ANTHROPOGENIC UNDERWATER NOISE: IMPACTS ON MARINE AND COASTAL BIODIVERSITY AND HABITATS, AND MITIGATION AND MANAGEMENT MEASURES

DRAFT TECHNICAL SERIES

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EXECUTIVE SUMMARY

Introduction and Background

Anthropogenic noise in the marine environment has increased markedly over the last 100 or so years as anthropogenic use of the oceans has grown and diversified. Technological advances in vessel propulsion and design, the development of marine industry and the increasing and more diverse human use of the marine environment have all resulted in a noisier underwater realm. Long-term measurements of ocean ambient sound indicate that low frequency anthropogenic noise has increased, which has been primarily attributed to commercial shipping. As well as an increase in commercial shipping, the last half century has also seen an expansion of industrial activities in the marine environment, including oil and gas exploration and production, commercial fishing, and more recently, the development of marine renewable energy. An increase in the number of small motorised vessels in coastal areas has also been reported, where they can dominate some coastal acoustic environments such as partially enclosed bays, harbours and estuaries.

Anthropogenic noise has gained recognition as a major global pollutant and an important stressor for marine life and acknowledged as an issue that needs to be addressed. The impacts of sound on marine mammals have received particular attention, especially impacts from military use of active sonar, and industrial seismic surveys that coincide with cetacean mass stranding events. Extensive investigation mainly over the last decade by academia, industry, government agencies and international bodies has resulted in a number of reviews of the effects of sound on marine fauna. The issue of underwater noise and its effects on marine biodiversity has received increasing attention at the international level, with recognition by a number of international and regional bodies and organisations.

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids). **Water is an excellent medium for sound transmission** because of its high molecular density. **Sound travels almost five times faster through sea water than through air** (about 1500 vs. 300 m/s), and low frequencies can travel hundreds of kilometres with little loss in energy, thereby enabling long distance communication, but potentially a long-distance effect of noise on aquatic animals as well. Sound propagation is affected by four main factors: the frequency of the sound, water depth, and density differences within the water column, which vary with temperature and pressure. Therefore, the sound arriving at an animal is subject to propagation conditions that can be quite complex, which can in turn significantly affect the characteristics of arriving sound energy.

Natural and Anthropogenic Underwater Sound

There are a range of natural sound sources in the marine environment from physical and biological origins. Natural physical phenomena that contribute to the underwater soundscape include wind, waves, and swell patterns; bubbles; currents and turbulence; earthquakes; precipitation and ice cover and activity. Marine mammals (cetaceans and pinnipeds) produce sounds that are used for communication, orientation and navigation, and foraging. Many marine fish species produce sound for communication, either as individuals, but also in choruses. A number of invertebrates also contribute to ambient sound, particularly in tropical or sub-tropical reef environments, including snapping shrimp, squid, crabs, lobsters and urchins.

The underwater world is subject to a wide array of man-made noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar. Human activity in the marine environment is an important component of oceanic background noise and can dominate the acoustic properties of coastal waters and shallow seas. Human activities introduce sound into the marine environment, either intentionally for a specific purpose (e.g., seismic surveys) or unintentionally as a by-product of certain activities (e.g., shipping or construction). Anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds. Examples of impulsive sounds are those from explosions, airguns or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations. The level of human activity and corresponding noise production in the marine environment is predicted to rise over the coming decades as maritime transportation and the extraction of marine resources continue to grow.

The Importance of Sound to Marine Animals

Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators. The distinctive properties of underwater sound and the limitations of other senses, such as vision, touch, taste and smell in the marine environment, in terms of range and speed of signal transmission, mean that sound is an important and often essential sensory medium for many marine animals.

Almost all marine vertebrates rely to some extent on sound for a wide range of biological functions, including the detection of predators and prey, communication and navigation. Marine mammals use sound as a primary means for underwater communication and sensing. They emit sound to communicate regarding the presence of danger, food, a conspecific or other animal, and also about their own position, identity, and reproductive or territorial status. Underwater sound is especially important for odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects, for example, in relation to coordinated movement between conspecifics and feeding behaviour.

Sound is also especially important for other vertebrate taxa such as marine turtles and many teleost fishes. Fishes utilize sound for navigation and habitat selection, mating, predator avoidance and prey detection and communication. Impeding the ability of fishes to hear biologically relevant sounds might interfere with these critical functions. Marine turtles are also thought to use sound for navigation, locating prey, avoiding predators and environmental awareness.

Many invertebrate marine taxa also rely on sound including decapod crustaceans. Although the study of invertebrate sound detection is still rather limited, based on the information available it is becoming clear that many marine invertebrates are sensitive to sounds and related stimuli. However, the importance of sound for many marine taxa is still rather poorly understood and in need of considerable further investigation.

The Impacts of Underwater Noise on Marine Biodiversity

A variety of marine animals are known to be affected by anthropogenic noise. Negative impacts for at least 100 marine species (cetaceans, teleost fishes, marine turtles and invertebrates) have been reported in scientific studies to date.

A wide range of effects of increased levels of sound on marine fauna have been documented both in laboratory and field conditions. However, there are still many gaps and uncertainties in our understanding of the effects of sound on marine taxa. The known effects can range from mild behavioural responses to complete avoidance of the affected area, masking of acoustic cues, and in some cases serious physical injury or death. Low levels of sound can be inconsequential for many animals. However, as sound levels increase, the elevated background noise may disrupt normal behaviour patterns impeding the ability to efficiently feed, for example. Masking of important acoustic signals or cues can reduce communication among conspecifics and may interfere with larval orientation, which could have implications for recruitment. Some marine mammals have been able to compensate for elevated background noise levels by changing their vocalisations.

Intense levels of sound exposure have caused physical damage to tissues and organs of marine animals, and can lead to mortality, with lethal injuries of cetaceans documented in stranded individuals caught up in atypical stranding events. Lower sound levels have been shown to cause permanent or temporary loss of hearing in marine mammals and fishes. Behavioural responses such as strong avoidance of the sound source can lead to habitat displacement. Some marine animals, such as beaked whales appear to be particularly susceptible to anthropogenic sound, and some populations have experienced declines for years after a sonar-induced stranding event.

There are increasing concerns about the long-term and cumulative effects of noise on marine biodiversity. The long-term consequences of chronic noise pollution for individuals and populations are still largely unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested. There is also growing concern regarding the cumulative effects of anthropogenic sound and other stressors as well as how this can affect populations and communities. Although there is currently little empirical evidence for noise effects on marine populations, acoustic studies for terrestrial vertebrates indicate that features such as fitness and reproductive success can be compromised. The additional threat of living in a noisy environment may intensify the problems for already stressed marine animals with potentially negative effects on individuals and populations.

Mitigation and Management of Anthropogenic Underwater Noise

The use of mitigation measures and protocols is well established in the military and in industries that produce impulsive noise emissions during seismic surveys or offshore construction. However, there can be substantial variation in mitigation procedures between regions and navies for seismic surveys and active sonar respectively. Although mitigation guidelines are available, the degree to which they are followed and implemented varies. International voluntary guidelines to reduce underwater noise from commercial vessels should encourage the shipping industry to use more efficient and quieter ships.

Recent examples of best environmental practise used by or developed for industry are presented for seismic surveys and offshore construction. These involve drawing up detailed mitigation and monitoring strategies that are specifically designed for each operation. They also include substantial pre-and post-operation stages containing comprehensive environmental impact assessments and an evaluation of mitigation effectiveness respectively. Examples of current guidance on mitigation and monitoring protocols during operations are provided with specific reference to marine mammals. Most existing protocols are not designed for other marine taxa. There is a need to develop and test operational protocols for species of concern in other taxa such as teleost fishes, marine turtles and invertebrates.

There are a range of technologies either in development or actual use for industrial activities in the marine environment to reduce noise emissions. These include various designs for ships to quieten propulsion systems and minimise acoustic emissions from the hull, alternative technologies for seismic surveys such as marine vibroseis and alterations in airgun design and operation, and a range of techniques that can reduce or eliminate noise propagation from pile driving including the use of alternative non-impact foundation designs.

Acoustic mapping tools are being developed to provide spatio-temporal assessments of low frequency noise for specific regions. Cetacean density maps are also being created using field data and predictive modelling of environmental factors. When combined, these tools may provide relevant information for risk assessment and decision-making processes with regard to temporal and spatial noise restrictions in sensitive areas. Modelling tools have also been developed to measure communication masking in cetaceans, which can support the development of management guidelines for a particular region or species.

The use of acoustic monitoring tools in mitigation strategies is now well established. A range of GIS-based passive acoustic monitoring (PAM) tools are available, which enable detailed real-time monitoring of vocalising marine mammals during industrial or military operations. Clear guidelines for the use of PAM in monitoring protocols are set out in legal codes of conduct for some countries. Although PAM does have some limitations, it is quickly developing into a useful tool for certain (vocal) species of marine mammal. Further development and testing of PAM systems is required to determine whether it can be used for vocalising species of other taxa. Active acoustic monitoring (AAM) tools are also available and may be better suited to marine fishes and some invertebrates.

There are a range of existing management frameworks for the marine environment that currently consider underwater noise or have the potential to do so. These include marine spatial planning approaches as part of an overall ecosystem-based management strategy that considers multiple stressors, and risk or impact assessments, usually for particular species of concern. Examples are provided from a number of countries. A more generic framework for the spatio-temporal prioritisation of noise mitigation developed for cetaceans could also be adapted and applied to other marine taxa.

Underwater noise and its impacts on marine fauna have been addressed in different regional and international intergovernmental processes. The setting of national, regional and international standards for the measurement of underwater sound is still at a relatively early stage with examples of progress provided for the United States, European Union and by the International Standards Organisation. Examples of a number of other types of standard regarding underwater noise are also provided including training and data collection standards during monitoring and regional standards for noise mapping and marine spatial planning.

Although mitigation practises have developed considerably over the last few decades, there has been an overall focus on marine mammals (cetaceans in particular) and the use of simplistic dose-response techniques involving exposure thresholds. There is a need to develop mitigation measures that take into account behavioural and cumulative effects where known, but also consider noise impacts in combination with other stressors. Specific mitigation guidelines are needed for marine taxa other than mammals, but this will also require substantial further research to determine the effectiveness of existing practises for these groups.

Acoustic Research and Future Research Needs

Previous acoustic research for marine fauna has focused on cetaceans and, to a lesser extent, other marine mammals such as pinnipeds, but there are still many knowledge gaps. Acoustic research for marine fishes and invertebrates is still at an early stage and requires systematic studies of the effects of marine noise on these animals. Consequently, many sound-induced impacts for less well-studied taxa are currently potential effects, some of which have been inferred from studies of other faunal groups.

Research needs can be split into four main areas: (1) Further characterization of underwater noise and properties of emitted sound in a changing marine environment; (2) Baseline data on the biology, distribution, abundance and behaviour of marine species; (3) Detailed information on the impacts of sound on marine animals at the individual, population and ecosystem level; and (4) Assessment and improvement of mitigation procedures and measures.

Research is required to better understand the effects of anthropogenic sound on marine biodiversity. The lack of scientific knowledge regarding the issue is also currently one of the most important limitations for effective management. There are high levels of uncertainty for noise effects on all marine taxa. There is a need to conduct further detailed research on noise effects on species, populations, habitats and ecosystems in addition to cumulative effects of other stressors. However, the extensive knowledge gaps also mean that prioritization will be required.

Identified priorities for research include species that are already highly threatened, endangered or particularly vulnerable through a combination of multiple stressors and intrinsic characteristics, but also representative groups of understudied taxa. Knowledge for some faunal groups such as teleost and elasmobranch fishes, marine turtles, seabirds and invertebrates is lacking. Other priorities for acoustic-related research are the identification and protection of critical habitats that endangered or threatened marine species depend upon for important activities such as foraging or spawning. Impacts of anthropogenic noise on fisheries should also be assessed and considered.

New Challenges

New challenges such as global changes in ocean parameters (e.g., acidity and temperature) are also likely to have consequences for marine noise levels at a range of geographic scales through changes in sound absorption. The retreat of Arctic sea ice, opening up waters for exploration and resource extraction, also presents important noise-related considerations, as areas not previously subjected to extensive human use are highly likely to be exposed to increased levels of anthropogenic sound, with potentialeffects on marine biodiversity. Management frameworks in the Arctic need to consider anthropogenic noise as a stressor alongside others when deciding the extent of activities permitted in these waters.

1. BACKGROUND AND INTRODUCTION

Anthropogenic noise in the marine environment has increased markedly over the last century as use of the oceans has expanded and diversified[1,2] although there is both spatial and temporal variation between oceans[3]. Technological advances in vessel propulsion and design, the development of marine industry and the increasing and more diverse use of the oceans have all resulted in a noisier underwater environment. Long-term measurements of ocean ambient sound indicate that low frequency anthropogenic noise has generally increased in certain areas over the last 50 years, which has been primarily attributed to noise from commercial shipping[4,5]. In coastal areas, the increase in the number of small vessels (mainly fishing and recreational boats) may also be a cause for localised concern where their sounds can dominate some coastal acoustic environments such as partially enclosed bays, harbours and estuaries[6].

Anthropogenic noise has gained global recognition as a major global pollutant[7] and a potentially important stressor for marine biodiversity. Initial concerns of the potential negative effects of anthropogenic noise on marine biodiversity were raised by the scientific community in the 1970s and research on the subject expanded in the 1980s[8]. The effects of sound on marine mammals have received particular attention, especially those from the military's use of active sonar, and industrial seismic surveys[9,10]. Extensive investigation mainly over the last decade by academia, industry, government agencies and international bodies has resulted in a number of reviews of the effects of sound on marine fauna (see Chapter 4 for references).

The issue of anthropogenic underwater sound and its effects on marine biodiversity has also received increasing attention at the international level, with recognition by a number of regional and international bodies. The Convention on the Conservation of Migratory Species of Wild Animals (CMS), the International Whaling Commission (IWC), the United Nations General Assembly (UNGA), the European Parliament and European Union, the International Union for Conservation of Nature (IUCN), the International Maritime Organization (IMO), the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, the Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), the Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) have all considered the negative effects of anthropogenic underwater noise through the adoption of resolutions or recognition of the issue for the marine environment.

The underwater world is subject to a wide array of man-made noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar[11]. Human activity in the marine

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[10] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp. 101-124

[11] Ibid.

environment is an important component of oceanic background sound[12] and can dominate parts of the acoustic spectrum of coastal waters and shallow seas. Although there is a continuum of sound characteristics, man-made noise can be broadly split into two main types: impulsive and non-impulsive sounds. Examples of impulsive sounds are those from explosions, airguns, navigation (depth-finding) sonar or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations. At certain distances from the source, lower frequency impulsive sounds can "smear" and become non-impulsive. The level of human activity and corresponding noise production in the marine environment is predicted to rise over the coming decades as maritime transportation and the exploration and extraction of marine resources continues to grow[13]. In combination with other stressors, underwater noise pollution may contribute to marine defaunation, which is predicted to increase as human use of the oceans industrialises[14].

Sound is extremely important to many marine animals enabling them to detect the 'acoustic scene'[15] and collect information about their environment. Sound plays a key role in communication, navigation, orientation, feeding and the detection of predators and hazards[16]. Almost all marine vertebrates rely to some extent on sound for these biological functions. Marine mammals use sound as a primary means for underwater communication and sensing. For example, underwater sound is important for Odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects[17], and is used in relation to feeding behaviour. However, the use of sound is also very important for a wide range of animals during all parts of their life-history stages.

Many other marine taxa also rely on sound on a regular basis, including teleost and non-teleost fishes and invertebrates such as decapod crustaceans. Fishes utilize sound for navigation and selection of habitat, mating, predator avoidance and prey detection and communication[18,19]. Although the study of invertebrate sound detection is still very limited, it is becoming clearer that many marine invertebrates are sensitive to sounds and related stimuli. However, the importance of sound for many marine taxa is still poorly understood and in need of considerable further investigation.

A variety of marine animals are known to be affected by anthropogenic noise. Negative effects for more than 100 marine species (cetaceans, teleost fishes, marine turtles and invertebrates) have been reported in scientific studies[20]. A wide range of effects of increased levels of sound on marine taxa have been documented both in laboratory and field conditions. The effects can range from mild behavioural responses to complete avoidance of the affected area, masking of important acoustic cues, and in some cases serious physical injury or death. Low levels of sound can be inconsequential for many marine animals. However, as sound levels increase, the elevated background noise can disrupt normal behaviour patterns potentially leading to less efficient feeding, for example. Masking of important acoustic signals or cues can interfere with communication between conspecifics[21] and may interfere with larval orientation, which could have implications for recruitment, although further research is required to verify the latter.

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Research is illuminating some of the less obvious effects of noise on aquatic animals (e.g., stress responses[22] [23] [24], communication masking[25] [26], cognitive bias, fear conditioning, and attention and distraction[27]), but we still have very restricted knowledge and understanding of how these effects could influence overall impacts on individuals, let alone populations. In addition, very little is known about potential cumulative effects on marine fauna or their recovery from such effects. Most of the existing mitigation measures are not thought to be very effective in reducing possible cumulative and synergistic impacts on marine fauna[28]. They also do not fully consider the exposure context of individuals and how a combination of acute and chronic noise can interact with animal condition to elicit a behavioural response[29], particularly in marine mammals.

Moreover, a behavioural response is not necessarily the most reliable measure of a population consequence, as harmful impacts may occur without any visible change in behaviour in some species and situations[30]. Animals do not always react in an observable or obvious manner even if they are seriously impacted. Individuals with lower energy reserves or no alternative habitat cannot afford to flee repeatedly from disturbance but are forced to remain and continue feeding, apparently unresponsive to disruption[31]. For example, sea lions (*Zalophus californianus*) have been reported to remain in a prime feeding area despite the presence of noise presumably loud enough to harm their hearing[32].

It is important to note that, a number of studies have also reported no effects of noise on certain marine taxa. The presence of an anthropogenic sound does not infer that an animal will be harmed or affected in a detrimental way. There are a wide range of sounds in the marine environment from both natural and anthropogenic sources. Some sounds can have negative effects whilst others will be neutral.

Although there have been major advances in the knowledge of the main types of anthropogenic sound in the ocean and the effects of these sounds on marine biodiversity over the last few decades there are still substantial gaps in our knowledge of underwater noise and the effects it may have on marine species and populations.

Underwater Noise and the Convention on Biological Diversity

The tenth meeting of the Conference of Parties (COP 10) to the Convention on Biological Diversity in Nagoya, Japan, in 2010 requested in decision X/29 (paragraph 12) that a scientific synthesis report is produced on the impacts of anthropogenic underwater noise on marine and coastal biodiversity[1]. This draft report was presented and finalised at the 16th meeting of the Subsidiary Body on Scientific,

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Technical and Technological Advice (SBSTTA 16) in Montreal in May 2012 and submitted as an information document[33] to COP 11 in Hyderabad in October 2012, with the kind financial support of the Government of Japan through the Japan Biodiversity Fund.

Noting the gaps and limitations in existing guidance, including the need to update it in the light of improving scientific knowledge, and recognizing a range of complementary initiatives underway, COP 11 requested, in decision XI/18, the Executive Secretary to collaborate with Parties, other Governments, and competent organizations, including the International Maritime Organization, the Convention on Migratory Species, the International Whaling Commission, indigenous and local communities and other relevant stakeholders, to organize an expert workshop with a view to improving and sharing knowledge on underwater noise and its impacts on marine and coastal biodiversity, and to develop practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals, in order to assist Parties and other Governments in applying management measures. Pursuant to the above request, the CBD Secretariat convened an expert workshop on underwater noise and its impacts on marine and coastal biodiversity at the International Maritime Organisation in London (25-27 February 2014), and the Executive Secretary invited Parties, other Governments and relevant organizations to provide relevant information concerning the objectives of the workshop, in particular regarding:

(i) The impacts of underwater noise on marine and coastal biodiversity; and

(ii) Practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals.

COP 11 also requested the Executive Secretary to make the report of the workshop available for consideration by a meeting of the CBD Subsidiary Body on Scientific, Technical and Technological Advice prior to the twelfth meeting of the Conference of the Parties (COP 12) in Pyeongchang, the Republic of Korea. A background information document was prepared in order to provide participants at the expert workshop with relevant up-to-date information that can contribute to the development of practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals.

In paragraph 2 of decision XIII/10, the Conference of the Parties to the CBD requested the Executive Secretary, subject to the availability of resources, to continue work on the compilation, synthesis and dissemination of these experiences, including scientific research on the adverse impacts of underwater noise on marine and coastal biodiversity, and, based on scientifically identified needs, to develop and share, in collaboration with Parties, other Governments and relevant organizations, practical guidance and toolkits on measures to avoid, minimize and mitigate these impacts, and to make this compilation available to the CBD Subsidiary Body on Scientific, Technical and Technological Advice. At its fourteenth meeting in 2018, the COP, in decision 14/10 took note of the work of the Executive Secretary, and requested the continuation of this work, on the compilation and synthesis of information related to the impacts of anthropogenic underwater noise on marine and coastal biodiversity, and means to avoid, minimize and mitigate these impacts. In the same decision, the COP also encouraged Parties, and invitee other Governments and relevant organizations to use th is information in their efforts to avoid, minimize and mitigate the impacts of anthropogenic underwater noise.

This document summarises the known and potential impacts of underwater noise on marine and coastal biodiversity and habitats, and is mainly based on the information presented in the 2012 scientific synthesis. In addition, any new pertinent information published since January 2012 regarding underwater noise impacts is included. The document also includes knowledge and guidance on the mitigation and management of anthropogenic underwater noise to minimise impacts on marine and coastal biodiversity, building on the background information document prepared for the CBD expert workshop held in London in 2014.

[33] UNEP/CBD/SBSTTA/16/INF/12

2. UNDERWATER SOUND: CHARACTERISTICS, RELEVANCE AND TRENDS

Overview of Underwater Sound

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids)[34]. Sound is created when particles in an elastic medium are displaced by an external force and oscillate. These oscillating particles will also set neighbouring particles in motion as the original disturbance travels through the medium. This oscillation can be slow or fast, producing what we perceive as low pitch sounds (slow oscillation) or high pitch sounds (fast oscillation). The concept of frequency is used to put values on these oscillations, which establish the oscillations per second that are produced in the particles. The units for measuring oscillations are hertz (Hz). Humans can hear frequencies between 20 Hz to 20 kHz (kilohertz), but the audible spectrum for marine mammals and other species can extend far beyond the human hearing range. Sounds outside the human hearing range are referred to as infrasound (below 20 Hz) and ultrasound (above 20 kHz). Particle motion refers to the vibrations of the molecules around an equilibrium state and can be quantified by measuring either velocity or acceleration of the particles. The total energy contained in a sound wave consists of the sum of its potential energy (PE) and its kinetic energy (KE). The PE arises from the compression and expansion of the fluid and hence is related to the sound pressure, whereas the KE arises from the particle motion[35].

Water is an excellent medium for sound transmission because of its high molecular density. Sound travels almost five times faster through sea water than through air (about 1500 vs. 300 m/s), and low frequencies can travel hundreds of kilometres in certain conditions[36]with little loss in energy[37], thereby enabling long distance communication, but also a long-distance effect of sound on aquatic animals[38]. Sound propagation is affected by three main factors: the frequency of the sound, water depth, and density differences within the water column, which vary with temperature and pressure. Therefore, the sound arriving at an animal is subject to propagation conditions that can be quite complex, which can in turn significantly affect the characteristics of arriving sound energy[39].

All sources of underwater sound are made up of both sound pressure and particle motion. The total energy contained in a sound wave is the sum of its potential energy (PE) and its kinetic energy (KE). When a sound is generated, KE is imparted to the medium (e.g., seawater) and in turn is passed on, travelling as a propagated elastic wave in which particles of the medium are move back and forth[40]. Particles transmit this oscillatory motion to neighbouring particles but do not travel with the sound, oscillating in the same location. Particles oscillate along the line of transmission and are accompanied by waves of compression (pressure increase) and rarefaction (pressure decrease), which is referred to as the sound pressure[41]. To help understand particle motion in comparison to sound pressure, please refer to the animation on the "Discovery of Sound in the Sea website[42]. There are international definitions for particle displacement, particle velocity or particle acceleration[43].

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[34] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[35] Popper, A.N. and Hawkins, A.D. 2018. The importance of particle motion to fishes and invertebrates. J. Acoust. Soc. Am. 143: 470-488.

[36] Possible in deeper water but in shallow water where the depth is less than the sound wavelength then low frequencies will attenuate very rapidly i.e. on shallow sloping coastlines or shallow bays

[37] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.

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[39] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[40] Ibid

[41] Ibid

[42]https://dosits.org/science/sound/what-is-sound/.

[43] ISO/DIS 2017. ISO 18405:2017, "Underwater acoustics—Terminology". International Organization for Standardization, Geneva, Switzerland.

Sound levels or sound pressure levels (SPL) are referred to in decibels (dB). However, the dB is not an absolute unit with a physical dimension, but is instead a relative measure of sound pressure with the lower limit of human hearing corresponding to 0 dB in air. Underwater dB-levels are different from above water dB-levels[44]. Sound pressure levels above water are referenced to 20 µPa, while underwater they are referenced to 1 µPa[45]. There are different measurements and units to quantify the amplitude and energy of the sound pressure level[46] [47], which are also defined in internationally accepted ISO standards[48]:

- The **spectrum** of a sound, provides information on the distribution of the energy contained in the signal or the 'frequency content' of a sound. The term bandwidth describes the frequency range of sound. A normalised bandwidth of 1 Hz is standard practice in mathematical analysis of sound, while 1/3 octave bandwidths are most common in physical analysis. Spectra therefore need some indication of the analysis bandwidth;
- **Peak-to-peak sound pressure** ($p_{\text{pk-pk}}$) is the sum of the peak compressional pressure and the peak rarefactional pressure during a specified time interval, for a specified frequency range[49]. In other words, it is the difference of pressure between the maximum positive pressure and the maximum negative pressure in a sound wave. Positive and negative peak pressures can have different effects resulting in compression or expansion / cavitation respectively. Peak-to-peak SPLs are expressed in pascals (Pa) and are usually used to describe short, high intensity (impulsive) sounds;
- The **root-mean-square** sound pressure (RMS) value is calculated as the square-root of the mean-squared pressure of the waveform. RMS sound values can change significantly depending on the time duration of the analysis. The values of a continuous signal measured in RMS or in peak value usually differ by 10-12 dB. RMS with a reference value of 1 µPa is interchangeable with the term mean-square sound pressure with a reference value of 1 μPa^2;
- **Impulse** is the time integral of pressure through the waveform expressed in Pa S or can also be defined as the sum of the pressure over the duration of the sound wave. As neither RMS or peak levels are sufficient for describing the total energy or temporal characteristics of single impulsive sounds[50] (e.g., from explosions, pile driving or seismic airguns), the impulse can better describe the energy from these types of anthropogenic sounds;
- The **Sound Exposure Level** (SEL) is another important metric and can be defined as the time integral of the pressure squared for a sound event, which is an index of the total energy in a sound[51] and depends on both amplitude and duration. SELs are considered useful when making predictions about the exposure risk and potential impact ofpulses and transient sounds but are less useful for longer exposure durations. The SEL metric can also be used to combine the sound energy across multiple exposures from sources such as pile driving, seismic airguns and most type of sonar[52]. Further definitions have been made for types of SEL:

[44] Finfer, D.C. et al. (2008) Issues relating to the use of 61.5 conversion factor when comparing airborne and underwater anthropogenic noise levels. Appl. Acoust. 69, 464–471
[45] micro-Pascal or one millionth of one Pascal (1 Pascal is equal to the force of 1 Newton applied uniformly over the surface of 1 square metre and is abbreviated 1 Pa)
[46] Richardson, W.J., Malme, C.I., Green, C.R. jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp.
[47] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).
[48] ISO 18405:2017 Underwater Acoustics – Terminology (https://www.iso.org/obp/ui/#iso:std:iso:18405:ed-1:v1:en)
[49] Ibid
[50] Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., Ellison, W. T., Gentry, R. L., Halvorsen, M. B., Lokkeborg, S., Rogers, P. H., Southall, B., Zeddies, D. & Tavolga, W. A. 2014. ASA S3/SC1. 4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. New York: Springer.
[51] Ibid
[52] Ibid

- Sound Exposure Level – single strike (SEL_{SS}) – an index of energy used in pile driving studies for when the pile is struck once
- Cumulative Sound Exposure Level (SEL_{cum}) – an index of total energy over the duration of a sound-making activity.

