

Based on Chapter 5, the below list of urgent priority actions has been identified. It has a large overlap with the actions in Chapter 5 but we attempt to make it more tangible by concretizing each point.

1.	Develop collaborative international standards applicable to all steps of the risk framework.
2.	Conduct comprehensive monitoring combined with spatial ecological modelling of marine species' dynamic habitat use, movements, behaviour and distribution to establish baselines.
3.	Foster comprehensive monitoring and data collection of current soundscapes / ambient noise, including via joint monitoring programmes in existing and new areas.
4.	Shortlist high priority (and biologically relevant) sound sources and perform standardized source characterization studies.
5.	Promote hearing studies on baleen whales and on selected fish and invertebrate species.
6.	Conduct field and modelling studies on changes in acoustic habitats to identify masking risks to communication in fishes and marine mammals.
7.	Conduct further studies on behavioural response of marine mammals and fishes due to exposure to high intensity impulsive sounds to assess population consequences via e.g. displacement.
8.	Conduct taxa-relevant studies on hearing impairment and physiological stress to address existing knowledge gaps in invertebrates, fishes and marine mammals. Priorities for marine mammals are understanding the relationship between Temporary- and Permanent Threshold Shift and physiological stress; priorities for fishes are stress; and priorities for invertebrates are a basic description of physiological impacts.
9.	Conduct dedicated studies including multi-species investigations, predator-prey interactions, and interaction with other food web levels, addressing the question of how noise impacts combine with other stressors.
10.	Develop frameworks and conduct studies to allow population-level assessment of effects from cumulative impact of noise and other pressures.
11.	Conduct dedicated modelling and field studies to improve understanding on effectiveness, safety and cost-effectiveness of noise mitigation devices, mitigation measures and management options. This requires a shortlist of relevant industries and their sound sources (e.g. shipping, marine renewables, unexploded ordnances and geophysical surveys).
12.	Develop regional action plans and guidelines for Environmental Impact Assessment and policies.
13.	Initiate international collaborative projects (via European Union, International Maritime Organization etc.) to develop stakeholder and societal capacity in understanding and addressing underwater noise. These projects should include technical guidance and workshops, sharing data and best practices globally and openly, and supporting transdisciplinary (e.g. between acousticians, biologists and others) science and communication.

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List of abbreviations

ABM	Agent Based Models
ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
ADD	Acoustic Deterrent Device
AIS	Automatic Identification System
AQUO	Achieve Quieter Oceans by Shipping Noise Footprint Reduction project
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
AUV	Autonomous Underwater Vehicle
BIAS	Baltic Sea Information on the Acoustic Soundscape project
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Germany)
CBD	Convention for Biological Diversity
CEDA	Central Dredging Association
CEE	Controlled Exposure Experiments
CEFAS	Centre for Environment, Fisheries & Aquaculture Science, UK
CMS	Convention on the Conservation of Migratory Species of Wild Animals
CS	Communication Space
CT	Computed tomography
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GES	Good Environmental Status
GHG	Greenhouse gas
HELCOM	Commission for the Helsinki Convention
ICES	International Council for the Exploration of the Sea
IMO	International Maritime Organization
INR-MED	Mediterranean Impulsive Noise Register
IOC	International Oceanographic Commission of UNESCO
iPCoD	Interim Population Consequences of Disturbance

IQOE	International Quiet Ocean Experiment
ISO	International Organization for Standardization
IWC	International Whaling Commission
JNCC	Joint Nature Conservation Committee
JOMOPANS	Joint Monitoring Programme for Ambient Noise North Sea project
JONAS	Joint Framework for Ocean Noise in the Atlantic Seas project
LFAS	Low Frequency Active Sonar
MEPC	Marine Environment Protection Committee
MFAS	Medium Frequency Active Sonar
MMO	Marine Mammal Observer
MSFD	Marine Strategy Framework Directive
NGO	Non-Governmental Organization
NRC	National Research Council (US)
OSPAR	Commission for the Oslo and Paris Conventions
PAM	Passive Acoustic Monitoring
PCAD	Population Consequences of Acoustic Disturbance
PCoD	Population Consequences of Disturbance
PTS	Permanent Threshold Shift
SATURN	Developing Solutions for Underwater Radiated Noise project
SEA	Strategic Environmental Assessment
SEL	Sound Exposure Level
SONIC	Suppression of Underwater Noise Induced by Cavitation project
SPL	Sound Pressure Level
TNO	Toegepast Natuurwetenschappelijk Onderzoek, the Netherlands
TTS	Temporary Threshold Shift
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNCTAD	United Nations Conference on Trade and Development
URN	Underwater Radiated Noise
UXO	Unexploded ordnances
WODA	World Organization of Dredging Associations