If the SEL_{SS} is approximately the same for all events, then the SEL_{cum} can be estimated as SEL_{ss} +10log 10 (N), where N is the number of impulsive events[53]. The period over which the SEL_{cum} is accumulated must be carefully specified.

- **Transmission loss** refers to the loss of acoustic power with increasing distance from the sound source. Sound pressure diminishes over distance due to the absorption and geometrical spreading of waves. In an ideal scenario, without reflections or obstacles, the sound pressure diminishes by a factor of 1 over the considered distance (1/r, where r = radius from the source). In realistic scenarios, due to differing layers of water, the propagation of sound and its attenuation may be very different. For example, the reduction of sound pressure could diminish if the sound is channelled due to seabed topography and/or water column stratification. The effects of topography and the characteristics of the water column can induce very complex situations[54], which should be taken into account when predicting sound impacts. Absorption losses are negligible for low frequencies (<1 kHz) but can be significant for high frequencies;
- **Source Levels** (SL) describe the level of sound pressure referred to the nominal distance of 1 metre from the source[55].
- **Rise time** is the time from the start of a sound to its peak pressure, in milliseconds, or the rate of increase to this peak pressure (decibels/second).
- **Duty cycle** is the proportion of time that the sound is 'on', for example, a sound consisting of one 300 ms long pulse every second has a 30% duty cycle.

There is now scientific consensus, through the ISO, regarding the means to express sound levels in marine acoustics[56]. All values are expressed in the same values (points) of reference and averaged in the same time intervals for all measures allowing comparison between measurements. RMS values are useful for relatively long sounds but less effective for brief sounds such as pile-driving strikes and echolocation clicks of whales[57]. Peak-to-peak values in the amplitude waveform provide an alternative measure, but comparisons between peak-to-peak and RMS levels are difficult[58]. Impulse and SEL values provide a better measure of the total energy or temporal characteristics of impulsive sounds than RMS or peak values.

It is also important to define the terms 'sound', 'noise' and 'signal'. Sound is an allusive term for any acoustic energy. Noise is a type of unwanted sound for the receiver that interferes with the detection of other sounds of interest[59]. The opposite of noise is a signal; i.e., a sound that contains some useful or desirable information. A particular sound can therefore be noise to one receiver and a signal to others[60]. Noise is also used in some cases to describe background levels of sound in the sea, including the naturally occurring and spatially uniform sounds generated by various biological sources, weather

[53] Ibid

[54] Bain, D.E. & Williams, R. 2006: Long-range effects of airgun noise on marine mammals: Responses as a function of received sound level and distance. – IWCSC/ 58E35.

[55] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.

[56] ISO 18405:2017 Underwater Acoustics – Terminology

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events, and/or physical phenomena that cannot be entirely assigned to individual sources[61]. Underwater sound is comprised of three components[62]:

- Geophony – sounds produced by the physical environment (e.g., wind, waves, tidal actions, ice, lightning strikes, earthquakes);
- Biophony – sounds produced by non- human organisms (e.g., fishes, marine mammals, invertebrates); and
- Anthrophony – sounds that result from human activity (or produced by humans)

In addition, a 'soundscape' has been defined as the 'collection of biological, geophysical and anthropogenic sounds that emanate from a landscape and which vary over space and time reflecting important ecosystem processes and human activities'[63]. However, in the marine context, it is the collection of sounds in an underwater landscape or 'seascape'.

Natural Underwater Sound

There are a range of natural sound sources in the marine environment which can be of physical or biological origin. Natural physical phenomena that contribute to underwater ambient sound include wind, waves, and swell patterns; bubbles; currents and turbulence; earthquakes and sub-sea volcanic eruptions; lightning strikes; precipitation and ice cover and activity (movement of ice sheets or icebergs that cause the release of energy as sound)[64]. Wind-driven waves are the dominant natural physical noise source in the marine environment. In the absence of anthropogenic and biological sound, ambient noise is wind dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz[65]. In the open ocean, underwater noise levels can be increased by more than 20 dB (10 Hz to 10 kHz band) by spilling and plunging breakers[66], while precipitation can raise ambient noise levels by up to 35 dB across a broad band of frequencies (100 Hz to more than 20 kHz)[67]. Closer to shore, sounds from pack ice cracking may increase underwater noise levels by as much as 30 dB. Seismic waves from undersea earthquakes can be up to 30–40 dB above ambient noise levels, with a sharp onset, and can last from a few seconds to several minutes[68].

Marine mammals (cetaceans and pinnipeds) produce sounds that are used for communication, orientation and navigation, and foraging. Sounds range from the 10 Hz low-frequency calls of blue whales to the ultrasonic clicks of more than 200 kHz in certain offshore dolphins[69]. Source levels of click sounds used by sperm whales in navigation and foraging can be as high as 235 dB re 1μPa peak-to-peak[70]. Baleen whales are thought to use low frequency sound for long distance communication[71]

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over hundreds of kilometres[72][73]. Most toothed whales (odontocetes) emit three main types of sounds; tonal whistles, short duration pulsed sounds used for echolocation and less distinct pulsed sounds such as cries, grunts or barks[74]. Odontocete echolocation clicks are highly directional forward-projecting pulsed sounds of high intensity and frequency. Some species of seal produce strong underwater sounds that may propagate for great distances[75]. Many marine fish species produce sound for communication[76]. The low frequency sounds created by fishes can make a significant contribution to ambient sound[77]. Fishes can produce sounds as individuals, but also in choruses[78] and the increase in low-frequency sound can be as much as 20 - 30 dB in the presence of chorusing fishes[79]. The dominant source of ambient sound in tropical and sub-tropical waters is snapping shrimp, which can increase ambient levels by 20 dB in the mid-frequency band[80]. In addition to shrimp, a number of other invertebrates contribute to ambient reef sound, including squid[81], crabs[82], lobsters[83] and urchins[84], with the latter producing dawn and dusk choruses of feeding sounds which are amplified by their skeletons.

The Importance of Sound for Marine Organisms

Sound is an important sensory modality for many marine animals[85]. The distinctive properties of underwater sound mentioned previously and the limitations of other senses, such as vision, touch, taste and smell in the marine environment in terms of range and speed of signal transmission, mean that sound is the preferential sensory medium for a large proportion of marine animals. Underwater sound around marine species can be called their "soundscape" and provides animals with sensory information about the surrounding marine environment in three dimensions. Almost all marine vertebrates rely on sound for a wide range of biological functions, including the detection of predators and prey, communication and navigation[86][87]. Sound is particularly important as it provides information from distances well beyond visual ranges. The ability to use information about the soundscape also requires that an organism is able to discriminate among acoustic signals, determine the location of the sound source (localisation), and perceive biologically important sounds in the presence of 'masking sounds'. Although communication among organisms is an important use of sound, detection of the overall soundscape is of great importance. Disrupting the ability to hear and use the soundscape has the

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potential to affect the fitness and survival of an individual. If a sufficient number of individuals or significant parts of their habitat are affected, then adverse effects could occur at the population scale.

A range of marine taxa, including marine mammals, many fishes and some invertebrates have developed special organs and mechanisms for detecting and emitting underwater sound. To maximise the use of the underwater acoustic environment, marine mammals have developed broader hearing frequency ranges than are typically found in terrestrial mammals[88]. Marine fishes possess two sensory systems for acoustic and water motion detection; the inner ear and the lateral line system. Marine fauna utilise and hear underwater sound in different ways[89]. While the ears of mammals primarily sense pressure changes, the sensory systems of fishes and invertebrates can also sense movement of particles directly[90] [91]. Baleen whales, most fishes, sea turtles, and invertebrates hear best at lower frequencies, while the dolphins and porpoises, those species that have been studied, can hear ultrasonic frequencies above human hearing range[92] [93] [94] [95] [96].

Marine mammals use sound as a primary means for underwater communication and sensing[97]. They can emit sound to communicate about the presence of danger, food, a conspecific or other animal, and also about their own position, identity, and reproductive or territorial status[98]. Underwater sound is especially important for odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects[99], for example, in relation to coordinated movement between conspecifics and feeding behaviour.

Marine turtles likely use sound for navigation, locating prey, avoiding predators and environmental awareness[100]. Fishes utilize sound for navigation and selection of habitat, mating, predator avoidance and prey detection and communication[101]. Impeding the ability of fishes to hear biologically relevant sounds might interfere with these critical functions and use of the 'acoustic scene' or 'soundscape'[102] to learn about the overall environment[103]. Larval stages of coral reef fishes can detect and are attracted

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to the sound of coral reefs thereby using reef noise as an acoustic cue for orientation[104]. Although the study of invertebrate sound detection is still rather limited, many species have mechano-sensors that have some resemblance to vertebrate ears[105] and, based on the information available, it is becoming clear that many marine invertebrates are sensitive to sounds and related stimuli[106]. This has been demonstrated in tropical waters where crustacean and coral larvae can respond to acoustic cues (reef noise)[107 108]. Research is also showing that different shallow coastal habitats can be characterised by the acoustic signals that they produce[109] and that juvenile fishes can use these signals to detect different habitats in coral reefs[110]. Settlement-stage coastal crab species and oyster larvae are also able to interpret and show strong settlement responses to habitat-related differences in natural underwater sound[111 112]

The Increase in Anthropogenic Underwater Sound

Over the past one hundred years, there has been an unprecedented increase in the amount of anthropogenic noise emitted within the marine environment[113]. During this time, the oceans have become more industrialised and noise levels associated with human activities have increased[114]. Greater shipping density in the northern hemisphere was thought to explain why ambient noise at some sites in the southern hemisphere may be 20 dB less than the northern hemisphere average[115]. Long-term measurements of ocean ambient sound have revealed that low frequency anthropogenic noise has been increasing in the North Pacific (Figure 1) and Indian Oceans and has been primarily attributed to commercial shipping noise[116 117 118]. Combining this information with data from other studies[119], it has been suggested that, globally, low frequency ambient noise has increased by at least 20 dB from pre-industrial conditions to 2009[120], although the rate of increase has slowed in some regions in the last decade[121] and a decrease in low frequency ambient sound has been reported in some areas[122]. Over the

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[122] Miksis-Olds, J.L. and Nichols, S.M. 2016. Is low frequency ocean sound increasing globally? J. Acoust. Soc. Am. 139: 501-511

past 50 years, the global commercial shipping fleet has almost tripled, while the total gross tonnage has increased by a factor of six[123]. The world commercial fleet has doubled since 2001 and reached 1.63 billion dead-weight tons by January 2013[124]. The volume of cargo transported by sea has been approximately doubling every 20 years[125]. As well as an increase in commercial shipping, the last half century has also seen an expansion of many industrial activities in the marine environment.

In coastal areas, the increase in the number of small vessels is also a cause for localised concern where they can dominate some coastal acoustic environments such as partially enclosed bays, harbours and estuaries[126]. The vast majority of these vessels also use high-frequency sonar for navigation and fish-finding. The use of mid and low frequency active sonar during military exercises has expanded since their introduction in the 1960's and 1980's respectively.

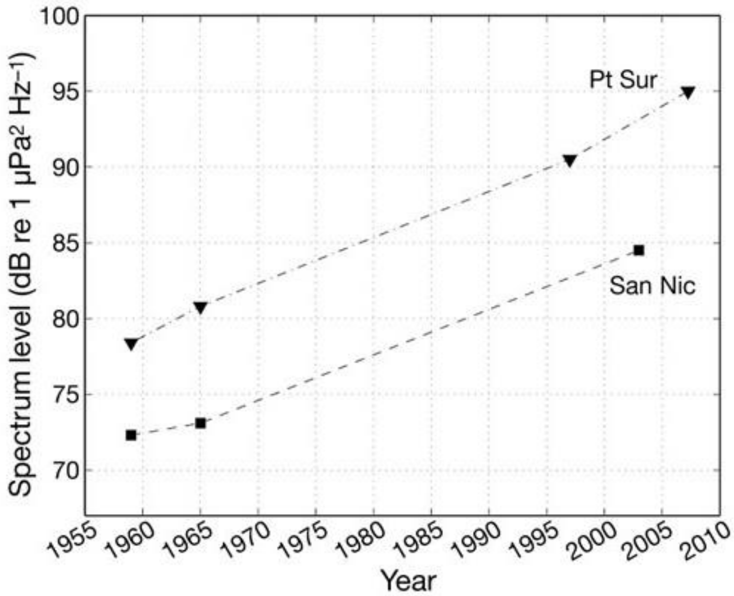

Figure 1. Historical ambient noise data from the North-eastern Pacific at 40 Hz suggest an increase of about 3 dB decade^{-1} averaged over the past 40 years. Data from the United States Navy hydrophone arrays near Point Sur and San Nicolas Island[127, 128, 129] and from recent measurements at these sites[130, 131, 132] (Adapted from Hildebrand, 2009)

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3. SOURCES AND TYPES OF UNDERWATER ANTHROPOGENIC NOISE

Human activity in the marine environment is a prominent component of oceanic background sound[133] and can dominate the acoustic properties of some coastal waters and shallow seas. Human activities introduce sound into the marine environment either intentionally for a specific purpose (e.g., seismic surveys using air guns for deep sub-bottom imaging of geological structures) or unintentionally as a by-product of their activities (e.g., shipping or construction)[134]. The main sources of anthropogenic sound in the marine environment and their acoustic properties are provided in Table 1.

At the source, anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds[135]. Impulsive sound sources are typically brief, have a rapid rise time (large change in amplitude over a short time), and contain a wide frequency range, which is commonly referred to as broadband[136]. Impulsive sounds can either be a single event or are repetitive and sometimes as a complex pattern. Non-impulsive signals can be broadband or more tonal (containing one or few frequencies), brief or prolonged, continuous or intermittent, and do not have the rapid rise time (typically only small fluctuations in amplitude) characteristic of impulsive signals[137]. Examples of impulsive sounds are those from explosions, air guns, or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations. There have been a number of reviews of the physics associated with the various sound sources[138] [139] and also of the acoustic and other characteristics of each source[140] [141] [142]. A summary of each type of anthropogenic sound source is presented below.

Explosives

Explosives are used for several purposes in the marine environment including construction, the removal of unwanted structures, ship shock trials, military warfare or practise, and small charges to deter marine mammals (seal bombs), catch fish (blast fishing) or for coral mining[143]. Underwater explosions are one of the strongest point sources of anthropogenic sound in the marine environment. For example, the large amount of explosives used in naval ship shock trials can produce a total Source Level (SL) of more than 300 dB (Table 1). Sound from explosions propagates equally in all directions and can be detected over great distances, sometimes across ocean basins. Underwater transmission of explosions is complex with an initial shock pulse followed by a succession of oscillating bubble pulses. Source levels can vary with the type and amount of explosives used and the water depth at which the explosion occurs, and usually range from 272 to 287 dB re 1 μPa zero to peak at 1 m distance (1 - 100 lb. TNT)[144].

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[143] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[144] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

Table 1. Main Sources of Anthropogenic Sound in the Marine Environment
(Adapted from Hildebrand 2009[145]; OSPAR 2009[146]; Rako-Gospić and Picciulin 2019[147])

Sound Source	SL (dB re 1 μPa-m)	Bandwidth (Hz)	Duration (ms)	Directionality	Source Material
Impulsive Anthropogenic Sound					
TNT (0.5 kg)	267	Broadband	1 - 10	Omni	Hildebrand (2009); Richardson et al. (1995)[148]
Seismic airgun array	260	5 – 300	30 - 60	Vertical	Hildebrand (2009); Popper and Hastings (2009)[149]
Military sonar mid-frequency	235	2000 – 10,000	2000	Horizontal	Hildebrand (2009); ICES (2005)[150]; Wiggins (2015)[151]
Pile driving (1000 kj hammer)	237	20 - >20 000	50	Omni	Hildebrand (2009);
Military sonar low-frequency	235	100 - 500	600 - 1000	Horizontal	Hildebrand (2009); ICES (2005); Prideaux (2016)[152]
Sonar high frequency	190	>10,000	variable	Vertical	Hildebrand (2009); Popper and Hastings (2009)
Sounder - multibeam shallow water	232	70,000 – 100,000	1	Vertical	Hildebrand (2009)
Sounder – multibeam deep water	220	> 11,500	24	Vertical	Boebel et al. (2004)[153]
Single beam sounder (shallow waters)	240	200,000 – 700,000	1	Vertical	Lurton (2010)[154]
Single beam sounder (deep waters)	240	12,000	0.1	Vertical	Lurton (2010)
Side scan sonar	220-230	50,000 – 500,000	0.1	Vertical	Richardson et al. (1995)
ADDs	130 – 150	5000 – 160,000	Variable 100 – 900	Omni	Hildebrand (2009); Shapiro et al. (2009)[155]; Tasker et al. (2010)[156]

[145] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
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[156] Tasker, M.L. et al. 2010. Marine Strategy Framework Directive. Task Group 11 Report: Underwater Noise and other forms of energy. JRC & DG ENV Joint Report. 55 pp. Doi: 10.2788/87079

AHDs	195	5000 – 40,000	500 - 2000	Omni	OSPAR (2009); Petras (2003)[157]; Tasker et al. (2010)
Continuous Anthropogenic Sound					
Container ship, 294 m, speed 10.6 m/s, gross tonnage 54,600	185	20 - 1000	CW	80˚ X 180˚	McKenna et al. (2012)[158]; Hildebrand (2009)
Speed boat (5.5 m length, at 20 kts)	160	1- 5 kHz	CW	80˚ X 180˚	Kipple and Gabriele (2004)[159]; Hildebrand (2009
Marine dredging at 1 m depth	160 – 180	broadband	CW	Omni	Hildebrand (2009); Prideaux (2016)
Offshore drilling (drill ship) at 1 m depth	190	10 – 10 000	CW	Omni	Hildebrand (2009); Prideaux (2016); Richardson et al (1995)
Acoustic telemetry SIMRAD HTL 300	190	25000 – 26500	CW	90° x 360°	Hildebrand (2009);
Wind turbine	123 - 142	16 – 1250	CW	Omni	ITAP, 2005 in Thomsen et al. (2006)[160]
Tidal and wave energy*	165 – 175	10 – 50 000	CW	Omni	OSPAR (2009)

Where: Omni = omnidirectional; CW = Continuous Wave; ADD = Acoustic Deterrent Device; AHD = Acoustic Harassment Device; * = Projection based on literature data levels back-calculated at 1 m

Industrial Activities

Industrial activities include pile driving, dredging, cable laying, drilling, the construction and operation of offshore wind farms and hydrocarbon production facilities[161]. These activities typically produce noise that has the most energy at low frequencies (20 – 1000 Hz)[162].

Pile driving is used for harbour works, bridge construction, oil and gas platform installations, and in the construction of offshore wind farm foundations. The noise produced enters the water column directly but also travels through the seabed, with sound propagation varying according to the type of seabed[163]. Source levels can vary depending on the diameter of the pile and the method of pile driving (impact or vibropiling) and can reach 250 dB re 1 µPa peak to peak at 1m[164]. The frequency spectrum ranges from less than 20 Hz to more than 20 kHz with most energy around 100 - 200 Hz (Table 1).

Drilling is done from natural or man-made islands, platforms, and drilling vessels (semi-submersibles and drilling ships), producing almost continuous noise. Underwater noise levels from natural or

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manmade islands have been reported to be moderate (SL ~ 145 dB re 1 μPa at 1 m or less)[165] with the main frequency content below 100 Hz[166]. Noise from fixed drilling platforms is slightly lower; e.g., 115 - 117 dB re 1 μPa at 405 and 125 metres respectively[167]. Drilling from drill-ships produces the highest levels with a maximum broadband source level of about 190 dB re 1 μPa rms at 1 m (10 Hz - 10 kHz)[168]. The ships use thrusters to remain in position, resulting in a mixture of propeller and drilling noise[169].

Dredging in the marine environment is undertaken to maintain shipping lanes, extract geological resources such as sand and gravel and to route seafloor pipelines. The activity emits continuous broadband sound during operations, mostly in the lower frequencies. One study estimated source levels ranged from 160 to 180 dB re 1 μPa at 1 m (maximum ~ 100 Hz) with a bandwidth between 20 Hz and 1 kHz[170]. Measurements of the sound spectrum levels emitted by an aggregate dredger show that most energy was below 500 Hz[171].

Mining operations will increase underwater ambient noise for taxa in the deep sea[172]. Sound will be emanated from support vessels on the sea surface and from machinery on the sea bed such as remotely operated vehicles[173]. Some operations are planned to operate on a non-stop basis, which will substantially increase ambient sound levels[174], but actual noise characteristics of the mining equipment in operation at depth are not known[175].

Offshore wind farms create low-frequency noise at high source levels during their construction (e.g., pile driving), but at low source levels during their operation[176]. Operational source levels of offshore wind farms depend on construction type, size, environmental conditions (i.e., depth, topography, sediment structure, hydrography), wind speed, and probably also the size of the wind farm[177]. Noise produced during operations has been measured from single turbines (maximum power 2 MW) by studies between 1994 and 2004[178]. Most of the sound generated was pure tones below 1 kHz, and mainly below 700Hz[179]. Data collected from Utgrunden, Sweden in 2005 revealed that operational sounds of an offshore turbine (1.5 MW) in shallow (5-10 m) waters at moderate to strong wind speeds of 12 m s^{-1} were sound pressure levels between 90 and 112 dB re 1 μPa at 110 m with most energy at

[165] The term moderate refers to an intermediate level of noise based on the range summarised in Table 1 and is quoted in the main review citations such as Richardson et al (1995) below.
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50, 160 and 200 Hz[180]. More recent measurements on four offshore wind farms around the UK in 2005 and 2007 (2 - 3 MW) confirmed rather low broadband received sound pressure levels (114 - 130 dB re 1 μPa) inside wind farm areas with a maximum difference in SPL to outside the wind farm of 8 dB re 1 μPa[181]. The highest source level reported for the tonal noise component during turbine operation is 151 dB re 1 μPa at 1 m, for a wind speed of 13 m s^{-1}, and at a frequency of 180 Hz[182]. Noise is also generated by maintenance (including vessels) and repair work.

Offshore tidal and wave energy turbines are a relatively recent technological development and there is currently limited information available on the acoustic signatures of these activities. Tidal turbines appear to emit broadband noise covering a frequency range from 10 Hz up to 50 kHz with significant narrow band peaks in the spectrum[183]. Depending on size, it is likely that tidal current turbines will produce broadband source levels of between 165 and 175 dB re 1μ Pa[184].

It is important to mention in this section both particle motion and vibration in the context of sources of anthropogenic sound. Marine mammals and many bony fishes are sensitive to sound pressure, while all fishes (bony and cartilagenous) and invertebrates are sensitive to particle motion[185]. Many industrial sources of anthropogenic sound also likely cause vibration within the seabed by direct means (e.g., contact with the sediment) or indirectly (propagation via the water column)[186]. Activities such as dredging, pile driving and drilling on the seabed all directly add to the level of vibration, while other marine-based activities operating in the water column (e.g., shipping, seismic surveys and sonar) have the potential to add vibration indirectly through propagation. For an explanation of how sound moves through seabed substrata and also the interface between the water column and the substrate, please refer to Popper and Hawkins (2018)[187]. Given the prevalence of seabed vibration producing activities, it is thought likely that many species are exposed to a stimulus that may cause damage or a physiological or behavioural change, as seen with acoustic stimuli[188].

Seismic Exploration

Marine seismic surveys are primarily used by the oil and gas industry for exploration, but are also used for other types of research purposes. There are >90 seismic vessels available globally[189], and roughly 20% of them are conducting field operations at any one time[190].

Essentially, a seismic or seabed survey involves directing a high energy sound pulse into the sea floor and measuring the pattern of reflected sound waves. A range of sound sources may be used depending on, amongst other things, the depth of penetration required. These include: air guns, 'sparkers',

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'boomers', 'pingers' and 'chirp sonar'[191]. The main sound-producing elements used in oil exploration are air-gun arrays, which are towed from marine vessels[192]. Air guns release a volume of air under high pressure, creating a sound wave from the expansion and contraction of the released air bubble[193]. To yield high acoustic intensities, multiple air guns (typically 12 to 48) are fired with precise timing to produce a coherent pulse of sound. During a survey, guns are fired at regular intervals (e.g., every 10 to 15 seconds), as the towing source vessel moves ahead. Seismic air guns generate low frequency sound pulses below 250 Hz, with the strongest energy in the range 10-120 Hz and peak energy between 30 to 50 Hz. Air guns also release low amplitude high-frequency sound, and acoustic energy has been measured up to 100 kHz[194]. The low frequency energy (10 to 120 Hz) is mainly focused vertically downwards, but higher frequency components are also radiated in horizontal directions.

The power of air-gun arrays has generally increased during the past decades, as oil and gas exploration has moved into deeper waters. The nominal source level of an air-gun array can reach up to 260-262 dB (p-p) re 1 μPa @ 1m[195]. Sound signals from seismic air-gun surveys can be received thousands of kilometres away from the source if spread in a sound channel. Autonomous acoustic seafloor recording systems on the central mid-Atlantic Ridge showed year-round recordings of air-gun pulses from seismic surveys conducted more than 3000 km away[196]. Low-frequency energy can also travel long distances through bottom sediments, re-entering the water far from the source[197].

Sparkers and boomers are high-frequency devices that are generally used to determine shallow features in sediments. These devices may also be towed behind a survey vessel, with their signals penetrating several hundred (sparker) or tens (boomer) of metres of sediments due to their relatively higher frequency spectrum and lower transmitted power. Typical source levels can be 204 - 210 dB (rms) re 1 μPa @ 1 m[198]. Chirp sonars also produce sound in the upper frequency range of seismic devices (approx. 0.5 to 12 kHz). The peak source level for these devices is about 210 – 230 dB re 1 μPa @ 1 m[199].

Sonar

The use of acoustic energy for locating and surveying is described as active sonar. Sonar was the first anthropogenic sound to be deliberately introduced into the oceans on a wide scale. There are a variety of types of sonars that are used for both civilian and military purposes. They can occur across all sound frequencies and are divided in this section into low (<1 kHz), mid (1 to 10 kHz) and high frequency (>10 kHz). Military sonars use all frequencies while civilian sonar uses some mid but mostly high frequencies. With the exception of military sonar, most types of sonar operate at one frequency of sound, but generate other unwanted frequencies (e.g., harmonics of the fundamental frequency due to non-linear processes). These extraneous lower intensity frequencies are rarely described in detail but are thought to possibly have wider effects than the main frequency used, especially if they are at low frequencies which propagate further underwater[200]. However, this is not proven at the time of writing.

Low-frequency sonar

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[199] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[200] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

Low-frequency active (LFA) sonars are used for broad-scale military surveillance, designed to provide the sound source over scales of hundreds of kilometres for other passive listening platforms to detect submarines[201]. Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. For example, the United States Navy's Surveillance Towed Array Sensor System (SURTASS) LFA sonar uses an array of up to 18 projectors operating in the frequency range from 100 to 500 Hz, with a 215 dB re 1 μPa @ 1 m source level for each projector[202]. These systems are designed to project beams of energy in a horizontal direction, with a vertical beam width that can be steered above or below the horizontal. The effective source level of an LFA array can be 235 dB re 1 μPa @ 1 m or higher[203]. The signal includes both constant-frequency (CF) and frequency-modulated (FM) components with bandwidths of approximately 30 Hz[204]. A ping sequence can last 6 to 100 seconds, with a time between pings of 6 to 15 minutes and a typical duty cycle of 10%. Signal transmissions are emitted in patterned sequences that may last for days or weeks. In 2009, there were 2 LFA source ships operated by the U.S. military, with a proposed expansion to 4 ships in 2011[205]. As of September 2018 there were four ships operating LFA sonar systems in the U.S. military; one with the original LFA system and three vessels with the compact LFA system (CLFA)[206].

Mid-frequency sonar

Military mid-frequency sonars at high source levels are used for detecting submarines at moderate range (<10 km). There are about 300 mid-frequency sonars in active service in the world's navies[207]. For example, a US Navy hull-mounted system (AN/SQS-53C) sonar system uses pulses in the 2 – 10 kHz range (normally 3.5 kHz) and can operate at source levels of 235 dB re 1 μPa @ 1m. Another US Navy system (AN/SQS-56) uses this same frequency band but with lower source levels (223 dB re 1 μPa @ 1m)[208]. These systems were formerly used mainly in offshore waters, but now also scan shallower inshore environments to detect submarines that are able to operate closer to shore[209].

Some non-military sonars also operate in the mid-frequency band. Bathymetric sonars use these frequencies for wide-area, low resolution surveys. For example, the Fugro Seafloor survey model SYS09 uses both 9 and 10 kHz transducers operated at 230 dB re 1 μPa at 1m[210]. Sub-bottom profilers produce a mid-frequency (3 to 7 kHz) and high source level (230 dB re 1 μPa at 1 m) pulse, to map seafloor sediment layers and buried objects[211].

High-frequency sonar

Military high-frequency sonars are used in attacking or defending systems and are designed to work over hundreds of metres to a few kilometres[212]. These sonars use a wide range of modes, signal types and strengths. As with other military sonars, their reported usage is generally within exercise areas but they are also used outside of these areas. Scanning sonars and synthetic aperture sonars are used for

[201] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[202] Anonymous (2007) Final supplemental environmental impact statement for surveillance towed array sensor system low frequency active (SURTASS LFA) sonar, Vols 1 and 2. Department of the Navy, Chief of Naval Operations, Arlington, VA
[203] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy. Available at: www.nmfs.noaa.gov/prof_res/overview/Interim_BahamasReport.pdf
[204] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[205] DoN (Department of the Navy) (2009) Notice of intent to prepare a Supplemental Environmental Impact Statement/ Supplemental Overseas Environmental Impact Statement for employment of surveillance Towed Array Sensor System Low Frequency Acrive (SURTASS LFA) sonar. Federal Register 74(12):3574–3575 (microfiche) – in Hildebrand 2009
[206] http://www.surtass-lfa-eis.com/systems-description/
[207] Watts AJ (2003) Jane's underwater warfare systems, 15th edn. IHS Jane's, Berkshire, UK
[208] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy. Available at: www.nmfs.noaa.gov/prof_res/overview/Interim_BahamasReport.pdf
[209] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[210] Ibid
[211] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[212] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

harbour defence, underwater search and recovery[213] and high intensity seabed mapping (side-scan sonar). Frequencies between 85 and 100 kHz are used for human diver/swimmer detection, while 100 kHz is optimal for obtaining a high resolution of seabed features including benthic cover. Hydroacoustic sonars are used to detect the presence of living organisms and particles in oceans, lakes, and rivers[214]. By transmitting sound at high frequencies (20 to 1000 kHz), hydroacoustic sonars can detect individual objects or aggregates, such as schools of fishes, in the water column[215].

Civilian and commercial sonars operating at high frequencies are used for detection, localization, and classification of various underwater targets (e.g., the seabed, plankton, fishes, divers)[216]. These sonars generally produce sound at lower source levels with narrower beam patterns and shorter pulse lengths than military sonars, but are more widespread due to the large number of commercial and recreational vessels that are equipped with sonar[217]. Such vessels operate mostly in shallow shelf-seas and sonar usage occurs continuously throughout the year and at both day and night. Most of the systems focus sound downwards, though some horizontal fish finders are available. Fish finding sonars operate at frequencies typically between 24 and 200 kHz, which is within the hearing frequencies of some marine mammals, but above that of most fishes[218] (Figure 2). Some horizontally-acting fish finding sonars are thought to be relatively powerful. For example, the Furuno FSV-24 sonar operates at 24 kHz and can detect and track shoals of tuna up to 5 km away[219]. Bathymetric mapping sonars use frequencies ranging from 12 kHz for deep-water systems to 70-100 kHz for shallow water mapping systems[220]. Multibeam sonars operate at high source levels (e.g., 245 dB re 1 μPa at 1 m) but have highly directional beams[221].

[213] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[214] Simmonds EJ, MacLennan DN (2005) Fisheries acoustics: theory and practice. Blackwell Publishing, London
[215] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[216] Ibid
[217] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp
[218] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[219] Ibid
[220] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[221] Ibid

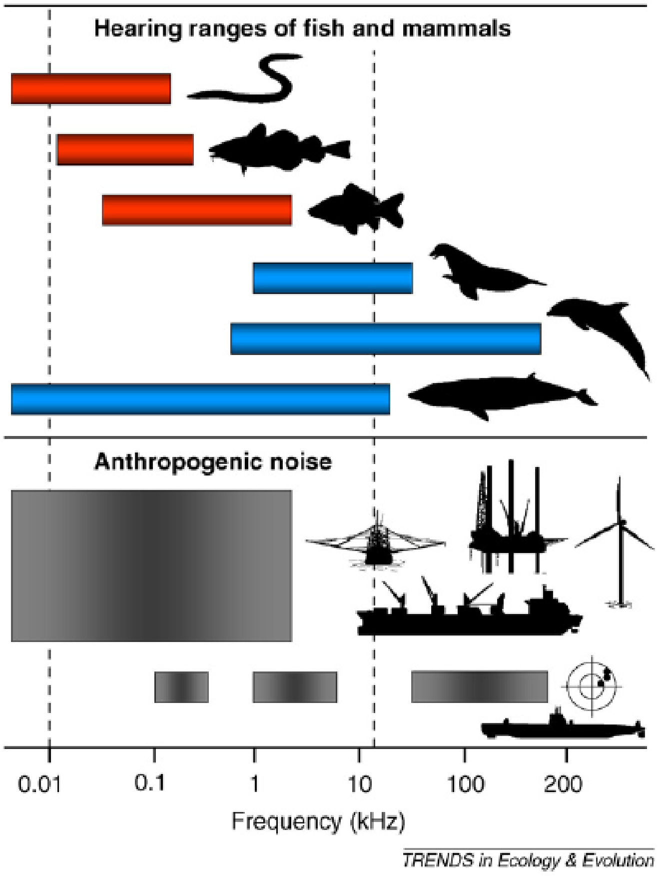

Figure 2. **The main frequencies of anthropogenic noise sources and the hearing ranges of marine mammals and fishes (from Slabbekorn et al., 2010)**

Ships and Smaller Vessels

Large commercial vessels (length greater than 100m; e.g., container/cargo ships, super-tankers, cruise liners)

Large commercial vessels produce relatively loud and predominately low-frequency sounds. Source levels are generally in the 180 - 195 dB (re: 1μPa) range with peak levels in the 10 – 50 Hz frequency band[222] [223] [224]. The propulsion systems of large commercial ships are a dominant source of radiated underwater noise at frequencies <200 Hz[225]. Individual vessels produce unique acoustic signatures, although these signatures may change with ship speed, vessel load, operational mode and any implemented noise-reduction measures[226] [227].

Most of the acoustic field surrounding large vessels is created by propeller cavitation (when vacuum bubbles created by the motion of propellers collapse), causing ships at their service speed to emit low-frequency tonal sounds and (high-frequency) noise spectra up to tens of kHz quite close to vessels[228].

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[222] Arveson, P. T. and D. J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. Journal of the Acoustical Society of America 107, 118-129.
[223] Heitmeyer, R. M., S. C. Wales and L. A. Pflug. 2004. Shipping noise predictions: capabilities and limitations. Marine Technology Society Journal 37, 54-65.
[224] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp
[225] Ross D (1976) Mechanics of underwater noise. Pergamon Press, New York
[226] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[227] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[228] Ibid

Smaller, but potentially significant, amounts of radiated noise can arise from on-board machinery (engine room and auxiliary equipment)[229]. Hydrodynamic flow over the ship's hull and hull attachments is an important broadband sound-generating mechanism, especially at higher speeds[230]. There are also significant depth and aspect-related elements of radiated vessel sound fields as a function of shadowing and the Lloyd mirror effect near the surface of the water[231] (where the air/water interface reflects the sound wave and the reflection has an opposite polarity of the original wave). Source (propeller) depth is also important in terms of long-range propagation. Large vessels are near-field sources in both offshore (in shipping routes and corridors) and coastal waters (mainly in traffic lanes, waterways/canals or ports). Due to their loud and low-frequency signatures, large vessels dominate low-frequency background noise in many marine environments worldwide[232] [233]. Modern cargo ships can also radiate sound at high frequencies, with source levels over 150 dB re 1μPa at 1m around 30 kHz[234]. Vessel noise from a range of different ship types recorded at four locations in Danish waters in 2012 elevated ambient noise levels across the entire recording band from 0.025 to 160 kHz at ranges between 60 and 1000m[235].

Medium sized vessels (length 50 - 100m; e.g., support and supply ships, many research vessels)

Tugboats, crewboats, supply ships, and many research vessels in the medium-sized category typically have large and complex propulsion systems, often including bow-thrusters[236]. Many fishing vessels also fall within this category. Typical broadband source levels for small to mid-size vessels are generally in the 165 - 180 dB (re: 1μPa) range[237] [238]. Most medium-sized ships are similar to large vessels in that most of the sound energy is low-frequency band (<1 kHz). While broadband source levels are usually slightly lower for medium-sized vessels than for the larger commercial vessels, there are some exceptions (e.g., as a function of age or maintenance of the ship), and medium-sized ships can produce sounds of sufficient level and frequency to contribute to marine ambient noise in some areas[239]. Mid-sized vessels spend most of their operational time in coastal or continental shelf waters, and overlap in time and space with marine animals.

Small vessels (length up to 50m; e.g., recreational craft, jet skis, speed boats, operational work boats)

Small boats with outboard or inboard engines produce sound that is generally highest in the mid-frequency (1 to 5 kHz) range and at moderate (150 to 180 dB re 1 μPa @ 1 m) source levels, although

[229] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp
[230] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
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[234] Arveson, P. T. and D. J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. Journal of the Acoustical Society of America 107, 118-129.
[235] Hermannsen, L., Beedholm, K., Tougaard, J., and Madsen, P. T. 2014. High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (*Phocoena phocoena*). The Journal of the Acoustical Society of America, 136: 1640–1653.
[236] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[237] Kipple B, Gabriele C (2004) Glacier Bay watercraft noise— noise characterization for tour, charter, private, and government vessels. Technical Report NSWCCDE-71-TR- 2004/545, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA
[238] Heitmeyer, R. M., S. C. Wales and L. A. Pflug. 2004. Shipping noise predictions: capabilities and limitations. Marine Technology Society Journal 37, 54-65.
[239] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

the output characteristics can be highly dependent on speed[240 241 242]. Source spectra for small craft and boats include tonal harmonics at the resonant vibrational frequencies of propeller blades, engines, or gearboxes below about 1 kHz, as well as significant energy resulting from propeller cavitation extending up to and above 10 kHz. Due to the generally higher acoustic frequency and near-shore operation, noise from smaller vessels is regarded as having more geographically-limited environmental impacts in that it does not extend far from the source. Small craft and boats can dominate some coastal acoustic environments at certain times, particularly partially-enclosed bays, harbours and/or estuaries[243.] In fact, recreational vessels have been identified as the most important contributor to mid-frequency ambient noise in some coastal habitats[244].

Acoustic Deterrent and Harrassment Devices

Acoustic Harassment Devices (AHDs) have been defined as high power devices operating at broadband source levels above 185 dB re 1µPa @ 1m, while those operating at a lower source level are termed Acoustic Deterrent Devices (ADDs)[245]. ADDs or "pingers" are generally used to deter small cetaceans from bottom-set gillnets or other fisheries in order to reduce bycatch and incidental mortality. Pingers operate at much lower source levels than AHDs; usually 130 to 150 dB re 1 µPa [246]. Acoustic characteristics of ADDs differ particularly with respect to randomisation of pulse intervals and pulse duration. However, the signal structure and source levels of pingers can be relatively consistent when they have to comply with national or regional guidelines (e.g., EU Council regulation (EC) No 812/2004). Devices falling under this regulation are known to produce either 10 kHz tones or wide-band sweeps covering a frequency range from 20 to 160 kHz. Such pingers that are based on analogue signal generation emit tones (10 kHz) at source levels (broadband) between 130 and 150 dB re 1 µPa, while digital devices can either have the same specifications or produce wideband sweeps at broadband source levels of 145 dB 1 µPa[247].

Acoustic Harassment Devices (AHDs) were originally developed to prevent pinniped predation on finfish farms, fisheries or salmon runs through the production of high source level acoustic signals. AHDs emit tone pulses or pulsed frequency sweeps at high source levels and there are a wide range of AHD specifications[248 249]. A common feature of most AHDs is that they produce substantial energy in the ultrasonic range in addition to the main frequency band. The broadband source level of most AHDs is approximately 195 dB re 1 µPa. Due to their relatively high source level and often broadband characteristics, AHDs can potentially be a significant source of noise in areas of dense fish farming[250].

[240] Erbe C (2002) Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca)*, based on an acoustic impact model. Mar Mamm Sci 18:394–418
[241] Kipple B, Gabriele C (2004) Glacier Bay watercraft noise— noise characterization for tour, charter, private, and government vessels. Technical Report NSWCCDE-71-TR- 2004/545, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA
[242] Jensen, F.H., et al., 2009. Vessel noise effects on delphinid communication. Mar Ecol Prog Ser 395:161-175
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[244] Haviland-Howell G, Frankel AS, Powell CM, Bocconcelli A, Herman RL, Sayigh LS (2007) Recreational boating traffic: a chronic source of anthropogenic noise in the Wilmington, North Carolina Intracoastal Waterway. J Acoust Soc Am 122:151–160
[245] Reeves, R. R., R. J. Hofman, G. K. Silber, and D. Wilkinson. 1996. Acoustic deterrence of harmful marine mammal-fishery interactions: proceedings of a workshop held in Seattle Washington, 20- 22 March 1996. US Dept. Commer.
[246] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[247] Ibid
[248] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115 (Table 2)
[249] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission (Table 8.1)
[250] Johnston, D. W., and T. Woodley. 1997. A survey of Acoustic Harassment Device (AHD) Use at Salmon Aquaculture Sites in The Bay of Fundy , New Brunswick, Canada. Aquatic Mammals 24:51-61.

Fish deterrent devices (FDDs) are mainly used in coastal or riverine habitats to temporarily displace fishes from areas of potential harm (e.g., guiding fishes away from water intakes of power plants)[251]. There is considerable variation between devices in terms of the frequency range which depends on the fish species to be targeted. If the device needs to be effective against a broad range of species, relatively low or infrasonic frequencies are generally used. For example, some devices produce infrasound at frequencies of about 10 Hz[252] or between 20 and 600 Hz[253]. Other devices produce primarily ultrasonic frequencies and are specifically designed to deter high-frequency hearing specialists. FDDs for some clupeid species which have ultrasonic hearing operate at frequencies between 120 kHz and 130 kHz, with source levels up to 190 dB[254]. FDDs generally produce sequences of short pulses (e.g., 100 - 1000 ms) at intervals of one to several seconds and duty cycles up to 50%[255].

Other Anthropogenic Sources

Research Sound

Ocean science studies use a variety of different sound sources to investigate the physical structure of the ocean. Ocean tomography studies measure the physical properties of the ocean using sound sources with frequencies between 50 and 200 Hz and high source levels (165 - 220 dB re 1 μPa). The "Heard Island Feasibility Test" projected signals with centre frequencies of 57 Hz in the 'SOFAR channel' (175 m depth) at source levels up to 220 re 1 μPa[256]. The signals could be detected across ocean basins with received levels up to 160 dB re 1 μPa at 1 km distance. Another ocean-wide experiment was the "Acoustic Thermometry of Ocean Climate" (ATOC) research programme, which was initiated in the early 1990s to study ocean warming across the North Pacific basin[257]. The ATOC sound source emitted coded signals at four hour intervals at source levels of 195 dB re 1 μPa for up to 20 min with a 5 minute ramp-up period[258].

Research projects also use sound to estimate current speed and direction by using drifting sources called SOFAR floats[259]. These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1 μPa at 1 m) between 185 and 310 Hz. The sounds are detected by distant receivers and their timing is used to determine the float location and therefore the distance drifted as a proxy for deep currents[260].

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[251] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

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[257] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

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[260] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

Icebreakers

Ice-breaking ships are a source of noise in polar regions[261]. Two types of noise have been identified during ice breaking: bubbler system noise and propeller cavitation noise[262]. Some ships are equipped with bubbler systems that blow high-pressure air into the water around the ship to push floating ice away. The noise is continuous while the bubbler system is operating, with a broadband spectrum below 5 kHz. A source level of 192 dB re 1 µPa at 1 m has been reported for bubbler system noise. Icebreaker propeller cavitation noise occurs when the ship rams the ice with its propeller turning at high speed. The spectrum of propeller cavitation noise is broadband up to at least 20 kHz, and has a source level of 197 dB re 1 µPa at 1 m[263].

Acoustic Telemetry

Acoustic telemetry is used for underwater communications, remote vehicle command and control, diver communications, underwater monitoring and data logging, trawl net monitoring and other industrial and research applications requiring underwater wireless communications[264]. For seafloor monitoring, acoustic modems are used as an interface for subsurface data transmissions, sending data using modulated acoustic signals between seafloor instruments and surface buoys. Long-range systems can operate over distances of up to 10 km using frequencies of 7 to 45 kHz, at source levels of up to 190 dB re 1 µPa @ 1 m. A relatively new integrated communications project is the "Acoustic Communication Network for Monitoring of Underwater Environment in Coastal Areas (ACME)". This system uses chirps of continuously varying frequencies and frequency-shift keying noise covering a frequency range of 5 - 15 kHz[265].

[261] Erbe, C and Farmer, D.M. 2000. Zones of impact around icebreakers affecting Beluga whales in the Beaufort Sea. J. Acoust. Soc. Am. 108

[262] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

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4. KNOWN AND POTENTIAL IMPACTS OF UNDERWATER NOISE

Underwater sound is an extremely important component of the marine environment and plays an integral part of the lives of most marine vertebrates[266] and also many invertebrates[267] [268]. This chapter provides a synthesis of current scientific knowledge concerning the impacts of anthropogenic sound on marine life. Most of the information available is concerned with the effects of sound and noise on marine mammals, particularly cetaceans. Considerably less research has been completed for marine fishes, other vertebrates (e.g., marine turtles) and marine invertebrates.

Anthropogenic underwater noise is known to have a variety of impacts on marine species, ranging from exposures that cause no adverse impacts, to significant behavioural disturbances, to hearing loss, physical injury and mortality. The potential effects depend on a number of factors, including the duration, nature and frequency content of the sound, the received level (sound level at the animal), the overlap in space and time with the organism and sound source, and the context of exposure (i.e., animals may be more sensitive to sound during critical times, like feeding, breeding/spawning/, or nursing/rearing young)[269]. Marine animals can be impacted by instantaneous high pressure sound waves, but damage increases with total acoustic energy received for a given type of sound stimulus[270]. Adverse impacts can be broadly divided into three categories: masking, behavioural disturbance and physiological changes (hearing loss, discomfort, injury)[271] although there is some overlap between these categories. In extreme cases, where there are very high levels of received sound pressure often close to the source, the intense sounds can lead to death. There have been a number of extensive reviews of the impacts of anthropogenic sound on marine organisms during the last two decades[272] [273] [274] [275] [276] [277] [278]

[266] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

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[270] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

[271] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

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[273] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[274] NRC (2005) Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects. National Research Council of the National Academies of Science, Washington, DC.

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[277] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

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[279] [280] [281] [282] [283]. In addition, the potential for further more subtle biological effects (e.g., physiological, developmental, cellular and genetic responses) of anthropogenic noise on mainly terrestrial animals has been suggested[284], which merit investigation in the marine environment.

The chronic and cumulative effects of anthropogenic noise exposure on marine species and populations also require attention[285]. The degree of cumulative effects will also depend on the mobility of marine organisms (and also of the sound source). Highly mobile species may be able to avoid stationary sounds, while more sedentary or sessile species will not be able to move away from a stationary sound source. Migratory species may be subjected to multiple sound sources along their migration route.

This chapter summarizes current scientific knowledge on the observed and potential effects of anthropogenic noise on marine biodiversity and is divided into three main sections comprised of marine mammals, marine fishes and other fauna such as further vertebrate taxa and invertebrates.

Impacts on Marine Mammals

The theoretical zones of underwater noise influence on marine mammals have been defined and are mainly based on the distance between the source of the sound and the receiver[286] (Figure 3).

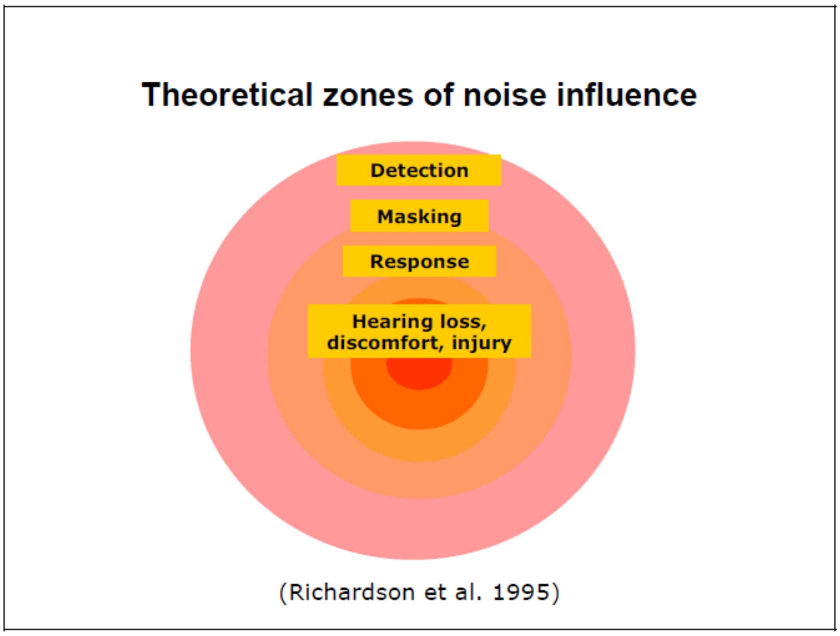

Figure 3. **Theoretical zones of noise influence (after Richardson et al. 1995)**

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[279] Popper, A.N., and Hastings, M.C. 2009b. The effects of human-generated sound on fish. Integrative Zoology, 4: 43 – 52.
[280] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.
[281] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029
[282] Radford, A.N., Kerridge, E. and Simpson, S.D. 2014. Acoustic communication in a noisy world: can fish compete with anthropogenic noise? Behav. Ecol. doi:10.1093/beheco/aru029
[283] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).
[284] Kight, C.R. and Swaddle, J.P. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. Ecology Letters doi: 10.1111/j.1461-0248.2011.01664.x
[285] Wright, J.W., Deak, T. and Parsons, E.C.M. 2009. Concerns Related to Chronic Stress in Marine Mammals. IWC SC/61/E16 7 pp.
[286] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

This model has been used extensively for impact assessments where the zones of noise influence are determined, based on a combination of sound propagation modelling or sound pressure level measurements and information on the hearing capabilities of marine species. However, the model gives only a very rough estimate of the zones of influence as sound in the marine environment is always three-dimensional. Interference, reflection and refraction patterns within sound propagation will also lead to considerably more complex sound fields than those based on the above model. This complexity may result in particular effects such as an increase in received sound energy with distance, especially when multiple sound sources are used simultaneously, for example during seismic surveys[287].