Annexes

Annex I: Members of the European Marine Board Working Group on Underwater Noise

NAME	INSTITUTION	COUNTRY
	Working Group Chairs	
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Annex 2: Assessment of prioritization of issues

The table below presents the risk assessment framework as applied to the issue of marine animals and underwater noise with an assessment of prioritization. The table is originally presented in Boyd *et al.,* (2008) relating to marine mammals only, and we present an update extending the scope to fishes and invertebrates as well. Areas highlighted in blue indicate high priority issues, and these are reflected in the recommendations presented in Chapter 5.

Note that there is some overlap between the main research issues across the stages of risk assessment. For example, the distribution and abundance of anthropogenic sound sources is relevant to hazard identification, as well as exposure and dose-response assessments and is hence included twice.

STAGE IN RISK ASSESSMENT FRAMEWORK	MAIN RESEARCH ISSUES	SUB-ISSUES	DEGREE OF UNCERTAINTY FOR MAMMALS *(Boyd et al., 2008)*	DEGREE OF UNCERTAINTY FOR MAMMALS (2021)	DEGREE OF UNCERTAINTY FOR FISHES (2021)	DEGREE OF UNCERTAINTY FOR INVERTE-BRATES (2021)
STEP 1: Risk identification	Sources of sound in the marine environment	Characteristics of natural and anthropogenic sound sources	Moderate	Moderate / Low	Moderate / Low	Moderate / Low
		Distribution and abundance of sound sources	High	Moderate / High	Moderate / High	Moderate / High
	Sound fields in the marine environment	Ambient noise fields	High	Moderate	Moderate	Moderate
		Sound fields of individual sources	Moderate	Moderate / High	Moderate / High	Moderate / High
		Auditory detection of sound	Moderate	Moderate	Moderate / High	High
		Non-auditory sensitivity of sound	Moderate	Moderate	Moderate / High	Moderate / High
STEP 2 & 3: Exposure assessment and dose-response assessments (both long-and short-term)	Marine species as receivers of sound	Distribution and abundance of marine animals (including vertical)	High	High	Moderate	High
		Auditory detection of sound	Moderate	Moderate	Moderate / High	High
		Non-auditory sensitivity to sound	Moderate	Moderate	Moderate / High	Moderate / High
		Distribution and abundance of sound sources	High	Moderate / High	Moderate / High	Moderate / High
	Effects of sound on individuals	Physiological effects (e.g. TTS, PTS, stress)	Auditory effects: moderate	TTS: Low	TTS: Moderate / High	TTS: High
				PTS: High	PTS: Moderate	PTS: High

STAGE IN RISK ASSESSMENT FRAMEWORK	MAIN RESEARCH ISSUES	SUB-ISSUES	DEGREE OF UNCERTAINTY FOR MAM-MALS (Boyd *et al.*, 2008)	DEGREE OF UN-CERTAINTY FOR MAMMALS (2021)	DEGREE OF UNCERTAINTY FOR FISHES (2021)	DEGREE OF UNCERTAINTY FOR INVERTE-BRATES (2021)
			Stress effects: High	Stress effects: High	Stress effects: Moderate / High	Stress effects: High
		Masking (including potential chronic effects	High	High	High	High
		Behavioural effects	High	Moderate	Moderate / High	High
		Life function effects (e.g. body condition, reproductive condition)	High	High	High	High
		Morbidity	High	Moderate / High	Moderate	High
		Issues related to mass strandings (e.g. nitrogen bubble, tissue resonance, and haemorrhagic diathesis hypotheses)	High	Low	N/A	High
		Effects of sound on feeding through prey availability	High	High	High	High
	Effects on populations	Changes in vital rates (e.g. fecundity, survival)	High	High	High	High
	Cumulative and synergistic effects	Effects of multiple exposures to sound	High	High	High	High
		Effects of sound in combination with other stressors	High	High	High	High
STEP 4: Risk characterization	Risk of impact	Overlap of exposures and effects	High	Moderate	High	High
STEP 5: Risk management	Methods to prevent or reduce risk	Mitigation tools and determining trigger levels for management action	High	Moderate / High	High	High

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