Injury and Physical Effects

Marine mammals are known to be susceptible to a range of physiological effects and injuries that have been attributed to sources of anthropogenic sound. The most striking evidence of serious injury to marine mammals has been accumulated in the last decade and is concerned with the impact of naval sonar on cetaceans, particularly deep diving beaked whales of the genera *Ziphius* and *Mesopolodon*, and the occurrence of mass stranding events[288] [289]. Atypical mass stranding events of mainly beaked whales first began to be reported in the mid 1980's and usually coincided with the use of mid-frequency active sonar by the military[290] [291] [292]. Necropsies of beaked whales stranded in the Bahamas in 2000 clearly revealed that the animals had suffered acoustic trauma resulting in haemorrhaging around the brain, in the inner ears and in the acoustic fats (fats located in the head which are involved in sound transmission)[293]. The official interim report for the mass stranding event concluded that an acoustic or impulse injury caused the animals to strand and that mid-frequency active sonar used by the navy, while transiting was the most plausible source of the acoustic trauma or impulse[294]. Analysis of subsequent mass stranded beaked whales found acute systemic micro-haemorrhages and gas and fat emboli in individuals that mass-stranded during a naval exercise in the Canary Islands in 2002[295] [296]. Similarly, four species of stranded cetacean (one beaked whale, two dolphin and one porpoise species) had acute and chronic lesions in liver, kidney and lymphoid tissue (lymph nodes and spleen) associated with intravascular gas bubbles (emboli)[297]. The mechanism for gas bubble generation (gas bubble disease) in supersaturated tissue of diving marine mammals (that leads to symptoms similar to decompression

[287] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[288] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

[289] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57.

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[291] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[292] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[293] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

[294] Ibid

[295] Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraez, P., Pocknell, A. M., Rodriguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A. and Fernández A. 2003. Gas-bubble lesions in stranded cetaceans. Nature 425: 575–576.

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[297] Jepson, P. D., Deaville, R., Patterson, I. A. P., Pocknell, A. M., Ross, H. M., Baker, J. R., Howie, F. E., Reid, R. J., Colloff, A. and Cunningham, A. A. 2005. Acute and chronic gas bubble lesions in cetaceans stranded in the United Kingdom. Veterinary Pathology 42: 491–305.

sickness in humans) is thought to be an adverse behavioural response to exposure to noise[298], or a direct physical effect of sound energy on gas bubble precursors in the animal's body[299] (see Figure 4). In the case of beaked whales, if individuals change behaviour to a series of shallower dives with slow ascent rates and shorter stays on the surface, they could experience excessive nitrogen tissue supersaturation driving potentially damaging bubble formation in tissues[300]. However, this is currently a working hypothesis and requires testing through a specific programme of research[301]. Beaked whales are also thought to be more acoustically sensitive to active sonar than other species. A comparison of the effect of mid-frequency sonar on Blainville's beaked whale and three other non-beaked species (pilot whale, false killer whale and melon-headed whale) showed that there was a stronger response by affected individuals compared to controls for the beaked whales than in the other species[302]. Direct measurements of behavioural responses of Cuvier's beaked whales to mid-frequency active sonar indicate that this species reacts strongly to the acoustic disturbance at low received levels[303]

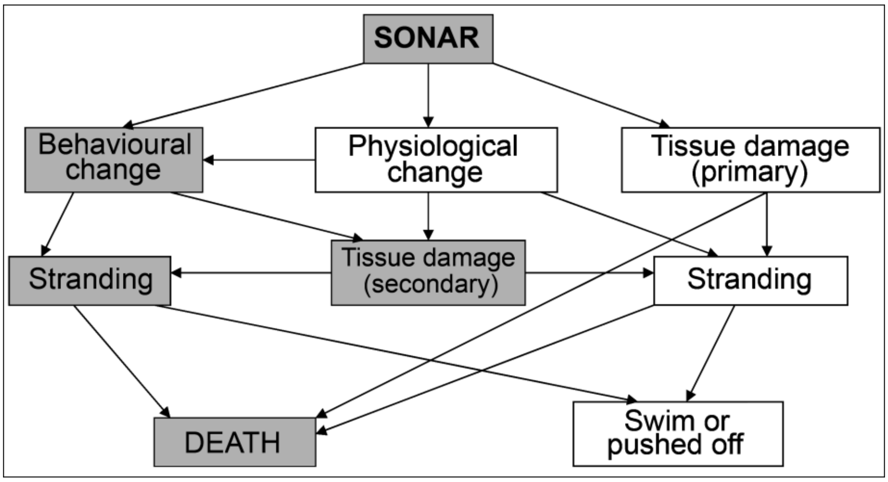

Figure 4. Potential mechanistic pathways by which beaked whales are affected by active sonar. (See Cox et al., 2006 for detailed discussion)

Further mass stranding events of beaked whales and other cetaceans have been reported in a range of locations around the world[304] [305] [306]. Research for Cuvier's beaked whale indicates that there have been 40 mass stranding events of two or more individuals since 1960 and 28 of these events occurred at the same time and place as naval manoeuvres or the use of active sonar or near naval bases[307]. A number

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[298] Cox, T. M., et al. 2006. Understanding the impacts of anthropogenic sound on beaked whales? Journal of Cetacean Research and Management 7: 177–187.

[299] Crum, L.A., Bailey, M.R., Guan, J., Hilmo, P R., Kargl, S.G., Matula, T.J. & Sapozhnikov, O.A. (2005) Monitoring bubble growth in supersaturated blood and tissue ex vivo and the relevance to marine mammal bioeffects. Acoustics Research Letters Online. DOI: 10.1121/1.1930987

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[307] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

of other (non-beaked) species such as minke whales and pygmy sperm whales have stranded concurrently with beaked whales in sonar-related stranding events, while other species including long-finned pilot whales, melon headed whales, dwarf sperm whales, common dolphins and harbour porpoises, have stranded in noise-related events[308] [309] [310]. The fact that deep diving cetaceans other than beaked whales that have stranded have been shown to have gas embolism disease suggests that sonar or other noise impacts may be more widespread than previously thought[311]. Additionally, mortality may be underestimated if based solely on stranded individuals, as affected cetaceans are also highly likely to die at sea[312] and not be washed up or detected[313].

There is little evidence of other sources of anthropogenic underwater noise causing direct physical damage to marine mammals. There are a few poorly documented cases of injury (e.g., organ damage and rupture of gas filled cavities such as lungs, sinuses and ears) and deaths of marine mammals that have been caused by the use of explosives[314]. A dramatic pressure drop, such as occurs from blast waves, may cause air-filled organs to rupture[315]. The death of two humpback whales was attributed to acoustic trauma caused by a 5000 kg explosion through severe injury to the temporal bones[316]. Underwater detonations as part of military exercises resulted in the death of three (possibly four) long-beaked common dolphins which had sustained typical mammalian blast injuries[317]. There is no documented case of injury caused by pile driving for marine mammals at sea and there remains uncertainty on the effects of pile driving for these taxa[318]. However, experimental studies in captivity using simulated source levels[319] [320] suggest that the levels of intense sound produced during pile driving are strong enough to cause noise induced hearing loss in some species. Hearing losses are classified as either temporary threshold shifts (TTS) or permanent threshold shifts (PTS), where threshold shift refers to the raising of the minimum sound level needed for audibility[321]. Increasing the exposure sound pressure level (SPL) and/or the sound duration results in greater levels of TSS until, at some level of exposure, a sufficiently severe shift in threshold occurs, which results in an incomplete hearing recovery[322]. This

[308] Ibid

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[310] Southall, B.L., Rowles, T., Gulland, F., Baird, R. W., and Jepson, P.D. 2013. Final report of the Independent Scientific Review Panel investigating potential contributing factors to a 2008 mass stranding of melon-headed whales (*Peponocephala electra*) in Antsohihy, Madagascar

[311] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[312] International Whaling Commission Scientific Committee (IWC/SC). 2005. Report and Annex K of the 2005 Scientific Committee Report: Report of the Standing Working Group on Environmental Concerns. J. Cetacean Res. Manag. 7 (Suppl.): 267-305

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[320] Kastak, D., Southall, B. L., Schusterman, R. J. & Kastak, C. R. (2005) Underwater temporary threshold shift in pinnipeds: effects of noise level and duration. Journal of the Acoustical Society of America 118: 3154-3163.

[321] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[322] Saunders, J.C. and Dooling, R.J. 2018. Characteristics of Temporary and Permanent Threshold Shifts in Vertebrates. In: Slabbekorn, H. et al. (Eds.). 2018. Effects of Anthropogenic Noise on Animals. ASA Press, Springer Handbook of Auditory Research, Springer, New York, U.S.A., 309 pp.

incomplete recovery is a hearing loss for the animal and constitutes a PTS. Hearing losses can reduce the range for communication, interfere with the ability to forage, increase vulnerability to predators, and may cause erratic behaviour with respect to migration, mating, and stranding[323]. Current research indicates that sound from pile driving has the potential to induce hearing loss in marine mammals if they remain within a certain distance of the source (estimated between 100 and 500 metres for PTS)[324] [325]. However, using the exposure criteria developed by Southall et al. (2007), a recent study indicates that 50% of tagged harbour seals were predicted to exceed estimated permanent auditory damage thresholds during the construction of an offshore wind farm, even though the seals remained at least 4.7 km from the pile driving source[326]. Previously, the most severe acoustic impacts recorded on cetaceans (active sonar) were due to exposures thought too low to induce TTS, according to predictive models[327]. However, there is considerable variation within the taxa in terms of functional hearing groups[328], with more recent research on TTS indicating that harbour and finless porpoises are more sensitive to sound than expected from extrapolations based on results from bottlenose dolphins[329]. Hearing damage in marine mammals from shipping noise has not been widely reported and is thought to be unlikely to occur from the passage of a single vessel[330]. However, there is the potential for permanent damage to hearing from sustained and/or repeated exposure to shipping noise over long periods[331]. Increasing collision rates between sperm whales and high-speed ferries in the Canary Islands were thought to be linked to hearing damage. Inner ear analysis of two whales killed in collisions revealed low frequency inner ear damage and auditory nerve degeneration leading to the suggestion that low frequency sounds could be considered a marine hearing hazard[332].

Noise from Acoustic Deterrent Devices (ADDs) may result in TTS or PTS of hearing sensitivity for marine mammals (pinnipeds and cetaceans), particularly if they remain in the vicinity of the ADD location for extended time periods (hours)[333] or are exposed to multiple ADDs with overlapping signals[334].

Masking

The term masking refers to what happens when increased levels of background or ambient noise reduces an animal's ability to detect relevant sound[335] such as important acoustic signals for communication and echolocation for marine mammals. If the anthropogenic noise is strong enough relative to the received signal, then the signal will be 'masked'[336]. If features within the signal convey information, it may be

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[323] Ibid

[324] Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. & Thompson, P. (2010) Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals. Marine Pollution Bulletin 60: 888-897.

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important to receive the full signal with an adequate signal-to-noise ratio to recognize the signal and identify the essential features[337]. As ambient noise or transmission range increases, information will be lost at the receiver, ranging from inability to detect subtle features of the signal to complete failure to detect the signal[338]. Consequently, the active space in which animals are able to detect the signal of a conspecific[339] or other acoustic cue will decrease with increased masking noise.

Masking in the marine environment is regarded as a key concern for marine mammals[340], especially for those that communicate using low frequencies, such as baleen whales, seals and sea lions, and also some of the of vocalisations of toothed whales[341] (Figure 5). The principal constituent of low–frequency (5–500 Hz) ambient noise levels in the world's oceans are acoustic emissions from commercial shipping[342]. Masking can also occur at higher frequencies (1–25 kHz) when vessels are in close proximity to an animal and exposed to cavitation noise from propellers. Concerns regarding the impacts of noise from large vessels have focused mainly on marine animals that use low frequencies for hearing and communication. Vessel noise in higher frequency bands has the potential to interfere (over relatively short ranges) with the communication signals of many marine mammals, including toothed whales[343]. Masking of harbour porpoise communication and echolocation at close range (up to 500m) by high-speed ferries and other large vessels has been highlighted as a cause for concern in shallow waters of high traffic coastal areas[344]. More localised masking in the coastal and inshore zone is a growing cause for concern, as the number and speed of smaller motorised vessels increase dramatically in many regions[345].

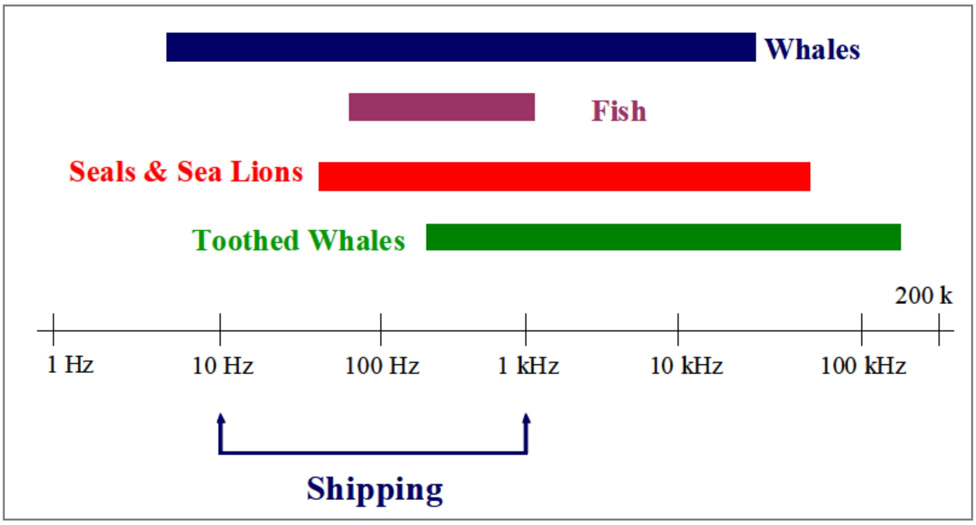

Figure 5. Typical frequency sound bands produced by marine mammals (and fishes) compared with the nominal low-frequency sounds associated with commercial shipping (after OSPAR 2009)

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There have been numerous studies of the effects of masking from vessel noise on marine mammals, including baleen whales[346], belugas[347], bottlenose dolphins[348 349 350], short-finned pilot whales[351] and killer whales[352 353]. Some of these have estimated or modelled the extent to which low-frequency noise from shipping or other vessels can dramatically reduce communication ranges for marine animals[354 355]. For example, the noise of an icebreaker vessel was predicted to mask beluga calls up to 40 km from the vessel[356], while pilot whales in deep water habitat could suffer a 58% reduction in communication range caused by the masking effect of small vessels in the coastal zone[357]. Using a metric to measure 'communication masking' the acoustic communication space for the highly endangered north Atlantic right whale has shown to be seriously compromised by noise from commercial shipping traffic[358]. Increasing anthropogenic noise levels in the oceans therefore have the potential to significantly affect threatened populations of marine mammals. Masking effects on marine mammals have also been suggested for other anthropogenic noise sources including low-frequency sonar on humpback whales[359 360], pile driving sound on bottlenose dolphins[361], low-frequency wind turbine noise on harbour seals and harbour porpoises[362 363], and low frequency sound from dredging on baleen whales and seals[364]. There is also the potential for certain Acoustic Harassment Devices to mask the communication signals of some species of Delphinid cetaceans or seals[365]. Low-frequency sounds produced by fish deterrent

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[351] Ibid
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devices or tidal turbines have the potential to mask baleen whale communication or the vocalisations of some seal species[366].

There is increasing evidence that cetaceans are compensating for the masking effects of anthropogenic noise by changing the frequency, source level, redundancy or timing of their signals[367 368 369 370 371 372 373]. This phenomenon suggests that the anthropogenic noise levels in the marine environment, such as vessel noise, are clearly interfering with communication in marine mammals[374]. Temporary changes in signalling may enable animals to cope with different noise levels[375]. Changes in signal parameters may adequately compensate for small increases in masking noise and are not likely to have any adverse effects during short periods of time, but may not be sufficient to compensate for more severe levels of masking[376]. The energetic and functional costs of making changes to vocalisations for individuals or populations are currently unknown[377].

Behavioural Changes

A wide range of anthropogenic sound sources are known to elicit changes in behaviour in marine mammals[378 379] and the responses elicited can be complex. Behavioural responses may range from changes in surfacing rates and breathing patterns to active avoidance or escape from the region of highest sound levels. Responses may also be conditioned by certain factors such as auditory sensitivity, behavioural state (e.g., resting, feeding, migrating), nutritional or reproductive condition, habit or desensitization, age, sex, presence of young, proximity to exposure and distance from the coast[380 381]. Therefore, the extent of behavioural disturbance for any given acoustic signal can vary both within a population as well as within the same individual[382]. Since the first extensive review of marine mammals

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and anthropogenic noise was completed in the mid-nineties[383], there have been a number of further detailed appraisals that document how various sources of anthropogenic sound can affect marine mammal behaviour[384] [385] [386] [387]. Many of the studies reporting behaviour up to this time were observational rather than experimental and often lacked proper controls.

The subjects of vocal plasticity and mass strandings have been covered previously in sections for masking and physiological effects of anthropogenic sound respectively. This section provides information on three broad areas of behavioural change in marine mammals (disturbance responses, interruption of normal activity and habitat displacement), and leads onto a discussion of potential population effects, physiological responses and chronic effects.

There is extensive information documenting the disturbance responses of marine mammals to anthropogenic sounds such as recreational boat noise, industrial maritime traffic activities, seismic surveys, oceanographic tests, sonar, acoustic hardware, airplanes and explosions[388] [389]. Short term reactions of cetaceans to man-made sounds include sudden dives, fleeing from sound sources, vocal behavioural change, shorter surfacing intervals with increased respiration, attempts to protect their young, increased swim speed and abandonment of the polluted area[390]. For example, both killer whales and dolphins are known to change their motor behaviour in response to small vessel presence and noise[391] [392], while baleen whales such as blue and fin whales have similarly responded to shipping movements and noise[393]. Manatees have been shown to respond to approaching vessels by changing fluke rate, heading and dive depth[394]. Cessation of singing was shown in humpback whales with transmissions of an experimental sound 200 km away[395]. The use of air-gun arrays during seismic surveys and their impact on marine mammal behaviour has been thoroughly assessed in terms of behavioural responses. A range of conclusions have been drawn with respect to behavioural reactions to seismic surveys, and there is currently a lack of a consensus in the scientific community on the occurrence, scale and significance of such effects[396]. However, many types of marine mammals have reacted strongly to the intense sound of seismic surveys. A number of species of baleen whale show

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avoidance behaviour[397], as do pinniped species[398 399]. As assessment of cetacean responses to 201 seismic surveys resulted in the suggestion that odontocetes may adopt a strategy of moving out of the affected area entirely, while slower moving mysticetes move away from the seismic survey to increase the distance from the source, but do not leave the area completely[400]. A causal connection between seismic surveys and ice entrapment events leading to narwhal mortality has been proposed recently along with a call for research of the effects of airgun use on narwhals[401]. Observations of sperm whales that were resident in an area with seismic surveys occurring over many years did not record any avoidance behaviour, which may indicate habituation. The observations did, however, show more subtle changes in foraging behaviour at sound levels that were considerably below the threshold level used to predict a disruption of behaviour[402]. These subtle changes were able to be picked up because of a rigorous experimental design. Long-term in-depth studies are also important to detect subtle effects. The apparent habituation of a dolphin population to vessel noise was actually a result of more sensitive individuals avoiding the affected area whilst the less sensitive ones remained[403]. Subtle behavioural responses to ship noise have also been documented for killer whales[404].

It is also important to consider that animals that are most vulnerable to a disturbing stimulus may not be the most responsive, in that the most stressed animals may have less capacity to alter their behaviour[405]. For example, a starving animal may choose to keep feeding when exposed to a disturbing stimulus rather than stop feeding and move away[406]. Such trade-offs may influence activity budgets, potentially affecting fecundity, survival[407] and population health[408].

It is thought that repeated short-term changes in behaviour may lead to long-term impacts at the population level through continual avoidance leading to habitat displacement[409 410] or by reducing energy acquisition in terms of lost feeding opportunities[411]. The displacement of numerous cetacean

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species has been well documented in the scientific literature[412] [413] and, in some cases, individuals have been displaced for a number of years, only returning when the activities causing the anthropogenic noise ceased[414]. If the displacement results in the animals being excluded from important feeding, breeding or nursery habitats then this is likely to have a deleterious impact on survival and growth of the population group[415]. Similarly, a prolonged disruption in normal behaviour can reduce foraging time and efficiency. For example, vessel activity is thought to reduce foraging success in killer whales[416] and dolphins[417] [418]. Vessel noise also influenced the foraging behaviour of Blainville's beaked whale up to at least 5 km away from the source[419]. Noise levels generated by vessels in close proximity may be impairing the ability to forage using echolocation by masking echolocation signals[420]. Sonar-induced disruption of feeding and displacement from high-quality prey patches could have significant and previously undocumented impacts of baleen whale foraging ecology, individual fitness and population health[421], particularly for endangered species.

There is growing awareness of the potential problem of chronic stress in marine mammals through the prolonged or repeated activation of the physiological stress response[422], as well as the life-saving combination of systems and events that maximises the ability of an animal to kill or avoid being killed[423]. The goal of this stress response is to enable the animal to survive the perceived immediate threat. Prolonged disturbance of marine mammals to intermittent or continuous anthropogenic noise has the potential to induce a state of chronic stress if the exposures are of sufficient intensity, duration and frequency. The stress response may be triggered repeatedly either through a direct response to sound (e.g., small vessel noise) or indirectly via one or more noise-related impacts (e.g., shipping noise masking communication, navigation or foraging abilities)[424]. Chronic stress is known to have adverse health consequences for populations of terrestrial animals by affecting fertility, mortality and growth rates. Moreover, it is known that a range of biological systems and processes in animals are impacted by exposure to noise: the neuroendocrine system, reproduction and development, metabolism, cardio-vascular health, cognition and sleep, audition and cochlear morphology, the immune system, and DNA integrity and genes[425]. It therefore seems logical to infer that noise-induced chronic stress has the potential to detrimentally alter similar critical life history parameters in marine mammals (e.g., disease susceptibility, reproductive rates, mortality rates), that may have long-term consequences for populations. North Atlantic right whales, for instance, showed lower levels of stress-related faecal

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glucocorticoids after 9-11 due to decreased shipping with an attendant 6 dB decrease in shipping noise[426].

However, no study to date has found a population level change in marine mammals caused by exposure to anthropogenic noise, though noise is listed as a contributing factor to several species' decline or lack of recovery (e.g., Western gray whales[427] [428] [429] and Southern Resident killer whales[430]). A detailed review found little response by cetacean populations to human acoustic disturbance in four case study areas[431], which was attributed to a number of reasons, including the lack of accurate population estimates for marine mammal species and the ability of individuals to adapt and compensate for negative effects[432]. Indeed, behavioural change should not necessarily be correlated with biological significance when assessing the conservation and management needs of species of interest[433]. Modelling of coastal bottlenose dolphins to assess the effect of increased levels of vessel traffic on behaviour suggested that the dolphins' response to disturbance is not biologically significant, as they were able to compensate for the change in behaviour so that their health was unaffected[434]. This modelling scenario was based on the condition that increased commercial vessel traffic was the only escalation in anthropogenic activity affecting the dolphin population. When ADDs are used over large areas and extended time periods, they may represent a source of chronic underwater noise pollution which may negatively affect animals' individual fitness, potentially with long-term population consequences[435].

The process by which a temporary change in an individual's behaviour could lead to long-term population level consequences is addressed by the Population Consequence of Acoustic Disturbance (PCAD) Model (Figure 6)[436]. The model, developed for marine mammals but theoretically applicable to other fauna, involves different steps from sound source characteristics through behavioural change, life functions impacted and effects on vital rates to population consequences.

At the present time, most of the variables of the PCAD model are unknown and there are challenges to fill in the gaps, including those related to uncertainties in population estimates for species or regions, difficulties in weighting noise against other stressors and the inherent inaccessibility of the marine environment[437]. No one factor is likely to be harmful enough to cause a direct population decline, but a combination of factors may create the required conditions for reduced productivity and survival in some

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cases[438]. Bioenergetic approaches have been used to parametise some of the PCAD variables for elephant seals[439] and modelling efforts are ongoing.

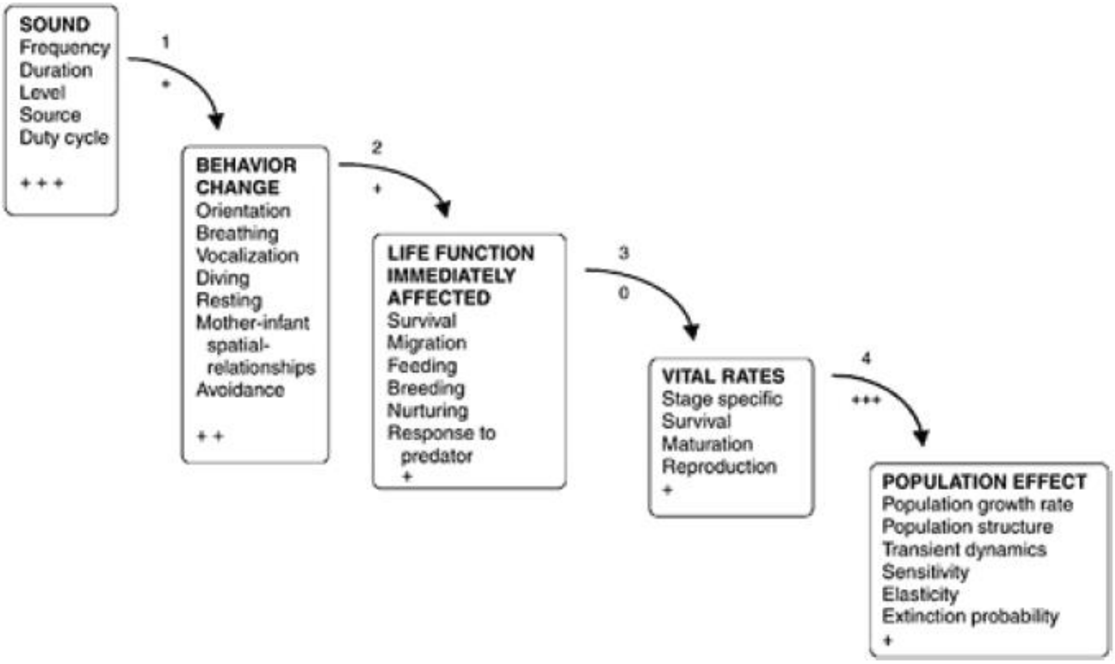

Figure 6. Overview of the PCAD Model by NRC (2005)

Note: The + signs within the boxes indicate how well these features can be measured, while the + signs under the transfer arrows indicate how well these transfer functions are known. As can be seen, some transfer functions such as 1-3 are not well known.

The potential impacts of sound also need to be considered in a wider context through addressing the consequences of acoustic disturbance on populations in conjunction with other stressors such as bycatch mortality, overfishing leading to reduced prey availability and other forms of pollution such as persistent organic pollutants[440] [441]. These various stressors may also act synergistically or cumulatively. For example, underwater noise could interact with bycatch or ship strikes in that the individual is less able to detect the presence of fishing nets or nearby vessels[442]. Multiple sources of anthropogenic sound may also interact cumulatively or synergistically such as when naval sonar emissions from multiple vessels produce confusing sound fields[443].

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Effects on Marine Fishes

In comparison to marine mammals, research into the effects of anthropogenic noise on marine fishes is at an earlier stage and there is generally less information available [444]. Initially, much of the material available was in the form of technical reports or 'grey literature'[445]. An evaluation of both the peer-reviewed and grey literature in 2009 concluded that very little was known then about the effects of anthropogenic sound on fishes and that there was a need for a systematic programme of study on a range of species[446]. Since then, the number of peer-reviewed publications has increased considerably, but there are still large gaps in our knowledge of the effects of underwater noise on fishes[447]. Notable reviews of the effects of sound on fishes over the last decade include those by Popper and Hawkins[448] [449] [450] [451]. A recent critical review of the impacts of low frequency sound (mainly from seismic surveys) on marine fishes[452] is briefly summarised in Annex 1. For further information please refer to the review's supplementary materials[453].

Marine fishes are susceptible to the same range of effects as has been discussed previously for marine mammals, although the principles of hearing differ considerably between the two groups and these differences influence how noise impact assessments should be conducted[454] [455]. The impacts of intense sound over short periods have been studied in some detail with respect to physical trauma and behaviour [456] [457] [458] [459] [460], but there is currently very little data available for the effects of ambient noise on fish behaviour[461], although this area of research has received more attention in recent years. Where data are lacking, inferences can be drawn by assessing noise-related impacts on the behaviour of other

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vertebrates[462]. For fishes, it is also important to consider the effects of noise on eggs and larvae and to consider both sound pressure and particle motion when assessing noise effects or impacts[463].

Another important point to note is that most studies of the effects of noise on fishes have been conducted in conditions where the sound fields can be very complex and are not like the sound fields that a fish would encounter in a normal aquatic environment[464]. A prerequisite for studies intended to examine the hearing of fishes and their responses to sounds is that they be done under appropriate acoustic conditions where both sound pressure and particle motion can be monitored[465]. Such studies have been conducted in highly specialised tanks[466] or in midwater in the sea. Overall, relatively few studies have been carried out under suitable acoustic conditions, and many of the measurements made in tanks and expressed solely in terms of sound pressure are unreliable[467].

Another fundamental issue to consider is that captive animals rarely show the full range of behaviours observed in wild animals[468], especially if they have been bred in captivity[469]. Therefore, one must take very considerable caution in extrapolating behaviour from studies of captive animals to how wild animals may respond to the same stimulus[470].

Injury and Physical Effects

Hearing loss and auditory damage

Temporary hearing loss may affect the ability of a fish to avoid predators, capture prey or communicate with other individual mates[471]. Most of the studies investigating hearing loss in fishes have been laboratory-based using different types of sound (e.g., pure tones or white noise) and exposure durations, with mixed results. There are only a few field-based studies of auditory effects involving actual anthropogenic sound sources (seismic surveys and military sonar) experienced at sea or using playbacks of sounds. Laboratory work on two freshwater species showed that temporary loss of hearing (i.e., temporary threshold shifts [TTS]), can occur at sound pressure levels (SPL) of 140–170 dB re 1 µPa and hearing loss did not recover for at least two weeks after exposure[472]. A significant hearing threshold shift was reported for rainbow trout (*Oncorhynchus mykiss*) exposed to a playback of low-frequency active (LFA) sonar at an SPL of 193 dB re 1 µPa[473]. More recent studies found no TTS in rainbow trout exposed to mid frequency active (MFA) sonar at an SEL_{cum} of 220 dB re 1 μPa^2 s[474] but TTS in channel

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catfish (*Ictalurus punctatus*) both for MFA[475] and LFA sonar[476]. For MFA sonar, the frequencies presented were lower than the hearing range of rainbow trout, while the same frequency spectrum overlapped with the upper end of the hearing frequency range of the channel catfish[477]. In both studies conducted on channel catfish (MFA and LFA sonar), not all of the individuals tested showed a temporary loss of hearing. No loss of hearing was also reported for largemouth bass (*Micropterus salmoides*) and yellow perch (*Perca flavescens*) in the same experimental conditions[478]. Channel catfish have morphological adaptations that increase pressure sensitivity and change the frequency range of hearing, while the other species analysed in these two studies[479] [480] do not. In addition, the variation of effects on the auditory system suggests that susceptibility to intense sound is more a factor of genetic stock, developmental conditions, seasonal variation and the state of the animal during exposure than interspecific differences[481]. A study of hearing loss in four coral reef fish species during a seismic survey did not find any loss of hearing up to 193 dB re 1 µPa[482]. Hearing impairment, namely TTS, associated with long-term, continuous exposure (2 hours), and masked hearing thresholds have been reported for fishes exposed to simulated noise (playback) of small boats and ferries[483] [484]. However, the two studies mentioned here were conducted in conditions with questionable sound fields.

Overall, the amount of hearing loss in fishes appears to be related to the noise intensity compared to the threshold of hearing at that frequency[485]. At frequencies where a fish was more sensitive (i.e., had a lower threshold), TTS produced by constant, broadband white noise was greater[486]. How hearing loss could affect the survival and fitness of fishes during the recovery time associated with hair cell regeneration has not been directly tested[487]. There is no evidence that a permanent threshold shift (PTS) occurs in fish as a result of sound exposure[488] and, since fishes are able to repair or replace sensory hair cells that are lost or damaged[489], PTS may not occur. Further research on the subject of hearing loss is required, particularly in a field-based setting using a variety of actual anthropogenic noise sources.

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Damage to sensory hair cells of the inner ear of fishes exposed to sound has been reported in a few studies[490] [491] [492] [493] but no damage was reported in some others[494] [495] [496]. Exposure of two fish species (hybrid striped bass (*Morone* sp.) and Mozambique tilapia (*Oreochromis mossambicus*)) to intense pile driving sound between 210 – 216 dB re 1 µPa s SEL_{cum} resulted in damage to a significant number of sensory hair cells in the inner ear of hybrid striped bass at the highest sound level but no damage at the lower levels[497]. Only one study has correlated hair cell loss in a fish ear and hearing effects. Exposure to long-duration white noise resulted in extensive loss of sensory cells, which was closely correlated with decreased hearing sensitivity[498]. Subsequently, hearing sensitivy returned to near normal and was correlated with the start of sensory cell replacement. Fishes can regenerate lost hair cells following trauma to the inner ear with the process taking at least seven days[499]. However, in a field-based study using caged fishes exposed to a seismic air gun, a small proportion of hair cells (2.7 %) were severely damaged and showed no signs of recovery after 58 days[500]. Damage to the lateral line organ in fish has also been proposed when individuals are in close proximity to an intense sound source[501]. Mechanical stimulation of the lateral line may cause damage by decoupling the cupulae from the neuromasts[502]. The potential coupling issue merits investigation as damage to the coupling would have significant effect on the function of the lateral line. Sensory cell damage and regeneration has been studied in the lateral line neuromasts of larval zebrafish (*Danio rerio*) but it is unclear whether the observed effects are influenced by developmental plasticity or distinct hair cell death and regenerative pathways[503].

Non-auditory damage

The swim bladder of a fish is a gas-filled structure that can be susceptible to damage by high intensity, particularly impulsive sound. Gas oscillations induced by high SPLs can potentially cause the swim bladder to tear or rupture[504] [505]. In addition, sounds from an impulsive source can cause gas organs such

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as the swim bladder and lung to oscillate and push on the surrounding tissues. Rapid expansion and contraction of the swim bladder can damage proximate organs including the liver, kidney and gonads and the swim bladder itself[506] [507]. Ruptured swim bladders have been reported in fishes exposed to explosions[508] [509] [510] and to pile driving sound[511] [512] [513]. Fishes that do not possess swim bladders such as flatfish are less susceptible to damage from explosions[514] and pile driving[515] sound. The threshold for the onset of injury from pile driving sound in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) was recently defined as an SEL_{cum} of 210 dB re 1 μPa^2 s[516]. There is a general correlation between the extent of tissue damage and the cumulative level of sound energy a fish is exposed to[517]. However, the degree of effect also depends on a combination of the energy within single pile driving strikes (SEL_{SS}) and the number of strikes, but is not predicatable from just knowing the cumulative energy[518][519]. A series of studies using pile driving sound have quantified the physical effects of sound exposure on various types of tissue[520] which have been used to develop interim sound exposure criteria for fishes[521] [522]. Exposure to very high intensity continuous sound with no impulsive components did not result in tissue damage in five species of fish[523] [524] [525] [526].

There is limited information available on mortality of fish from sound exposure and only for impulsive sound sources such as pile driving and explosions, especially in terms of acoustic data. 'Blast fishing'

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explosions on tropical coral reefs are known to kill and injure fishes and invertebrates but also cause extensive damage to reef habitat[527]. Blasts occurring during the decommissioning of oil and gas platforms can also cause fish mortality[528]. Exposure of fishes to seismic airguns[529] or high intensity sonar (both low and mid frequency types)[530] [531] did not result in mortality.

It has been suggested that fishes may be susceptible to two types of tissue damage when exposed to intense sound[532]. Firstly, sufficiently high sound levels are known to cause the formation of micro-bubbles in the blood and fat tissue[533]. Growth of these bubbles by rectified diffusion[534] at low frequencies could create an embolism and either burst small capillaries, causing superficial or internal bleeding, or cause damage to fish eyes where tissue may have high gas saturation[535]. Secondly, exposure to transient high-level sound may cause traumatic brain injury.

Full recovery from tissue damage has been observed for Chinook salmon and striped bass within ten days after exposure to sounds up to 213 dB re 1 μPa2 s[536] [537]. However, whilst injured, fishes may be more susceptible to infection and have reduced ability to feed or evade predators[538].

Preliminary studies of the effect of impulsive sound (seismic air guns) on the eggs and larvae of marine fishes observed decreased egg viability, increased embryonic mortality, or decreased larval growth when exposed to sound levels of 120 dB re 1 μPa[539] [540]. However, the veracity of these experimental studies has been questioned in regard to the stated and actual acoustic conditions. Turbot (*Scophthalmus maximus*) larvae suffered damage to brain cells and to neuromasts of the lateral line[541]. The neuromasts are thought to play an important role in escape reactions for many fish larvae, and thus their ability to avoid predators[542]. Injuries and increased mortality from air guns occurred at distances less than 5 m from the sound source. The most frequent and serious injuries occur within 1.5 m, and fishes in the

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early stages of life are most vulnerable[543]. It has been suggested that juveniles and fry have less inertial resistance to the motion of a passing sound wave, and are potentially more at risk for non-auditory tissue damage than adult fishes[544].

A study that exposed larvae of the common sole to high levels of pile-driving sound in carefully controlled experimental conditions did not record any significant differences in larval mortality between exposure and control groups[545]. The highest cumulative sound exposure level used was 206 dB re 1µPa^2 s, which is more than the interim criteria for non-auditory tissue damage in fishes[546]. Juvenile European sea bass exposed 'in situ' to pile driving sounds resulting in an estimated cumulative sound exposure of between 215 and 222 dB re 1µPa^2 s did not differ in immediate mortality compared to controls[547]. There were also no differences in delayed mortality up to 14 days after exposure.

The very limited data available for the effects of sonar on fishes show no evidence of tissue damage or mortality to adult fishes[548] [549]. Studies focused on larval and juvenile fishes exposed to mid-frequency sonar recorded significant mortality (20-30%) of juvenile herring in 2 out of 42 experiments[550], which was estimated in a 'worst-case' scenario to be equivalent to a lower mortality rate than would occur due to natural causes in the wild[551]. However, there is a need to repeat these experiments, as the sound level was only tested once, and so it is unknown if the increased mortality was due to the level of the test signal or to other unknown factors[552].

Behavioural Responses

There have been a range of studies to determine the potential effects of anthropogenic sound on marine fish behaviour but very little is known about the long-term effects of exposure to sound or about the effects of cumulative exposure to loud sounds. Fish behaviour is also often observed in a cage or tank, which can provide some useful information regarding the initial response to a sound[553] but is not representative of behaviour when exposed to the same sound in the wild, for example in a spawning or feeding ground[554]. Animals in captivity also behave differently when confined to those in the wild

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whose movements anr unrestricted[555]. It is also important to recognise that the responses of fishes may vary with their age and condition, as well as under different environmental conditions[556]. Behavioural responses can vary between different sound sources, or with the same sound when the level of sound received by the animal differs[557] [558].

The response to sounds by fishes can range from no change in behaviour to mild "awareness" of the sound or a startle response (but otherwise no change in behaviour), to small temporary movements for the duration of the sound, to larger movements that might displace fishes from their normal locations for short or long periods of time[559]. Depending on the level of behavioural change, there may be no real impact on individuals or populations or substantial changes (e.g., displacement from a feeding or breeding site or disruption of critical functions) that affect the survival of individuals or populations[560] [561]. However, there may be long-term effects on reproduction and survival in species that are subject to national or international conservation efforts and/or commercial interest[562].

Avoidance behaviour of vessels, vertically or horizontally in the water column, has been reported for cod and herring, and was attributed to vessel noise[563] [564]. Vessel activity can also alter schooling behaviour and swimming speed of fishes[565]. A review of fish avoidance of research vessels indicates that simple behavioural models based on sound pressure levels are insufficient to explain how fishes react to survey vessels, and that research is needed into the stimuli that fishes perceive from approaching vessels, particularly low-frequency infrasound[566].

In a field-based study with reliable acoustic data, schools of two species of wild pelagic fishes, sprats (*Sprattus sprattus*) and mackerel (*Scomber scombrus*)), in a quiet coastal location mainly responded to simulated pile driving sound by dispersing and changing depth respectively[567]. Recent tank-based studies, where acoustic conditions were less reliable, did show that the shoaling behaviour of groups of juvenile seabass (*Dicentrarchus labrax*) was affected by playbacks of pile driving[568]. The groups exposed to pile-driving sounds were less cohesive, less directionally ordered and less correlated in speed and directional changes compared to those exposed to ambient sound playbacks. In this case, the additional noise disrupted the ability of individuals to coordinate their movements with one another.

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Whether this effect has functional consequences (e.g., changes in predation risk) for shoaling fishes in natural conditions is not known but requires further assessement[569].

There has been concern regarding the effect of impulsive sound on migratory fishes where pile driving was conducted in a narrow straight used by salmon during the migration season[570]. The recorded sound exposure level of 190 dB 1 μPa s at a distance of 28 m from the pile was deemed high enough to block migration and potentially cause hearing damage to fishes passing close to the pile. Modelling of pile driving effects on migrating European sea bass using experimental behavioural data predicted that fishes would take significantly longer to arrive at their spawning site which could have important implications at a population level[571]. The temporal structure of sound can also affect behaviour. Sea bass exposed to both intermittent and continuous sound showed significantly slower recovery from the former compared to the latter[572]. It was suggested that intermittent sound (e.g., pile driving) may have stronger behavioural impacts on some fishes than continuous sounds (e.g., drilling) although further research is required to verify this for other species. Responses may also vary for the same species depending on the age / size and condition of the fish[573].

Large-scale avoidance behaviour was inferred from studies of the effect of seismic surveys on catch rates in long-line and trawl fisheries. Significant declines in catches of cod (G*adus morhua*) and haddock (*Melanogrammus aeglefinus*) were recorded up to 25 miles from the air-gun source, which was the maximum distance examined, and catch rates did not recover until five days after the seismic survey ceased, which was the maximum time observed[574] [575]. Similarly, a 52% decrease in rockfish (*Sebastes* spp,) catch (hook-and-line fishery) was reported when the catch area was exposed to a single air-gun array [576] which may have been caused by a change in swimming depth or shoaling behaviour [577] .Conversely, gillnet catches of redfish (*Sebastes norvegicus)* and Greenland halibut (*Reinhardtius hippoglossoides*) doubled during seismic shooting, although longline catches of haddock and Greenland halibut dropped, compared to pre-shooting levels[578]. Pelagic species such as blue whiting (*Micromesistius poutassou*) reacted to air guns by diving to greater depths but also by an increased abundance of fishes 30–50 km away from the affected area, suggesting that migrating fishes would not enter the zone of seismic activity[579]. Conversely, a study using direct video observation showed that temperate reef fishes remained close to their territories after exposure to air-gun arrays with only minor behavioural responses observed[580]. More recently, fish abundance on temperate reefs declined by 78%

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during seismic surveys compared to previous assessments on days with no seismic noise[581]. Schools of herring (*Clupea harengus*) did not react to a full-scale 3D seismic survey, which was attributed to a strong motivation for feeding, a lack of suddenness of the air gun stimulus (use of ramp up procedures) and an increased level of tolerance to the seismic survey[582]. Mid-frequency active sonar did not elicit a significant behavioural response in herring in terms of vertical or horizontal escape reactions[583]. Similarly, herring did not react significantly to low-frequency sonar signals from a passing vessel but did show a reaction to the sound of a two stroke engine at a much lower SPL[584]. ADD's (or pingers) which produce frequencies lower than 10 kHz and have a source level above 130 dB re 1 μPa are likely to have a significant influence on the behaviour of fishes[585]. Although the responses of fishes to commercially available acoustic harassment devices (AHDs) have not been thoroughly tested it is thought that AHDs which produce substantial energy in the ultrasonic range may cause some behavioural avoidance responses in fishes with good ultrasonic hearing but only close to the device (within 20 metres)[586].

A tank-based study of foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*) exposed to acoustic noise found that the addition of noise resulted in decreased foraging efficiency, with more attacks needed to consume the same number of prey items[587]. Acoustic noise increased food-handling errors and reduced discrimination between food and non-food items, results that are consistent with a shift in attention. In this case, noise may have attracted the attention of the fishes, thus preventing them from focusing fully on foraging. A similar study involving the same species and the European minnow (*Phoxinus phoxinus*) found that both species foraged less efficiently but their foraging behaviour was altered in different ways, with the minnow feeding less often whilst the stickleback fed at the normal rate but made more mistakes[588]. A significant modification in foraging habits has also been reported for Mediterranean damselfish (*Chromis chromis*) due to recreational boat noise[589].

Increased levels of anthropogenic noise in the marine environment may also invoke a stress response in fishes. Stress is known to affect health and well-being in terrestrial vertebrates by influencing processes such as growth and reproduction. Highly stressed fishes may also be more susceptible to predation or other environmental effects than non-stressed fishes[590]. Studies of captive freshwater fishes exposed to simulated boat noise for 30 minutes found increased level of the stress hormone cortisol in the blood[591]. Noise-related increases in heart rate, muscle metabolism and metabolic rates have also

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been reported for captive fishes[592] [593] [594]. Analysis of biochemical and haematological parameters, stress indexes and growth rate for farmed fish exposed to different types of background noise showed that fishes exposed to noise from onshore facilities were more stressed than those exposed to background noise from offshore aquaculture[595]. Although data are lacking for wild fishes in terms of noise-related stress effects, these studies at least suggest that anthropogenic noise could be a stressor in natural water bodies[596]. The issue of noise-related stress in marine fishes is clearly in need of investigation in the natural environment, which may involve developing new analytical techniques to accurately measure stress levels '*in situ'*. It is also important to mention that all the studies completed to date have been on captive animals in enclosed areas where the fish could not avoid the sounds[597]. It is therefore possible that the stress response could be related to the inability to move away from a sound rather than just the sound itself.

Reproductive success of fishes may also be sensitive to noise pollution, potentially reducing fitness[598] [599]. In aquarium experiments the courtship behaviour and spawning success of two closely related species of marine goby (two-spotted (*Gobiusculus flavescens*) and painted (*Pomatoschistus pictus*) gobies) were assessed when subjected to continuous noise. Reduced acoustic courtship by males was recorded in noise treatments for both species while less visual courtship was also shown for one species (painted goby). Female painted gobies were also less likely to spawn in the noise treatment. Overall the study provides experimental evidence of the negative effects of noise on acoustic communication for reproduction and spawning success[600]. Experimental evidence of disruption to reproductive success in natural conditions has also recently been reported. Parental behaviour and offspring survival for the spiny chromis on coral reefs was affected by playbacks of motorboat noise. Brood-guarding males were more defensive and interacted less with offspring when exposed to motorboat noise resulting in reduced likelihood of offspring survival[601].

<u>Masking</u>

Masking by anthropogenic noise can affect fishes in two main ways, by interfering with acoustic communication or through the masking of important environmental auditory cues.

The potential for masking of acoustic communication in marine fishes is considerable, while masking of auditory cues in a soundscape can potentially occur for all species of fishes. In terms of acoustic communication, over 800 species from 109 families of bony fishes are known to produce sounds and

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many more species are suspected to do so[602 603]. The hearing sensitivities of over 100 fish species have been determined[604]. In general, species that have potential specialisations for sound pressure detection detect sounds at higher frequencies (200 Hz – 3 kHz at best frequency) than fishes not known to be specialised[605]. The non-specialised fishes have a more diverse sensitivity and frequency range but generally have best frequencies of below 100 Hz to 1 kHz. Fishes are known to produce sounds during territorial fighting, when competing for food or when being attacked by a predator[606]. Acoustic communication can also be extremely important for courtship interactions[607] and in spawning aggregations[608]. There is some evidence that acoustic communication can affect the survival and reproductive success of fishes[609 610] and that communication and spawning success can be negatively affected by continuous noise[611]. However, it is not known whether the masking of the sounds produced by fishes for mate detection and recognition, or for aggregating reproductive groups have any significant fitness consequences for individuals or populations in the wild. It has been suggested that fishes offer a more feasible opportunity than marine mammals to investigate the effects of anthropogenic noise on acoustic communication to determine the impact on individual fitness and population viability[612].

A study in the Mediterranean Sea revealed that recreational boat noise can significantly increase detection threshold levels for conspecific sounds in brown meagre drums (*Sciaena umbra*) and Mediterranean damselfish (*Chromis chromis*). It was inferred that passing vessels were reducing detection distances in this environment by up to 100 times[613]. Signals may also be detected but not fully understood as some of the required information in the signal is lost. Although not reported in marine fishes to date, a reduction in detection distance that influenced mate attraction was reported in birds[614], while sexual signals for mate selection in frogs[615] have been masked in noisy conditions. Numerous studies on birds show that critical ratios can be used to predict the masked thresholds for pure tones when maskers consist of complex man-made and natural noises[616]. The general principles that hold for birds are very likely to hold for fishes[617]. Some fish communities that are located in busy shipping lanes or noisy coastal areas may be restricted in their ability to detect and respond to acoustic signals. The

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noise of large ferries masked the sound of Atlantic croaker calls, restricting communication[618]. On the Stellwagen Bank in Massachusetts Bay, commercial shipping activity elevates the amount of low frequency sound to near constant high levels. This is thought to reduce the communication space for Atlantic cod and haddock raising concerns that communication between conspecifics may be compromised during critical biological periods such as spawning[619] and therefore affect reproductive success. Vessel noise also reduced the communication space of the bigeye (*Pempheris adspersa*), a nocturnal fish species which uses contact calls to maintain group cohesion while foraging, by up to 62% with the passage of one large vessel less than 10 km from the listening station causing a reduction of 99%[620]. These results suggest that vessel noise may have chronic effects on some fish populations through the reduction of communication space.

Changes in fish acoustic behaviour in noisy environments have been found in a few cases. The mean pulse rate of sounds produced by brown meagres (*Sciaena umbra*) increased following repeated boat passes compared to ambient conditions, which was assumed to be caused by boat noise[621]. However, it was not known whether the increase in vocal activity was caused by an increased density of callers or by an increased acoustic output by those individuals already calling. More recently, evidence for the Lombard effect[622] in fishes has been reported for a freshwater fish, the Blacktail Shiner (*Cyprinella venusta*)[623]. This species increased its call amplitude in the presence of elevated background noise levels in experimental conditions by increasing the spectral levels of acoustic signals. The capacity of fishes to exhibit the Lombard effect is thought to be constrained by body size and the energetic costs of producing louder sounds[624]. Changes in call frequencies in response to abiotic noise sources[625] or to tidal state[626] have been also been reported in fishes but only for individual species. Further research is required in both laboratory and field conditions to determine whether the Lombard effect and other changes in vocal behaviour (see Radford et al., 2014 for potential ways) occur for many other fish species.

Anthropogenic noise may also interfere with prey or predator detection in marine fishes[627]. Predator avoidance by fishes may depend on species hearing or localizing specific sounds[628] [629]. Some herring species (Clupeidae) of the genus *Alosa* are capable of detecting ultrasound (up to 180 kHz), which could allow them to detect and avoid echo-locating whales[630]. Studies on European eels and juvenile salmonids revealed that they are able to detect and avoid infrasound (<20 Hz), which may allow them

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to sense the hydrodynamic noise generated by closely approaching predators[631] [632]. It has been suggested that predators that use sound for hunting (e.g., in dark or turbid environments) can be restricted by noisy conditions through lower availability of suitable foraging areas and a lower catching efficiency[633]. The latter has also recently been shown for predatory fishes that rely on vision to catch prey and was attributed to the sound interfering with the attention span of the fish, distracting it from feeding[634].

Antipredator behaviour has recently been shown to compromised by anthropogenic noise in some fish species for laboratory-based studies, but not for others. In playback experiments juvenile European eels were significantly less likely to be startled by an 'ambush predator' and caught more than twice as quickly by a 'pursuit predator'[635]. It was suggested that acoustic disturbance could have important physiological and behavioural impacts on animals, compromising life-or-death responses. Antipredator behaviour in two species of sympatric fish was not compromised when exposed to additional noise, with one species having a faster antipredatory response, which could be caused by increased vigilance[636]. More recently, studies of juvenile damselfish in natural conditions have shown that motorboat noise from two-stroke outboard engines compromised antipredator behaviour by changing the way the fish assess risk, which can reduce individual fitness and survival[637].

Anthropogenic masking of natural acoustic cues that are important for the orientation of marine fishes may also be occurring in coastal environments. The noise generated by temperate or tropical (coral) reef communities is one of the cues that may be used by the pelagic larval stages of reef fishes for orientation prior to settlement[638] [639] [640]. Fish larvae have also been shown to return to their natal reef[641] [642]. Recent studies of reef noise indicate that habitats within coral reefs produce different acoustic profiles[643] that are used by some species of juvenile reef fishes for nocturnal orientation[644]. It has also been found that reef fish larvae, after several hours of exposure, can become attracted to artificial sounds that would normally be avoided[645]. It has been suggested that increased levels of noise may inhibit orientation/settlement of fish larvae on coral reefs by masking the necessary acoustic cues received by larval fish[646], although the importance of acoustic cues compared to chemical ones has not been determined. Orientation of cardinalfish (Apogonidae) larvae was affected by boat noise in a choice

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chamber experiment, with significant directional responses recorded for reef+boat playback compared to reef only[647], although the acoustic properties of this type of tank-based experiment have been questioned. It does appear that anthropogenic noise has the potential to negatively influence the recruitment of fish larvae onto temperate or tropical reef systems, but this needs further verification. Shipping noise from engines has also been shown to attract settlement of mussel larvae, causing biofouling of ship hulls[648].

Anthropogenic-induced degradation of marine habitats such as coral reefs may also indirectly influence larval orientation and recruitment to habitats by changing the acoustic profile of these habitats. Quieter habitats combined with increasing anthropogenic noise may have an impact on larval recruitment through reduced settlement.[649].

This section has reviewed in some detail the known and potential impacts of anthropogenic noise on marine teleost fishes but elasmobranchs (sharks, skates and rays) have not been mentioned until now. In fact, there are no reported studies of the effects of anthropogenic noise exposure on elasmobranchs and only a few experiments exploring behavioural responses to sound in sharks (but not skates or rays)[650]. Studies of acoustic attraction in 18 species of coastal and oceanic sharks found that individuals would approach underwater speakers broadcasting low-frequency, erratically pulsed sounds from a distance of several hundred metres[651]. A few studies investigating avoidance behaviour, found that sudden loud sounds (20-30 dB above ambient noise levels) played when a shark approached a location would startle the shark and cause it to turn away from the area. In most cases involving attraction and repulsion, the sharks would habituate to the stimuli after a few trials[652].

Elasmobranchs do not have a swim bladder or any other air-filled cavity, meaning that they are incapable of detecting sound pressure. Therefore, particle motion is assumed to be the only sound stimulus that can be detected. The hearing bandwidth for elasmobranchs has been measured as between 20 Hz and 1 kHz, with similar thresholds in all species above 100 Hz[653]. Elasmobranchs do not appear to be as sensitive to particle motion as some teleost fishes when measured in comparable ways[654]. However, the current knowledge of elasmobranch hearing is based on data from only a few of the hundreds of species, and so one must be cautious in making generalizations about an entire subclass of fishes based on these data[655].

Anthropogenic noise sources that have the potential to affect elasmobranchs are thought to be pile driving, wind turbines and boat noise[656]. Elasmobranchs have been reported to aggregate around coastal and offshore man-made structures[657]. High intensity sounds produced by pile driving could damage

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[656] Ibid
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hearing in elasmobranchs in the form of a TTS and result in a temporary loss of sensitivity[658]. Secondly, the impact of the hammer on the pile may cause barotrauma in elasmobranchs. Tissue damage from pile driving sound was reported in some organs in teleost fishes including the liver and kidneys[659], although this was mainly caused by the rapid movement of the swim bladder walls, an organ absent in elasmobranchs. The continuous low frequency sound produced by operating turbines in offshore wind farms could potentially mask sounds that are important to elasmobranchs. Similarly, shipping noise may mask biologically important sounds or result in some of the effects observed in teleost fishes also occurring in elasmobranchs (e.g., the production of stress hormones)[660]. It is clear that extensive research is required to assess the effects of anthropogenic noise on elasmobranch (and also teleost) fishes in the marine and coastal environment.

Conclusion

Although our knowledge of the potential effects of anthropogenic sound on marine fishes has increased considerably over the past two decades the information available is still rather limited with large gaps in our understanding that require attention[661]. Many studies have been conducted on captive fishes under laboratory conditions, rather than on free living fishes in the wild[662], partly to the greater difficulty in undertaking acoustic studies on fishes in their natural environment. However, there are some advantages in conducting laboratory-based studies with a more refined experimental design that can be compared to field-based work[663]. In addition, although many laboratory-based studies may not have adequately measured the acoustic conditions, an effect of anthropogenic sound on fishes was often recorded. Further work with more refined experimental designs should be able to verify these studies and determine the actual acoustic conditions experienced by the animal in question. There is also a lack of information on the responses of fishes to particle motion, rather than sound pressure[664]. The current extent of the information gaps means that some researchers strongly argue that it is almost impossible to come to clear conclusions on the nature and levels of anthropogenic sound that have potential to cause changes in fish behaviour, or even physical harm[665].

More understanding of behavioural effects of anthropogenic sound on fishes and the potential for masking biologically important sounds is regarded as a critical research need given that the potential for these effects can extend for hundreds to thousands of metres from a sound source[666].

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Impacts on Other Marine Organisms

Other marine animals that are sensitive to underwater sound include marine turtles [667] and invertebrates[668 669]. There is limited information available for the effects of anthropogenic noise on these marine taxa at the present time although research and conservation interest is growing, more so for invertebrates than turtles. For example, a recent systematic review of the scientific literature for marine turtles and seismic surveys revealed only 29 references over a thirty year period (1983-2013)[670].

Marine Turtles

Marine turtles are sensitive to low frequency sounds within the range of 100 to 1000 Hz with greatest sensitivity between 100 to 400 Hz[671 672], which overlaps with the peak amplitude low frequency sound emitted by seismic airguns (10 – 500 Hz)[673]. Juvenile green turtles are sensitive to a broader and higher frequency range of 50 – 1600 Hz[674]. As for invertebrates, only studies involving air-gun arrays and their effect on marine turtles have been completed to date. These studies are either experimental where enclosed individuals are exposed to air guns or are part of monitoring assessments conducted during seismic surveys from the survey vessel[675]. Most experimental studies to assess short-term responses have demonstrated a strong initial avoidance response in marine turtles to air-gun arrays[676 677 678] at a strength of 175 dB re 1µPa rms or greater. Enclosed turtles also responded less to successive air-gun shots which may have been caused by reduced hearing sensitivity (TTS). For example, one turtle experienced a TTS of 15dB and recovered two weeks later[679]. It was estimated in one study that a typical air-gun array operating in 100–120 m water depth could cause behavioural changes at a distance of ~2 km and avoidance at around 1 km for marine turtles[680]. A recent monitoring assessment recorded that 51% of loggerhead turtles dived at or before their closest point of approach to the air-gun array[681]. Conversely, olive ridley turtles did not react to air gun shots[682]. No significant changes in behaviour were recorded for diamondback terrapins exposed to playback recordings of approaching boat engines[683].

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Long-term exposure to high levels of low frequency anthropogenic noise in coastal areas that are also vital habitat may affect turtle behaviour and ecology[684]. Acoustic disturbance could potentially lead to interruption of key behaviours such as for breeding, foraging or basking (thermoregulation) or changes in behaviour that compromise energy budgets[685]. Avoidance behaviour may result in significant changes in turtle distribution with potential consequences for individuals or populations if displaced from their preferred feeding habitat[686]. At lower sound levels turtles that remain in an affected area may show abnormal behaviour that reduces their foraging efficiency. However, there are currently no reported studies of the long-term effects of altered behaviour in marine turtles. This taxon requires substantial further research to determine the effects and impacts of various sources of anthropogenic noise on individuals and populations.

Marine Invertebrates

Most marine invertebrates that are sensitive to sound are receptive to low frequencies by detecting the particle motion component of the sound field. All cephalopods and some bivalves, echinoderms and crustaceans have a sac-like structure called a statocyst which contains a statolith and associated sensory hairs[687]. Statoliths are thought to allow an organism to detect particle motion. Epidermal hair cells (cephalopods) and sensory setae (crustaceans) also help to detect particle motion in their immediate vicinity. Crustaceans appear to be most sensitive to sounds of less than 1 kHz[688] but able to detect up to 3 kHz in some species[689]. Cephalopods are sensitive to water movement stimuli in a range between <20 and 1500 Hz[690] [691]. There have been a number of recent reviews on particle motion and vibration in relation to invertebrates with detailed information on assessment approaches, sensory mechanisms and potential effects including behavioural responses[692] [693] [694]. As well as being receptive to sound many invertebrates are also capable of producing sounds including species of barnacles, amphipods, shrimp, crabs, lobsters, mantis shrimps, sea urchins and squid[695] [696] [697] [698]. In some species, the sounds emitted are thought to be ecologically important in terms of acoustic communication between conspecifics[699].

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684 Samuel Y. et al., 2005. Underwater, low-frequency noise in a coastal sea turtle habitat. J. Acoust. Soc. Am. Volume 117, Issue 3, pp. 1465-1472

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686 Pendoley, K. 1997. Sea turtles and management of marine seismic programs in Western Australia. Petrol. Expl. Soc. Austral. J. 25:8-16.

687 Carroll, A.G. et al. 2017. A critical review of the potential impacts of marine seismic surveys on fish and invertebrates. Mar. Poll. Bull. 114: 9-24.

688 Budelmann, B. U. (1992a). Hearing in crustacea. In The Evolutionary Biology of Hearing (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 131-140. New York: Springer-Verlag

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697 Radford, C., Jeffs, A., Tindle, C., Montgomery, J.C., 2008. Resonating sea urchin skeletons create coastal choruses. Mar. Ecol. Prog. Ser. 362, 37–43.

698 Staaterman, E.R., Clark, C.W., Gallagher, A.J., deVries, M.S., Claverie, T. and Patek, S.N. 2011. Rumbling in the benthos: acoustic ecology of the California mantis shrimp *Hemisquilla californiensis.* Aquat Biol 13: 97-105

699 Ibid

It has been suggested that acoustic communication and perception in invertebrates might be related to as many functions as in marine vertebrates[700].

At the time of writing there are no reported research studies to determine the effects of a number of anthropogenic noise sources (e.g., some industrial activities and sonar) on marine invertebrates. In addition, there are currently no reliable data available on hearing damage in invertebrates as a result of exposure to anthropogenic noise[701]. Sensitivity to low frequencies indicates that marine invertebrates are likely to be susceptible to sources such as shipping noise, offshore industrial activities (e.g., wind or tidal turbines) and seismic surveys. These sources have been investigated to some extent in terms of physical and behavioural reactions, and recently for stress responses and effects on larvae for a few marine species[702]. The general lack of knowledge of noise effects or impacts on invertebrates means that thresholds for harmful sound exposure levels for these taxa have not been developed yet.

Initial studies primarily focussed on the impact of seismic surveys (air-gun arrays) on marine invertebrates, mainly crustaceans and cephalopods. A critical review of 20 studies completed up to 2004 found that only nine were quantitative and within these the effects on marine invertebrate species were mixed[703]. The authors concluded that the lack of robust scientific evidence for the effects of seismic surveys on marine invertebrates meant that no clear conclusions could be made.

Marine invertebrates can be affected by seismic surveys in terms of behaviour. Direct observation of squid exposed to air-gun sound showed a strong startle response involving ink ejection and rapid swimming at 174 dB re 1µPa rms and also avoidance behaviour[704].

There are however a number of more recent studies that should be mentioned for airgun effects. Firstly, an extensive critical review of the literature regarding marine invertebrates (and fishes) and seismic surveys was published in 2017[705]. This provides a detailed overview of the subject including summaries of published studies, current limitations and challenges and recommendations for further research.

A significant increase in the strandings of giant squid in Spain during 2001 and 2003 coincided with the proximity of seismic survey vessels conducting air-gun arrays[706]. Pathological analysis of stranded squid showed the presence of lesions in tissues and organs leading to the suggestion that they were caused by excessive sound exposure from air guns[707]. Secondly, an experimental study showed that moderately intense low frequency sound was responsible for the severe acoustic trauma and mortality in four species of cephalopod[708]. Lesions in the sensory and lining epithelia of the statocysts, and damaged sensory hair cells and nerve fibres were reported in each species[709]. In particular, massive lesions were found in cuttlefish for all noise exposed individuals[710]. The number of lesions also

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[710] Ibid

increased with greater exposure to low frequency sound. Regeneration of statocyst sensory epithelium was also tentatively identified but requires further study for verification. As relatively low levels of low-frequency sound and short exposure had induced severe acoustic trauma in these cephalopods, it was suggested that there may be considerable effects of similar noise sources on these species in natural conditions over longer time periods[711]. Mediterranean studies have more recently assessed the effects of low-frequency sound on cnidarians, with injuries observed to the statocyst sensory epithelium of two species of jellyfish (Scyphozoa) that are consistent with acoustic trauma observed in other species[712].

Noise effects on marine invertebrate larvae have recently been demonstrated for a number of types of low frequency sound. Almost half (46%) of scallop larvae (*Pecten novaezelandiae*) exposed to playbacks of seismic pulses developed body abnormalities and significant developmental delays were also evident[713]. Playbacks of boat noise to sea hare embryos (*Stylocheilus striatus*) also delayed development, and increased mortality of recently hatched larvae[714]. In laboratory experiments, exposure to continuous sound from tidal or offshore wind turbines significantly delayed megalopae metamorphosis in two species of brachyuran crab when compared to development in natural habitat sound[715].

A number of behavioural responses to anthropogenic noise have been reported in recent publications for marine invertebrates. Foraging and antipredator behaviour of shore crabs (*Carcinus maenas*) was negatively affected by playback of ship noise in controlled tank-based experiments suggesting an increased risk of starvation or predation[716]. Ship noise also increased the settlement rate of green-lipped mussel larvae (*Perna canaliculus*)[717], which may have connotations for ship fouling by mussels. A study of noise-related effects on cuttlefish behaviour indicates that interference of the acoustic sensory channel affected signalling in another (visual) sensory channel, i.e., anthropogenic noise, has a marked effect on the behaviour of a species that does not rely on acoustic communication[718]. All sensory channels should therefore be considered when trying to understand the overall effects of anthropogenic stressors such as noise on animal behaviour.

More subtle physiological changes could also occur in an environment exposed to noise. For example, brown shrimp exposed to increased background noise for up to three months demonstrated significant decreases in both growth and reproductive rates[719]. Shrimps were also more aggressive in the noisy treatments with increased mortality and decreased food intake. These are often regarded as symptoms of stress in vertebrates. Stress responses to playbacks of shipping noise have been reported for a number of marine crustaceans. Components of the haemato-immunological system of the Mediterranean spiny lobster (*Panulirus elephas*) were altered[720], while the metabolic rate of the shore crab (*Carcinus maenas*) increased for crabs experiencing ship-noise playbacks compared to ambient noise[721]. Exposing

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[712] Solé, M. et al. 2016. Evidence of Cnidarians sensitivity to sound after exposure to low frequency underwater sources. Scientific Reports 6: 379979.

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[719] Lagardère, J.P. 1982. Effects of noise on growth and reproduction of *Crangon crangon* in rearing tanks. Mar. Biol. 71:177-186.

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[721] Wale MA, Simpson SD, Radford AN. 2013 Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise. Biol Lett 9: 20121194.

red swamp crayfish (*Procambarus clarkii*) to low frequency sound also produced significant variations in haemato-immunological parameters[722].

Increased levels of background noise are likely to alter the acoustic environment of marine invertebrates. Low frequency anthropogenic noise may be masking acoustic communication in marine invertebrates such as crustaceans[723] or the detection of prey or predators by cuttlefish[724]. Masking of important acoustic cues used by invertebrates during larval orientation and settlement may also be a factor in the coastal zone and could lead to maladaptive behaviour that reduces successful recruitment[725].

Researchers are starting to pay more attention to the assessment of particle motion and vibration in relation to anthropogenic noise effects on invertebrates in the marine and coastal environment, particularly with regard to the epibenthos[726], but also sediment-dwelling taxa[727]. A review of the literature in 2017 found only four publications that directly linked marine benthic species to anthropogenically produced sediment vibration levels. One study used modelling to estimate the impact range of pile driving on the American lobster, at up to 500 m from the source[728]. The remaining three studies investigated the sensitivity and behavioural responses of blue mussels and hermit crabs to sediment vibration, which indicated that these species showed responses up to 300 m from blasting and 220 m from backhoe dredging[729] [730] [731].

For invertebrates living in the sediment, two functionally important species, a clam (*Ruditapes philippinarium*) and a decapod (*Nephrops norvegicus*) showed behavioural changes and stress response when exposed to underwater broadband sound fields that resembled offshore shipping and construction activity, which altered their contributions to fluid and particle transport, both key processes in mediating benthic nutrient cycling[732]. The study provides evidence that exposing coastal environments to anthropogenic sound fields is likely to have much wider ecosystem consequences than are presently acknowledged.

Although the number of scientific studies of underwater noise effects on marine invertebrates is growing, there are still large gaps in our knowledge about sound thresholds and recovery from impact in almost all taxa[733]. Studies on physical trauma, behavioural changes, and physiological indicators of stress are all required to provide a more mechanistic understanding of potential impacts. Without this information, it has been suggested that generalisations about impacts from low frequency sources are

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[728] Miller, J.H. et al. 2016. Pile-driving pressure and particle velocity at the seabed: quantifying effects on crustaceans and groundfish. In: Popper, A.N., Hawkins, A.D. (Eds.) The Effects of Noise on Aquatic Life II pp. 705–712. Springer, New York
[729] Roberts, L. et al. 2015. Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically generated noise. Mar. Ecol. Prog. Ser. 538: 185-195.
[730] Roberts, L. et al. 2016. Sensitivity of *Pagarus bernhardus* (L.) to substrate-borne vibration and anthropogenic noise. J. Exp. Mar. Biol. Ecol. 474: 185-194.
[731] Roberts, L. et al. 2017. Exposure of benthic invertebrates to sediment vibration: from laboratory experiments to outdoor simulated pile-driving. Proc. Meetings Acoust. 27.
[732] Solan, M. et al. 2016. Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. Sci. rep. 6: 20540.
[733] Carroll, A.G. et al. 2017. A critical review of the potential impacts of marine seismic surveys on fish and invertebrates. Mar. Poll. Bull. 114: 9-24

not scientifically valid[734]. Assessment of particle motion to determine anthropogenic noise effects or impacts on marine invertebrates is a key area of research that requires support and development.

Seabirds

More than 800 species of birds live on or near water, many of whom dive when foraging for food[735], including cormorants, grebes, auks, murres and sea ducks, not to mention penguins. Diving seabirds can be exposed to underwater noise when feeding but there are no reported studies of the effects of noise on the hearing of seabirds[736] [737]. Noise-induced damage to hair cells has been measured in terrestrial birds although as a group, birds are considered more resilient to auditory damage than mammals as they can replace hair cells of the cochlea and vestibular system[738]. Severe non-auditory damage of seabirds exposed to intense noise in the form of explosions has been reported for western grebes following an underwater detonation from military training activities[739]. Birds attracted to fish kills after initial detonations were subsequently impacted by further blasts leading to 70 individuals washed up on a nearby beach. Necropsy of 10 birds confirmed that the blast injuries were sustained by the grebes were the cause of death. Diving seabirds are likely to be at greater risk of a noise impact if they are attracted to feed on dead or disorientated fish in the vicinity of impulsive sources such as seismic arrays, pile driving or explosives[740].

There are very few studies of diving birds reacting to underwater noise. Underwater playback of chase-boat engines has successfully been used to scare diving birds and reduce predation of farmed mussels by eider ducks, long-tailed ducks and common scoters[741] [742]. Playbacks of underwater noise were also used to scare African penguins out of an area where blasting was planned[743]. However, no specific and detailed behavioural studies of the noise effects on seabirds have been conducted to date. Strong behavioural reactions to sudden or loud airborne sounds have been documented for seabirds such as king penguins[744] and crested terns[745]. However, it is not known whether seabirds are as sensitive to underwater noise as to airborne sound[746], although it has been suggested that diving birds may not hear well underwater and that the frequency of best hearing is lower (2 -4 kHz.) in water than in air[747]. If diving seabirds and penguins are vulnerable to underwater noise, a behavioural change could lead to

734 Ibid

735 Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_17

736 Ibid

737 Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

738 Dooling, R.J. and Blumenrath, S.H. 2013. Avian sound perception in noise. In H. Brumm, ed. Animal Communication and Noise. pp. 229-250. Springer, Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-41494-7_8.

739 Danil, K. and St. Leger, J.A. 2011. Seabird and dolphin mortality associated with underwater detonation exercises. Marine Technology Society Journal, 45(6), 89-95.

740 Aguilar de Soto, N. 2016. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York.

741 Ross, B.P., Lien, J. & Furness, R.W. 2001. Use of underwater playback to reduce the impact of eiders on mussel farms. ICES Journal of Marine Science 58: 517–524.

742 Lien, J., and Hennebury, P. 1997. You can fool all of the ducks some of the time; you can fool some of the ducks all of the time; but you can't fool all of the ducks all of the time: an investigation of diving duck predation on farmed mussels, and evaluation of a harassment procedure to minimize it. Report for the Department of Agriculture, Fisheries and Forestry, Government of PEI and the Department of Fisheries, Government of Nova Scotia. 69 pp.

743 Cooper J. 1982. Methods of reducing mortality of seabirds caused by underwater blasting. Mar. Ornith. 10, 109-113.

744 Wilson, R. P., Culik, B., Danfeld, R., and Adelung, D. 1991. People in Antarctica, how much do adelie penguins, Pygoscelis adeliae, care? Polar Biology, 11:363-370.

745 Brown, A. 1990. Measuring the effect of aircraft noise on lated jet aircraft noise on heart rate and behaviour of sea birds. Environment International, 16, 587-592

746 Aguilar de Soto, N. 2016. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York.

747 Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730.

reduced foraging or avoidance of a feeding area with possible implications for survival and fitness. This is especially applicable to penguins as they spend long periods in the water foraging and diving[748]. A recent study of African penguins revealed a strong avoidance of preferred foraging areas during seismic surveys[749]. The penguins foraged significantly further from the source vessel when in operation, increased their overall foraging effort and then resumed normal behaviour when the surveys ceased.

The lack of information available for diving seabirds hearing in water and whether there are significant effects of underwater noise strongly supports the need for a detailed programme of research. Comparative anatomical studies of diving birds middle and inner ears are required along with behavioural studies of hearing in air and in water[750]. Secondly, behavioural studies of these birds in their natural habitats are needed to determine whether sound is used to communication, foraging, predator avoidance or other behaviour[751].

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[748] Aguilar de Soto, N. 2016. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York.

[749] Pichegru, L. et al. 2017. Avoidance of seismic survey activities by penguins. Sci. Rep. 7: 16305.

[750] Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_17.

[751] Ibid.

5. MITIGATION AND MANAGEMENT OF UNDERWATER NOISE

This chapter reviews the existing measures and procedures in place to mitigate for the effects of underwater noise on marine biodiversity. It highlights examples of best environmental practise and best available technology to reduce the impact of anthropogenic noise on marine organisms. The other main topics covered here are recent advances in monitoring and mapping tools to support mitigation, assessment and management frameworks available for underwater noise, and progress in the development of regional and international standards for the measurement of underwater sound and noise from anthropogenic sources.

It should be noted here that the overall high level of uncertainty that currently exists regarding many of the effects of anthropogenic noise on marine fauna means that it is very important to use a precautionary approach when undertaking noise-emitting activities in the marine environment. The application of the precautionary principle to the issue of marine noise has been discussed in some detail[752]. Precautionary approaches may be inconvenient to those with narrow commercial interests, but precaution in the face of uncertainty is rational and is an approach that is now deeply embedded in the way that society operates[753]. Reducing uncertainty by increasing our knowledge and understanding of the issue will be the best guard against excessive precaution and over-regulation[754].

Mitigation measures for underwater noise fall into two main categories: noise control at source and spatio-temporal restrictions of noise producing activities. The type of mitigation and management also depends on the main characteristics of the anthropogenic sound in question, i.e., whether it is impulsive or continuous noise. Mitigation of the source can take the form of reducing the total amount of sound produced, by reducing power, duration and/or by reducing the number of times a system transmits sound. Where the species of concern has a well-defined hearing sensitivity, it may be possible to operate at frequencies where the animal's hearing is relatively insensitive.

Mitigation and management of anthropogenic noise through the use of spatio-temporal restrictions (STR) of noise generating activities has been recommended as the most practical and straightforward approach to reduce acoustic effects on marine animals[755]. Geographical and seasonal restrictions to avoid the ensonification of sensitive species and habitats can be a highly effective mitigation measure[756] as part of an STR approach within marine spatial planning. Sound-producing activities can be scheduled to avoid areas or times that sensitive marine mammals and other species use for susceptible activities such as mating, breeding, feeding, or migration. Enforcement of permanent or temporary exclusion zones does require effective and constant monitoring, control and surveillance[757]. However, preventing an intentional noise source in a targeted location is not always possible especially if there is a temporal overlap between the window of opportunity for industrial activities and the presence of the species of concern. In this situation, detailed and comprehensive mitigation procedures and measures are recommended, with more stringent measures needed if the area contains sensitive habitats used by marine fauna for feeding, breeding, nursing or spawning. The extensive data and knowledge gaps for many species also emphasises the need for a precautionary approach to minimise potential noise effects.

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752 Gillespie, A. 2007. The Precautionary Principle in the Twenty-First Century: A Case Study of Noise Pollution in the Ocean. The International Journal of Marine and Coastal Law 22(1): pp. 61-87

753 Boyd, I.L., G. Frisk, E. Urban, P. Tyack, J. Ausubel, S. Seeyave, D. Cato, B. Southall, M. Weise, R. Andrew, T. Akamatsu, R. Dekeling, C. Erbe, D. Farmer, R. Gentry, T. Gross, A. Hawkins, F. Li, K. Metcalf, J.H. Miller, D. Moretti, C. Rodrigo, and T. Shinke. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181, doi:10.5670/oceanog.2011.37.

754 Ibid

755 Agardy, T., Aguilar, N., Cañadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E., Martin, V., Notarbartolo di Sciara, G., Pavan, G., Servidio, A., Smith, B., Wang, J., Weilgart, L., Wintle, B. and Wright, A. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages

756 OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

757 André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029. www.lab.upc.es .

Although research is opening our eyes to some of the less obvious behavioural effects of noise on marine animals (e.g. stress responses, communication masking, cognitive bias, fear conditioning, and attention and distraction), we still have very restricted knowledge and understanding of how these effects influence overall impacts on populations. In addition, most current mitigation measures are not very effective in reducing cumulative impacts on marine fauna[758]. They also do not fully consider the exposure context of individuals and how a combination of acute and chronic noise can interact with animal condition to elicit a behavioural response[759].

The vast majority of mitigation measures in place have been primarily designed to reduce underwater noise effects on marine mammals. Similarly, considerably more research has been conducted on hearing and acoustic impacts on these taxa, with particular attention paid to cetaceans, although large knowledge gaps still exist for many species. There is scope to use or adapt the underlying mitigation frameworks and main procedures for non-mammal marine taxa such as teleost fishes, marine turtles and invertebrates. However, specific mitigation measures and protocols for these animals are on the whole still lacking and are urgently needed for many vulnerable and/or important species.

Mitigation of marine noise in the oceans is in place for industrial and military activities in some regions of the world through the use of practical measures and guidelines. However, critical analysis of this guidance has identified a number of significant limitations[760] [761], including the considerable variation in standards and procedures between regions or navies. Mitigation of anthropogenic sound levels in the marine environment require regular updating to keep in touch with changes in acoustic technology and the latest scientific knowledge of marine species such as acoustic sensitivity and population ecology. There have been calls for the setting of global standards for the main activities responsible for producing anthropogenic sound in the oceans. Progress is being made with regard to commercial shipping and quieting but standards for naval sonar or seismic surveys are also required to further reduce impacts on marine species.

Mitigation Measures and Procedures

This section provides selected best practise examples of mitigation measures and procedures currently used by Governments and/or Industry for a number of anthropogenic noise generating industrial or military activities including marine construction (including harbours and offshore renewable energy developments), naval sonar and explosives, and seismic surveys (for scientific exploration, as well as oil and gas) and shipping. Mitigation measures include the use of set noise exposure criteria; exclusion zones, spatio-temporal restrictions (MPAs), operational procedures, e.g., soft start / ramp-up, and quietening technology. The main technological and economic constraints of industry to meet best practise procedures are also discussed.

As well as undertaking specific real-time mitigation measures during the primary noise generating activity, mitigation procedures are becoming part of an overall process to assess the environmental characteristics of the area to be subjected to anthropogenic noise and identify, through modelling, the times and locations where species are most likely to be at risk. The vast majority of mitigation procedures have been designed for marine mammals, predominantly for cetaceans. However, many of the generic procedures are also applicable to other marine taxa such as fishes and invertebrates, although particular mitigation measures may not be (e.g., the use of visual observers to determine species

[758] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[759] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2011. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology

[760] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27

[761] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477.

presence and proximity to a noise generating activity), whilst the effectiveness of others is not known (e.g., soft start procedures for marine fishes). Limitations of existing mitigation guidelines and practises are not discussed in detail here as these have been thoroughly reviewed previously[762] [763].

Impulsive Noise Mitigation

A methodological guide was produced to address impulsive noise sources in the marine environment that can have an impact on cetaceans in the ACCOBAMS region[764]. Mitigation guidance is provided for offshore construction (predominantly pile-driving), military and civil sonar, seismic surveys and explosives. For each of these noise sources a mitigation framework is required that consists of three main stages; a planning phase, real-time mitigation and a post-activity phase (Table 3). Many of the mitigation measures are common to all four types of noise source (e.g., soft start and visual/acoustic monitoring protocols), while some measures are specifically recommended for one or two activities such as buffer zones for sonar use or the use of acoustic mitigation devices for offshore construction or the use of explosives.

Prior to the planning phase of the mitigation framework a comprehensive environmental impact assessment (EIA) should be conducted for the proposed activity. Although not always required by law, operators wishing to be regarded as adhering to the highest standards of environmental responsibility should make environmental impact assessment an intrinsic part of project planning[765]. A model EIA and consultation process for seismic surveys has recently been proposed[766]. This sets out in detail the requirements for a fully transparent process over three main stages: 1. developing a thorough EIA, 2. stakeholder consultation, and 3. ongoing stakeholder engagement. Ideally, baseline assessments and long-term monitoring of the affected area should be started as early as possible, preferably a number of years before the operation is planned. For example, industry-sponsored baseline assessments and long-term monitoring of cetaceans were initiated eight years before a specific hydrocarbon operation was planned to start in Angola, facilitating the development of mitigation measures and enabling the detection of behavioural changes in Humpback whales during seismic surveys[767]. For other marine taxa existing national or regional databases should be utilised, for example, datasets collected by the fishing industry or fisheries research organisations for commercial species.

[762] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27

[763] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477

[764] ACCOBAMS 2013. Methodological Guide: Guidance on underwater noise mitigation measures. ACCOBAMS-MOPS/2013/Doc24

[765] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377.

[766] Prideaux, G. and Prideaux, M. 2013. Seismic Seas: Understanding the impact of offshore seismic petroleum exploration surveys on marine species. Wild Migration technical and policy review #3. Wild Migration, Australia.

[767] Cherchio, S. et al., 2010. Humpback whale singing activity off northern Angola: An indication of the migratory cycle, breeding habitat and impact of seismic surveys on singer number in Breeding Stock B1. International Whaling Commission, Cambridge, UK.

Table 3. ACCOBAMS Mitigation Frameworks for Impulsive Noise Generating Activities

Stage	Action	Pile Driving, Drilling, Dredging	Seismic surveys	Military or Civil Sonar	Explosives
Planning Phase (expected outcomes of the EIA)	1. Review the presence of cetaceans in the candidate periods for the work and conduct or fund research where information is absent or inadequate	✓	✓	✓	✓
	2. Select periods with low biological sensitivity	✓	✓	✓	✓
	3. Define no-survey or exercise zones (biological reserves, protected areas etc.)		✓	✓	
	4. Define buffer zones			✓	
	5. Use sound propagation modelling results, verified in the field, to define the Exclusion Zone (EZ)	✓	✓	✓	✓
	6. Plan the lowest practicable source power or charge (explosive)	✓	✓		✓
	7. Consider alternative technologies	✓	✓		
	8. Plan noise mitigation technologies (if no alternatives are possible)	✓			
Real time mitigation	1. Use Acoustic Mitigation Devices prior to the beginning of the work	✓			✓
	2. Use noise mitigation technologies, e.g., air bubble curtain, hydrosound damper net				✓
	3. Use a soft start protocol	✓	✓	✓	✓
	4. Use the visual monitoring protocol (MMO's)	✓	✓	✓	✓
	5. Use the acoustic monitoring protocol (PAM equipment)	✓	✓	✓	✓
Post Activity	1. Detailed reporting of real-time mitigation	✓	✓	✓	✓

Further detail for the ACCOBAMS guidelines are available as an Annex to ACCOBAMS Resolution 4.17[768]. These consist of general guidelines to be followed for any noise generating activity and more specific guidance for each source type. Using the general guidelines as a baseline we can develop a 'working list' of best practise guidance for the mitigation of anthropogenic impulsive noise effects on marine biodiversity, with current emphasis on marine mammals:

General guidelines for Impulsive Noise Generating Operations in the Marine Environment (adapted from ACCOBAMS Resolution 4.17)

1. Consult databases of selected taxa spatial and seasonal distribution and habitats in order to plan and conduct activities at times and locations when animals are unlikely to be encountered whilst also avoiding critical habitats.
2. Collect information and, if required, organise field data collection (surveys or monitoring with fixed detectors) to assess the population densities in the areas selected for operation.
3. Avoid marine taxa's key habitats and marine protected areas, define appropriate buffer zones and consider the possible impact of long-range propagation.
4. Consider cumulative impacts of noise and other anthropogenic stressors over time including seasonal and historical impacts from all other impulsive and continuous noise sources in the specific operational area and adjacent region. Develop GIS/databases that track the history of noise generating activities in the region for the selected taxa.
5. Model the generated sound field in relation to oceanographic features to define the area likely to be affected by the noise source.
6. Determine safe/harmful exposure levels for various species, age classes, contexts that are precautionary enough to consider large levels of uncertainty.
7. Exclusion zones (EZ) should be determined on a scientific and precautionary basis rather than an arbitrary or static designation. EZ determination should be modelled on the source characteristics, the species in question and on local sound propagation features and verified in the field. Adopt the safest, most precautionary EZ option if there are multiple choices.
8. Consider the establishment of a larger exclusion zone to reduce behavioural disruption, based on the latest scientific information for the selected taxa/species.
9. Real-time mitigation guidelines should be adopted and publicised by all operators.
10. Use an automated system to record the acoustic source and document the amount of acoustic energy produced. Make this information available to noise regulators and the public.
11. Mitigation should include monitoring and reporting protocols to document the implemented procedures and their effectiveness, and provide datasets to improve existing databases for marine taxa.
12. During operations, existing stranding networks in the area should be alerted and additional monitoring of the closest coasts and for deaths at sea should occur if required (mainly for marine mammals).
13. If required, organise post-operation field data collection to determine whether population changes or anomalous deaths occurred as a possible consequence of operations (requires pre-operation knowledge of the area).
14. If strandings occur, possibly related to operations, acoustic emissions should stop and maximum effort devoted to understanding the causes of death (mainly for marine mammals).
15. If abnormal behaviours are observed in animals close to operations, acoustic emissions should stop and maximum effort addressed to monitoring those animals.
16. Trained and approved marine mammal observers (MMO) and bio-acousticians (e.g., PAM operators) should be employed for the monitoring and reporting programme including overseeing implemented mitigation rules.

[768] ACCOBAMS 2010. Resolution 4.17. Guidelines to Address the Impact of Anthropogenic noise on cetaceans in the ACCOBAMS area: (http://www.accobams.org/new_accobams/wp-content/uploads/2016/06/ACCOBAMS_MOP4_Res.4.17.pdf)

17. Observers and bio-acousticians must be qualified, dedicated and experienced, with suitable equipment.
18. Observers to report to the regulatory body using a standardized reporting protocol. Accurate reporting is required to verify the EIA hypothesis and the effectiveness of mitigation.
19. Procedures and protocols should be based on a conservative approach that reflects levels of uncertainty and should include mechanisms that create an incentive for good practise.
20. When uncertainties occur, a precautionary approach needs to be taken and unexpected events or uncertainties referred to the regulatory body.

Responsible practises to minimise and monitor the environmental impacts of seismic surveys have been published with an emphasis on marine mammals[769] but are also applicable to other marine taxa of concern such as teleost fishes, marine turtles and seabirds. The overall general approach described for predicting, minimising and measuring impacts could also be applicable to other impulsive noise sources as mentioned in Table 1. A practical roadmap for planning, executing, evaluating and improving the design of an impulsive noise generating activity (in this case a marine seismic survey) is set out in Figure 7. The main aspects of planning and executing the operation are provided in Table 4.

National seismic survey guidelines for operations in Canadian waters are set out in a 'Statement of Canadian Practise with respect to the Mitigation of Seismic Sound in the Marine Environment[770]. This statement both formalises and standardises mitigation measures in Canada for seismic operations and was developed using the best available and internationally-recognised mitigation techniques. It considers not only marine mammals, but also marine turtles and fishes, and at the population-level any other marine species. At the planning stage, seismic surveys must be planned to avoid:

- A significant adverse effect on individual marine mammals or sea turtles that are listed as endangered or threatened on Schedule 1 of the Species at Risk Act;
- A significant adverse population-level effect for any other marine species;
- Displacing individuals of endangered or threatened species of marine mammal or turtle from breeding, feeding or nursing;
- Diverting migrating individuals of endangered or threatened species of marine mammal or turtle from a known migration route or corridor;
- Dispersing aggregations of spawning fishes from a known spawning area;
- Displacing a group of breeding, feeding or nursing marine mammals, if it is known there are no alternate areas available to those marine mammals for those activities, or that if by using those alternate areas, those marine mammals would incur significant adverse effects; and
- Diverting aggregations of fish or groups of marine mammals from known migration routes or corridors if it is known there are no alternate routes or corridors, or if the fish aggregations or marine mammal groups incur significant adverse effects if they use an alternate migration route or corridor.

To avoid the seismic operation having any of the effects mentioned above will require extensive background knowledge of the area to be surveyed in terms of marine fauna distribution, migration and critical habitats and seasons for feeding, breeding/spawning and nursing. This emphasises the need to collect and analyse all available information prior to the proposed operation (Table 4).

Once there is sufficient baseline information for an area of proposed activity, it is possible to draw up a set of spatio-temporal restrictions, so that the species or taxa of concern are not affected or that disturbance is kept to a minimum. Geographical and seasonal restrictions to avoid the ensonification of

[769] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377

[770] http://www.dfo-mpo.gc.ca/oceans/management-gestion/integratedmanagement-gestionintegree/seismic-sismique/statement-enonce-eng.asp

particular species and habitats are widely regarded as a highly successful mitigation measure[771]. The noise generating activity should be scheduled to avoid times or locations that the marine fauna of concern use for activities such as breeding/spawning, feeding, or migration. However, in some cases, complete avoidance of an area during a particular temporal window may not be possible. For example, at high latitudes where sea ice occurs there can be an overlap between the time available for seismic surveys and the presence of sensitive species of marine mammals such as Gray or bowhead whales[772]. In such situations, there needs to be particular attention paid to planning, mitigation and monitoring and the analysis of potential effects. This more stringent and precautionary approach should be regarded as an indication of responsible practise by industry whether it is legally required or not[773].

Noise mitigation procedures are also required for decommissioning offshore structures in the marine environment such as oil and gas platforms or wind turbines. The ACCOBAMS methodological guide[774] provides some guidance for the mitigation of explosives which can be used to decommission structures in some cases. Other activities that will produce noise during decommissioning are ship movements and the mechanical lifting of materials from the water.

In a preliminary assessment of operational and economic constraints regarding the implementation of underwater noise mitigation measures by industry, consultations with both industry and the military were conducted to discuss the mitigation of underwater noise produced by wind farm construction, seismic surveys, naval sonar, marine traffic and dredging[775]. The mitigation guidelines in question were those established by international bodies (ACCOBAMS, ASCOBANS, OSPAR and ICES) and the draft guidelines for shipping within the IMO[776]. For the oil and gas industry, relatively few constraints were raised about implementing the guidelines for seismic surveys with two measures identified as expensive and difficult to implement; changing course during a survey and the use of low power sources. The shipping sector and the military regarded the use of many measures as problematic. Shipping authorities stated that implementing noise mitigation measures would be very expensive, and the use of alternative or new designs was not favoured until independent research could verify their effectiveness. The renewable energy industry were generally in favour of using most recommended mitigation practises and procedures but were less interested in adopting mitigation technologies because of the high cost and operational issues. There were also concerns with stopping piling if a cetacean was detected during the exclusion zone and rescheduling work to avoid sensitive times as this would mean shifting activities to winter months with increased cost.

[771] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.
[772] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377
[773] Ibid
[774] ACCOBAMS 2013. Methodological Guide: Guidance on underwater noise mitigation measures. ACCOBAMS-MOPS/2013/Doc24
[775] Maglio, A. 2012. Implementation of underwater noise mitigation measures by industries: operational and economic constraints. Prepared for the Joint ACCOBAMS-ASCOBANS noise working group. Sinay, Caen, France
[776] Ibid

Figure 7: A practical roadmap for planning, executing, evaluating and improving the design of a marine seismic survey (after Nowacek et al., 2013)

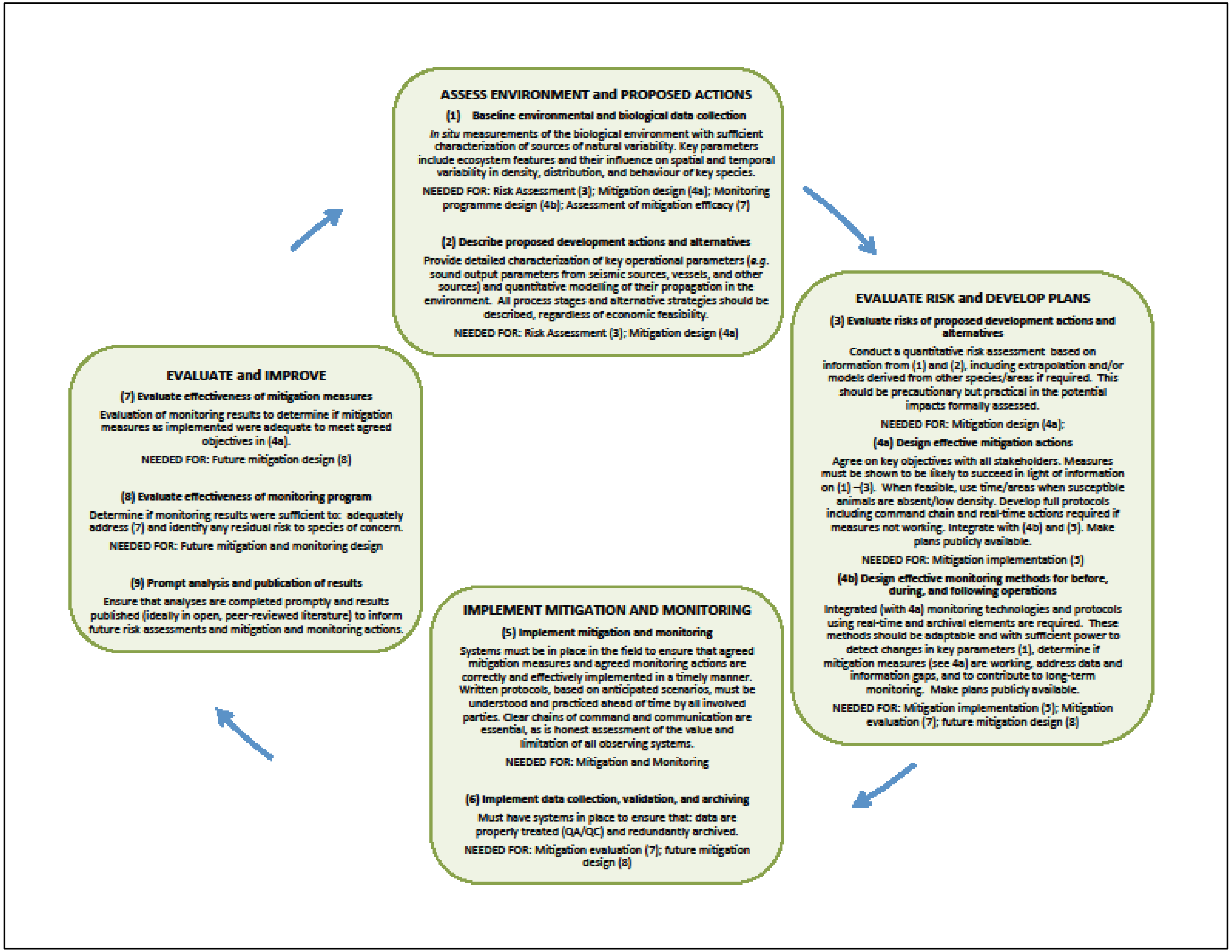

Table 4: Main elements for planning and conducting a marine seismic survey (adapted from Nowacek et al., 2013).

Primary Components	Notes
Assessment of background data with respect to species of concern (habitats, habits, life history) and environment (bathymetry, sound propagation)	• Identify multi-year data on general characteristics and natural variability of the relevant biological and ecological systems to understand environmental stochasticity and its influence on animal populations. • Collate and evaluate information on species of concern to gain a thorough understanding of seasonal occurrence and density, behaviour, reproduction, foraging and habitat use. • Collect and evaluate information on the areas physical properties (e.g., water temperature, currents, presence of sea ice) and how these influence the phenology and activities of the animals. • Ensure that pre-operation assessments such as EIAs are openly available to the public and decision-makers.
Spatial and/or temporal restrictions and requirements	• If possible ensure that operations occur when the species of concern is absent from the area. • Co-ordinate the timing of operations (seismic surveys) when there are the fewest possible individuals of species of concern present in the area. • Ensure operations can commence at the beginning of any temporal windows of opportunity especially where these are seasonally restricted (e.g. high latitude areas). • Consider the potential effects of mitigation measures on ‘non-target’ organisms during the planning process.
Generation of acceptable exposure criteria	• Key to the development of operational rules for seismic (or other impulsive) activities. • Critical that any received-level thresholds to be used are derived in conditions similar to those of the proposed operation. • Set criteria for the primary species or taxa of concern that consider both impulsive and continuous noise sources and also for both auditory and behavioural response thresholds. • Important to utilise all pertinent data to derive the best possible estimates for criteria.
Understanding the acoustic footprint of the survey: modelling of the acoustic source and the propagation environment	• Sound propagation model must be capable of reproducing all the relevant acoustic propagation properties of the region. • Selected environmental parameters for modelling should be as close as possible to the prevailing local properties including the time of year. • Modelled noise source (e.g., seismic array) should produce the same volumetric far-field levels as those produced by the operational equipment, in this case, airguns. • Consider the use of pre-modelled acoustic footprints to increase the efficiency of response to changing environmental conditions.
Pre-survey validation of source and propagation models	• If possible, conduct a site-specific validation of any acoustic modelling approach, preferably based on field measurements collected at or close to the location of the planned operation. • Less specific validations can reveal the accuracy of certain aspects of the estimation but do not provide verification for both source and propagation modelling.

	• Staging a limited trial of an activity similar to the planned one is the ideal scenario but may be logistically and economically unfeasible. • Site-specific validations can substantially increase estimation confidence and should be part of standard mitigation and monitoring planning.
Selection of appropriate techniques for implementing mitigation and monitoring elements (e.g. visual and/or acoustic survey methods)	• Consider all possible observation techniques during the planning phase. • Select a tailored set of mitigation and monitoring measures that are included in a programme-specific mitigation and monitoring plan. • Develop mitigation and monitoring plan as a collaboration between the operator, scientific experts, contactors, vessel owners and NGOs. • Final plan should be science-based, precautionary and practical. • For populations or individuals of particular concern (e.g., critical feeding, breeding areas or mother/calf pairs) active mitigation (operational shutdown) should occur at a behavioural threshold boundary. • The use of telemetered systems for real-time acoustic monitoring during the most critical circumstances (i.e., for species and times of most concern) is strongly recommended to ensure behavioural thresholds are not exceeded.
Creation of robust communication plan, including explicit chain of command	• Clear and robust communication protocols are essential during the operation to support efficient real-time decision making. • A clearly defined chain of command is required to enable decision-making and the most effective and productive coordination of a project. • All participants must have a thorough understanding of their roles and responsibilities, as well as those of the other parties involved and of the linkages between them. • The decision-making process relative to the agreed operational protocols should be coherent and transparent. • Consideration of communication issues caused by language differences is essential and the use of bilingual or multilingual participants is recommended. • Communication plan should be reviewed during the operation, especially at the beginning to identify weaknesses, flaws and areas that need clarification.
Post-survey assessment of mitigation measures	• Complete an initial assessment of mitigation and monitoring that documents the efficacy of mitigation protocols. • Prepare and disseminate a preliminary report that provides a general overview of operations and major events and some initial data analysis.
Publication of monitoring data to describe effects (or lack of), and to improve mitigation and monitoring of future surveys	• Regulators should insist that operators complete detailed analyses and rigorous, objective assessments of the efficacy of mitigation and monitoring measures. • Operators should regard the full and open publication of results as a mark of corporate responsibility. • Include funding for analysis and publication in project budgeting. • Open access to data will help fill data gaps for marine taxa and provide useful information for future operations to improve management, reduce risk and minimise environmental effects. .

Exposure Criteria

One way to regulate noisy activities is to set criteria for noise exposure that should not be exceeded. Exposure criteria or acoustic thresholds have been developed by the U.S. Government's National Oceanic and Atmospheric Administration (NOAA) for marine mammals and a few other taxa (marine fishes and turtles) to predict the noise exposure levels above which adverse physical effects (i.e., injury) or behavioural harassment are expected. Initial scientific recommendations for marine mammals were published in 2007[777] and split the taxon into five categories according to the functional hearing abilities of different marine mammal groups. Criteria suggestions were only provided for injurious exposure and not for behavioural responses of marine mammals, although a qualitative, 10 step index for the severity of behavioural response was proposed. However, when the severity index was compared to reports of behavioural observations relative to the received sound level, the exposure sound level (e.g., dose-response approach) failed to reliably predict the probability of identified behavioural responses[778] [779]. Current NOAA guidance on exposure levels for marine mammals does include acoustic thresholds for behavioural harassment but these are prone to the inaccuracies described previously. These thresholds are presented in the form of single received levels (RL) for particular source categories (e.g., impulsive, continuous or explosive).

In 2016 NOAA released technical guidance for assessing the effects of anthropogenic sound on marine mammals, which provides a revised set of acoustic threshold levels for the onset of permanent and temporary threshold shifts[780]. The guidance identifies the received levels above which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for all underwater anthropogenic sound sources. The guidance includes:

- A protocol for estimating PTS and TTS onset levels for impulsive and non-impulsive sound sources;
- The formation of marine mammal functional hearing groups (a modified version of the groups recommended in 2007): low-, mid-, and high frequency cetaceans, otariid and phocid pinnipeds, and;
- The incorporation of marine mammal auditory weighting functions into the calculation of thresholds.

The acoustic threshold levels are presented using both cumulative sound exposure level and peak sound pressure level. The cumulative sound exposure level (SEL_{cum}) is defined as the metric to account for accumulated exposure over the duration of the activity or for 24 hours (whichever is the shorter). However, this only accounts for the cumulative exposure to one particular noise source in the hearing range of an individual and does not consider the cumulative or aggregate effect of multiple noise sources. Advice is also provided in the guidance on how to combine multiple datasets and determine appropriate surrogates when little or no data exists.

The guidance is directed at marine mammals that reside or utilise marine waters under the jurisdiction of NOAA and so is U.S.-centric to a certain extent. An important point to note is that the updated thresholds are not supposed to represent the entirety of an impact assessment, but instead provide a tool to help evaluate the effects of a proposed action or activity on marine mammals[781]. Other aspects that should be considered within an overall assessment of risk include behavioural impact thresholds, auditory masking assessments and evaluations to help understand the ultimate effects of an impact on an individual's fitness and on populations.

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[777] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R. Jr., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., and Tyack, P. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33: 411-521

[778] Ibid

[779] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2011. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology

[780] National Marine Fisheries Service. 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

[781] Ibid

Interim exposure criteria for physical effects of pile driving on marine fishes were developed on the west coast of the U.S. over a number of years by the fisheries hydroacoustic working group (FHWG) and published in 2008. Prior to this, NOAA fisheries used peak sound pressure level (SPL) to assess the risk of injury to fishes, but this metric did not take into account the injury risk to non-auditory tissues in fishes with swim bladders[782]. The interim exposure criteria are the only known current criteria in use for the onset of physiological effects on fishes[783]. Although these criteria are in use, they were strongly criticized before being released as not using the best available science at the time and that they were based on limited, incomplete experimental data[784].

A revised version of suggested exposure guidelines for fishes and turtles from different noise sources was published in 2014[785]. A working group initiated by NOAA divided possible effects into three categories: mortal and potentially mortal effects, impairment (including recoverable injury, TTS and masking) and behavioural changes. Exposure guidelines for effects are based on five different 'animal' groups:

1. Fishes without a swim bladder (only detect particle motion);
2. Fishes with a swim bladder (primarily detect particle motion, and probably also pressure);
3. Fishes with a swim bladder 'connected' to the ear (phytostomes);
4. Sea turtles, and;
5. Fish eggs and larvae.

Many fishes and invertebrates and perhaps turtles are sensitive to particle motion in terms of behavioural responses[786]. There is a need to consider particle motion in the monitoring and mitigation of underwater noise for these taxa. However, little is known of particle motion detection by marine animals and the effects of elevated particle motion on their physiology and behaviour. There are currently no widely used exposure criteria developed for marine invertebrates. There is an urgent need to define sound exposure criteria for fishes and invertebrates in terms of particle motion as well as sound pressure, as it will be particle motion that they respond to in most instances[787].

Apart from the U.S., there are only a few other countries that specifically use exposure criteria to regulate anthropogenic noise production in the marine environment. A best practise example is the mandatory use of a noise exposure criterion for marine mammals as part of the licence for pile driving in offshore waters within the German EEZ when constructing offshore wind turbines[788]. The dual criterion is defined as: emitted sounds have to be limited to a received level of 160 dB re 1µPa^{2}s SEL and a sound pressure level of 190 dB$_{peak\text{-}peak}$ re 1 µPa at a distance of 750 m. These levels were selected following the precautionary principle in order to account for multiple exposures of pile driving impulses and keep disturbance as low as possible. The mandatory regulation has, along with government support, greatly stimulated industrial research programmes to develop noise reduction techniques that aim to meet the required criterion.

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[782] Stadler, J.H. and Woodley, D.P. 2009. Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria. Inter-Noise 2009. Ottawa, Ontario, Canada. 8 pp.
[783] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. A Literature Synthesis. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 135 pp.
[784] Ibid
[785] Popper, A.N., Hawkins, A.D., Fay, R.R. et al. 2014. Sound exposure guidelines for fishes and sea turtles. A technical report prepared by the ANSI-Accredited Standards Committee and registered with ANSI. ASA S3/SC1.4 TR-2014. ASA Press, Springer 76 pp.
[786] Ibid
[787] Popper, A.N. and Hawkins, A.D. 2018. The importance of particle motion to fishes and invertebrates. J. Acoust. Soc. Am. 143: 470-488
[788] Lucke, K. et al., 2013. Report of the workshop on international harmonisation of approaches to define underwater noise exposure criteria. Budapest, August 2013. IMARES, Wageningen UR, The Netherlands. Report No. C197.13. 40 pp.

There is increasing concern that the use of a received level (RL) dose-response approach for underwater noise management is inconsistent with current understanding, potentially misleading, and in some cases inaccurate[789] [790]. Focussing on the amplitude of the received sound ignores a range of biological, environmental and operational factors (i.e., context) that can affect both the perception of received sounds and the complex behavioural responses invoked[791]. Research indicates that a variety of factors can influence how an animal responds to sound in terms of the form, extent and probability of a response. There is a need to account for these factors in underwater noise management approaches, which is challenging given the limited understanding of behavioural responses for most species of marine animals. However, including context as part of behavioural-response assessment is deemed necessary by both the scientific community[792] and by federal government agencies in the United States that produce and regulate sound[793]. With this in mind, a new context-based approach that accounts for both acute and chronic noise and cumulative effects on marine animals (in this case mammals) has been proposed[794]. The approach consists of three parts:

1. Measurement and evaluation of context-based behavioural responses of marine mammals exposed to various sounds;
2. New assessment metrics that emphasise the relative sound levels (e.g. ratio of signal to background noise and level above hearing threshold); and
3. Considering the effects of both chronic and acute noise exposure.

These three aspects of sound exposure all need to be fully incorporated into marine spatial planning and ecosystem-based management of the marine and coastal environment[795]. Recent experimental and observational studies have revealed the integral role of context for the evaluating behavioural responses in marine mammals and the need for inclusion in assessments of potential impacts[796]. The above approach has also been developed into a quantitative method for the parameterization of the key contextual spatial and temporal elements of noise exposure, namely proximity and encroachment as the main determinants of the potential for behavioural response[797].

Real-time Mitigation Protocols

This section describes best practise for real-time mitigation protocols, namely soft start, visual and acoustic monitoring protocols used for industrial or military activities and highlights a number of examples. Succinct guidelines for noise generating activities that include real-time mitigation protocols have been developed by ACCOBAMS for cetaceans and are summarised in Table 5. Although developed for the ACCOBAMS agreement area (The Mediterranean), this general guidance is applicable for cetaceans in other marine regions including those areas where no statutory guidelines are in place. As mentioned in Table 4, for maximum effectiveness real-time mitigation procedures need to

[789] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2012. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology.
[790] Ellison, W.T., Southall, B.L., Frankel, A.S., Vigness-Raposa, K., and Clark, C.W. 2018. An acoustic scene perspective on spatial, temporal, and spectral aspects of marine mammal behavioral responses to noise. Aquatic Mammals 44: 239-243.
[791] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2012. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology.
[792] Southall, B.L., et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33: 411-521
[793] Southall, B., et al. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC
[794] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2012. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology
[795] Ibid
[796] Ellison, W.T., Southall, B.L., Frankel, A.S., Vigness-Raposa, K., and Clark, C.W. 2018. An acoustic scene perspective on spatial, temporal, and spectral aspects of marine mammal behavioral responses to noise. Aquatic Mammals 44: 239-243 (and references therein)
[797] Ibid.

be a tailored set of mitigation and monitoring measures as part of a project-specific mitigation and monitoring plan which should be science-based, precautionary and practical[798].

Table 5: Real-time Mitigation Protocols to address the impact of noise generating operation on cetaceans (Adapted from ACCOBAMS guidelines)

Protocol	Guidance	Comments / Notes
Soft start / ramp up	Noise emissions should begin at low power, increasing gradually until full power is reached. The procedure should take a minimum of 20 minutes Soft start procedure should be delayed if cetaceans enter the Exclusion Zone (EZ)	The effectiveness of this procedure is still debateable as it is not always science-based and generic.
Visual Monitoring	Marine Mammal Observers (MMOs) should watch the EZ for 30 minutes before the beginning of the soft start procedure (or 120 minutes for highly sensitive species). Continuous visual monitoring to be conducted for the entire duration of the noise emission. At least two dedicated MMOs continuously on watch with shifts not exceeding two hours. Activity should be stopped (or powered down) if cetaceans enter the EZ. If noise activity is stopped, then a new 30 minute period is required without animals in the EZ before emissions are restarted (120 minutes for highly sensitive species).	Highly sensitive species are predominantly deep-diving beaked whales. Ideally operations should not be conducted in areas that beaked whales are known to inhabit. MMOs main tasks are: • Monitoring and implementing mitigation measures as per the visual monitoring protocol; • Collection of abundance, distribution and behavioural data during operations (and in transit); • Reporting.
Acoustic Monitoring (PAM)	Acoustic monitoring should be used to alert the MMOs to the presence of cetaceans. Continuous acoustic monitoring to be conducted for the entire duration of the noise emission. At least one acoustician on watch at any one time (unless proven automatic detection systems are available). Acoustic monitoring is mandatory for operations at night or in bad weather conditions. In darkness or bad weather noise emissions should be stopped or powered down if cetaceans are detected acoustically.	Shut down of source(s) whenever aggregations of vulnerable species (e.g. beaked whales) are detected anywhere in the monitoring area. PAM may be inadequate mitigation at night if cetaceans are not vocal or easily heard. Ideally high power sources should be prohibited at night, during periods of low visibility and during significant surface ducting conditions, since current mitigation techniques may be inadequate to detect and localise cetaceans.

A recent and best practise example of operational guidelines to minimise acoustic disturbance from seismic surveys is the New Zealand Government's Department of Conservation 2013 Code of Conduct[799]. This code of conduct provides detailed guidance for operators on their legal requirements to minimise noise levels and the potential for disturbance to marine mammals in New Zealand waters. The code splits seismic surveys into three main types based on the air gun capacity:

- Level 1 (>427 cubic inches) – large-scale geophysical investigations with dedicated seismic survey vessels or other studies with high powered acoustic sources. This level has the most stringent requirements for marine mammal protection;

[798] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377.
[799] http://www.doc.govt.nz/conservation/marine-and-coastal/seismic-surveys-code-of-conduct/

- Level 2 (151-426 cubic inches) – lower scale seismic investigations often associated with scientific research. Smaller platforms using moderate power or smaller source arrays with less risk and therefore less stringent mitigation measures;
- Level 3 (<150 cubic inches) - all other small scale survey technologies that are considered to be of such low impact and risk that they are not subject to the provisions of the code.

Level 1 mitigation meets, and in some cases exceeds, all the measures listed in Table 5. The code also provides clear instructions on the specific roles and responsibilities of MMOs and PAM operators during operations and sets out procedures in the form of operation flowcharts that are practical and easy to use (Figure 8). The code of conduct was produced by the New Zealand Department of Conservation (DOC) in consultation with a broad range of stakeholders in marine seismic survey operations in the country, including international and domestic stakeholders representing industry, operators, observers, and marine scientists. The overall aim is to provide effective, practical mitigation measures for minimising acoustic disturbance of marine mammals during seismic surveys and the code has been endorsed as industry best practice by the Petroleum Exploration and Production Association of New Zealand (PEPANZ).

The 2013 DOC Code of Conduct is subject to a thorough review process every three years. In 2015, feedback collected from experts[800] was addressed through a number of technical working groups[801]. Based on the advice from the technical working groups, a series of technical reports were produced and the revised code of conduct was finalised in 2016. The revised code also incorporated feedback from stakeholder workshops such as increasing the flexibility of operators to use emerging technologies[802]. .

The real-time mitigation protocols described previously have been specifically designed for marine mammals and cetaceans in particular. Although there is considerably less information available on the effects of underwater noise on marine fishes, turtles and invertebrates than for marine mammals, the non-mammal taxa are beginning to receive more attention from the scientific community and regulatory bodies and agreements in the last decade. There is a need to develop or adapt real-time mitigation and monitoring procedures and measures for these taxa as more information becomes available. Whether measures such as soft starts are effective mitigation for fishes or turtles and more mobile invertebrates such as squid is not currently known. It is important to determine whether soft starts are effective in moving fishes, turtles or selected invertebrates from an area prior to operation. As some fishes and invertebrates occupy home ranges they may be reluctant to move, while others can move only slowly[803].Visual observation during operations will not be valid for marine fishes or invertebrates but can be used for marine turtles.

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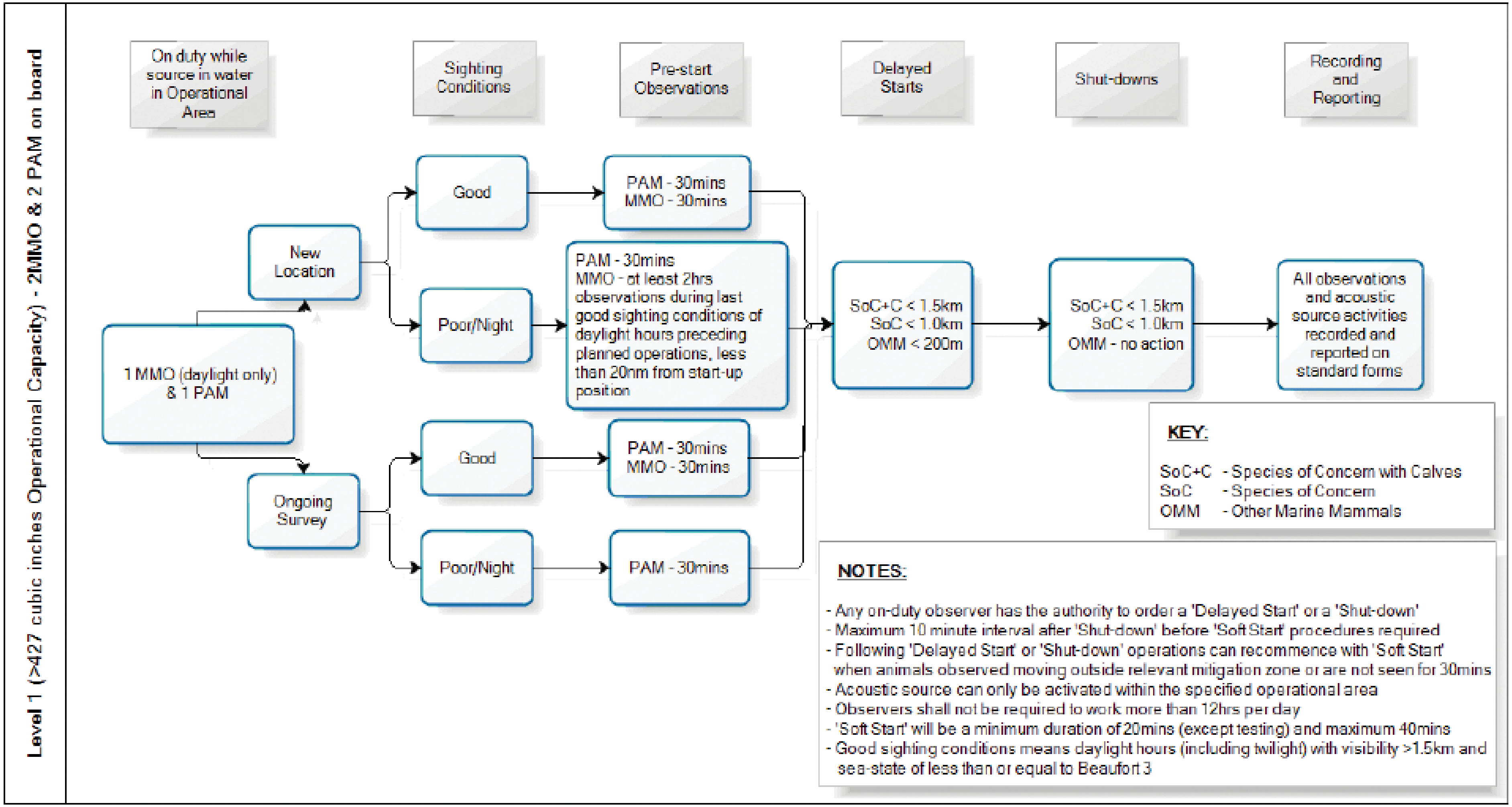
[800] For example: Wright, A.J. and Robertson, F.C. (Eds.). 2015. New mitigation methods and evolving acoustic exposure guidelines. Proceedings of the ECS Workshop. European Cetacean Society. ECS Special Publication Series No. 59. October 2015.

[801] https://www.doc.govt.nz/our-work/seismic-surveys-code-of-conduct/work-of-the-technical-working-groups/

[802] https://www.doc.govt.nz/our-work/seismic-surveys-code-of-conduct/providing-flexibility-to-the-code/

[803] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. A Literature Synthesis. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 135 pp.

Figure 8: Operation Flowchart for Level 1 Seismic Surveys in New Zealand waters (Source: NZ Department of Conservation 2013 Code of Conduct).



Alternative Noise Quietening Technologies

A summary of alternative noise quietening technologies for impulsive noise generating activities, notably seismic surveys and offshore construction, are summarised in Table 6 with information provided on their known effectiveness and state of development (in 2014). Information was mainly derived from two recent reviews [804][805] where considerable further detail can be found on the technologies, and also from the ACCOBAMS methodological summary[806].

Alternative acoustic source technologies are those that have the potential to replace existing commonly used technologies in certain conditions. Many of the alternative technologies are in various stages of development and are currently not commercially available for use, although considerable progress has been made in recent years, especially in the development of alternatives to pile driving for offshore wind turbines[807] (Table 6a). There are a number of alternative foundation types in existence or currently being developed including vibratory pile driving, foundation drilling, floating wind turbines and gravity-based or bucket foundations. Underwater noise measurements during installation are only available for a few of these technologies but many significantly reduce or completely eliminate the emission of impulsive sound generated by pile driving. Instead, continuous sound is emitted during installation generated by activities such as drilling, suction dredging and support ship movements, which can contribute to the overall level of background noise in an area.

Alternative technologies for seismic surveys to replace airguns have been under development for some time and include marine vibroseis (MV), the low level acoustic combination source (LACS) and a low impact seismic array (LISA) (Table 6b). Most of these technologies are still under development or testing. MV prototypes are currently being tested, but are not yet commercially available[808]. A LACS system is commercially available for shallow penetration of sediments, towed streamer seismic surveys or vertical seismic profiling. A modelling comparison of received sound levels produced from an MV array and an airgun array showed that, overall, MV produced lower broadband SELs, particularly at long range, and lower peak pressure, especially at short-range, than airguns[809].

Complementary Technologies for Seismic Surveys

As well as developing alternatives to airguns to conduct seismic surveys there is some potential to reduce the amount of seismic survey activity required through the use of existing complementary technologies or methods to investigate subsurface geology[810]. These include low-frequency passive seismic methods, electromagnetic surveys, gravity and gravity gradiometry surveys, and the use of fibre optic receivers.

Low-frequency passive seismic methods use natural sounds (natural seismicity, ocean waves and microseism surface waves) to image the subsurface and are currently being studied in academia and

[804] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.
[805] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.
[806] ACCOBAMS 2013. Methodological Guide: Guidance on underwater noise mitigation measures. ACCOBAMS-MOPS/2013/Doc24. 18 pp.
[807] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.
[808] Weilgart, L. 2018b. Keeping the noise down: approaches to the mitigation and regulation of human-caused ocean noise. In:Werle, D., Boudreau, P.R., Brooks, M.R., Butler, M.J., Charles, A., Coffen-Smout, S., Griffiths, D., McAllister, I., Moira, L.M., Porter, I. and Rolston, S.J. (Ed.). The Future of Ocean Governance and Capacity Development: Essays in Honor of Elisabeth Mann Borgese (1918-2002), Brill Nijhoff, Leiden, Netherlands. pp. 298-302. ISBN: 978-90-04-38027-1. DOI: 10.1163/9789004380271
[809] Duncan, A.J., Weilgart, L.S., Leaper, R., Jasny, M., and Livermore, S. 2017. A modelling comparison between received sound levels produced by a marine Vibroseis array and those from an airgun array for some typical seismic survey scenarios. Mar. Poll. Bull. 119: 277–288.
[810] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.

industry as a means to identify and delineate hydrocarbon reservoirs[811]. Of the three natural sounds that are recorded, the use of microseism surface waves is still at an early stage of development, the ocean waves method requires further testing and measuring natural seismicity takes longer to collect sufficient data to produce results than the other two[812]. However, all three ways are regarded as promising and worthy of further investigation and development.

[811] Habiger, 2010. Low frequency passive seismic for oil and gas exploration and development: a new technology utilising ambient seismic energy sources. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos –Foundation for the Sea. 29+iii pp.
[812] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.

Table 6: Summary of Alternative Quieting Technologies available for pile driving (4a) and seismic surveys (4b) and their development status in 2014.

6a: Marine Construction – Pile Driving (Sources; Koschinki and Lüdemann, 2013; CSA Ocean Sciences Inc., 2013, and references therein)

Technology	Description	Emissions	Development Status / Comments
Vibratory pile driving	Vertical oscillation of the pile at a specific low frequency (10-60 Hz) by the use of rotating weights. Often used in combination with impact pile driving	Lower peak pressure levels than impact driving, 15-20 dB. Some broadband sound emitted at higher frequencies between 500 Hz and several KHz.	Proven technology. Routinely used on smaller piles. Total energy imparted can be comparable to impact pile driving as more time is required for installation. Technology for larger piles and deeper water recently developed
Vibrio-drilling	Combination of a vibrator tandem PVE and a drill head in one unit. Pile is driven into the seabed by vibration, drilling is applied when there is resistance to vibration	<130 dB @ 750 m (estimated, not field tested)	Development stage not known
Vertical drilling (and cast-in-place concrete piles)	Drill head is clamped to the pile base and drills a cavity into which the pile sinks. Various technologies currently being developed. Used in combination with impact driving for particular circumstances	In shallow water emitted sound levels are much lower than impact pile driving and continuous levels are lower than those from large vessels	Proven technology for a number of offshore deep foundation applications but some technologies still under development. Sound levels have not been fully documented in offshore conditions.
Press-in-piles	Use of hydraulic rams to push piles into the ground. Self-contained units that use static forces to install piles. Designed for urban areas but also used in shallow waters	Underwater noise measurements not available but sound levels are expected to be very low	Not known for offshore developments
Gravity-based Foundations	Steel-reinforced concrete structures held in place by their weight and supplementary ballast. Excavation of the seabed required by suction hopper dredging for most designs.	No specific sound measurements available but impact pile driving / impulsive noise is eliminated. Main emissions are ship noise and dredging	Proven technology in shallow waters (<20 m depth). Very limited use in deeper waters but developments are planned for up to 45 m. One design, the cranefree gravity foundation is self-installing and does not require dredging or levelling of the seabed. This currently needs testing at the full-scale prototype stage.
Floating Foundations	Three main types: spar, tension leg platform and barge floater. Aimed at expanding wind farms into greater depths. Can involve pile driving to fix anchor points or use gravity base or suction anchors	No specific sound measurements available but no reduction in emissions expected if pile driving is used for anchor installation. For other anchoring systems emissions from gravity base and suction anchors are expected	Mainly at the concept or prototype stage but often based on proven technology from the oil and gas industry

		to be similar to gravity and bucket foundation installation respectively.	
Bucket or suction-based foundations	A large steel caisson that is embedded into the seabed by suction pumps. Water is pumped out of the cavity underneath the caisson – the vacuum in combination with the hydrostatic pressure enables the caisson to penetrate the seabed	No specific sound measurements available but noise levels thought to be negligible as impact pile driving / impulsive noise is eliminated. Noise sources are support ships and the suction pump	A proven technology in the oil and gas industry. Designs for wind farms are currently at the full-scale prototype and demonstration project stage.

6b: Seismic Surveys (Sources: CSA Ocean Sciences Inc., 2013 and references therein)

Technology	Description	Emissions	Development Status / Comments
Marine Vibroseis	Hydraulic and electromechanical MV's can be towed in the same configuration as airgun arrays or operated in a stationary mode. MV's have lower source signal rise times, lower peak pressures and less energy above 100 Hz. Electromechanical systems have a number of technical and logistical advantages over hydraulic ones.	Source level: 203 dB re 1µPa; 6-100 Hz. Auditory masking is likely to be more of a problem than with using airguns as signals are for a longer duration and will have a higher duty cycle (% time 'on').	Electromechanical system licenced for shallow water proposed to be available in 2014 depending on field tests. MV prototypes still being tested, but are not yet commercially available (Weilgart, 2018b). Previous hydraulic systems successfully field tested but not cost-effective due to expense to retrofit vessels. New 'seavibe' prototype is reliable and more efficient than airguns.
Low Level Acoustic Combination Source (LACS)	The LACS system is a combustion engine producing long sequences of acoustic pulses at a rate of 11 shots/second with low intensity at non-seismic (>100 Hz) frequencies.	Source level: 218 dB re 1µPa at 1 m (peak to peak)	One system is market available and suitable for shallow penetration, towed streamer seismic surveys or vertical seismic profiling. Second system for deeper penetration is under development and needs field testing once built.
Deep-towed Acoustics/Geophysics System (DTAGS)	Current model uses a Helmholtz resonator source to generate a broadband signal greater than two octaves. Source is extremely flexible enabling changes in waveform and a decrease in sound level to suit specific requirements. Towed 100 m above the seabed at depths down to 6000 m with a sediment penetration of 1 km.	Source level of 200 dB re 1µPa at 1 m. Proximity to the seafloor ensures that impulsive sound levels are minimised in the above water column.	Recent field trials for the single DTAGS in existence. Number of technical and operational disadvantages compared to airguns – mainly less sediment penetration and slower towing speed. Effect on marine fauna in shallow waters thought to be minimal
Low Impact Seismic Array (LISA)	Large array of small, powerful electromagnetic projectors that use a low frequency electromagnetic transducer system. Signal can be well controlled for frequency and directionality	Source level of 223 dB re 1µPa at 1 m possible for a small array according to initial testing	Very suitable for environmentally sensitive areas as there is little or no collateral environmental impact. Development stage not known
Underwater Tunable Organ-Pipe	Pipe is driven by an electro-mechanical piston source to create a tunable Helmholtz resonator capable of large acoustic amplitudes at a single frequency	Not available	Can be deployed to depths of 5000 m. Early prototype stage - only frequencies above 200 Hz.

Electromagnetic (EM) surveys are often used in conjunction with seismic surveys and there are currently two techniques that have been used as an exploration tool in the last decade: controlled source electromagnetic (CSEM) and magnetotelluric (MT) surveys. The CSEM technique involves the transmission of very low frequency (< 1 Hz) EM signals into the upper layer of the seafloor. The environmental impacts of CSEM are expected to be negligible as the CSEM source uses extremely low spatial and temporal frequencies with a small region of potential influence to marine life[813]. MT surveys are a passive measurement of the Earth's EM fields by detecting the natural electrical and magnetic fields present[814]. Both methods are often used in combination for subsurface mapping. At the present time, these methods do not have the resolution or penetration to replace seismic surveys but broader application of EM methods does have the potential to reduce the level of 3D seismic surveying required[815]. The technology is underutilised by industry due to a lack of understanding and adoption[816].

Gravity and gravity gradiometry surveys are passive remote-sensing methods that measure variations in the naturally occurring gravity field. Both technologies are fairly well developed and have been used by mining and petrochemical industries for decades[817]. Gravity gradiometry involves measuring the Earth's gravity gradient and provides better resolution than gravity surveys but also requires more complex and expensive equipment. The techniques are not applicable in all geological settings but have the potential to reduce the amount of seismic survey effort required[818].

Fibre optic receivers are sensors that incorporate optical fibres to transmit the received acoustic signal as light[819]. They are mainly used for seismic permanent reservoir monitoring but the technology is not currently available for towed streamer surveys. However, several key characteristics have been identified that could lead to noise reduction during airgun surveys[820]:

- Reduced amplitude – fibre optic receivers on the seafloor have greater sensitivity and achieve a better signal-to-noise ratio than towed conventional sensors which are subject to additional noise in the water column. This allows the use of smaller airgun sources for 4D surveys;
- Reduced airgun volume – fibre optic receivers have better low-frequency performance meaning that the requirement for large airgun volumes may be reduced;
- Reduced survey duration – as the receivers are permanently deployed, total survey time is reduced compared to towed streamer surveys because no infill is needed and weather downtime is minimized.

813 Ridyard, D. 2010. Potential application of 3D EM methods to reduce effects of seismic exploration on marine life. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos –Foundation for the Sea. 29+iii pp.
814 CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.
815 Ridyard, D. 2010. Potential application of 3D EM methods to reduce effects of seismic exploration on marine life. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos –Foundation for the Sea. 29+iii pp.
816 Ibid
817 Bate, D. 2010. Gravity gradiometry. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos –Foundation for the Sea. 29+iii pp.
818 Ibid
819 CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp
820 Nash, P. and Strudley, A.V. 2010. Fibre optic receivers and their effect on source requirements. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos – Foundation for the Sea. 29+iii pp.

The technology is particularly suited to future use with alternative seismic sources that produce less high frequency output. To accommodate conventional airgun sources the sensors require a large dynamic range at higher frequencies to avoid sensor saturation[821] and these sensors are currently expensive. Combining fibre optic receivers with techniques that emit less high-frequency sound such as marine vibroseis will eliminate the need to use the more expensive sensors[822].

Noise Limitation Technologies

A number of mitigation techniques have been developed to attenuate noise from activities that generate impulsive sound in the marine environment (Table 7). This section focusses on techniques designed to reduce noise levels from marine construction activities, particularly pile driving (Table 7a) and seismic surveys (Table 7b). Information sources used to compile the tables were primarily two reviews of noise mitigation techniques produced by the U.S.[823] and German[824] Governments, with additional information from documents produced by two regional management bodies, ACCOBAMS[825] and OSPAR[826].

It should be noted that the information provided here is an overview of existing and developing noise reduction techniques and the information sources mentioned above should be consulted for more detailed information. In addition, one of the main sources of information used[827] was compiled as an information synthesis background document for a recent workshop on quieting technologies for seismic surveying and pile driving, organised by the U.S. Government's Bureau of Ocean Energy Management (BOEM)[828]. The final summary report describing the discussions, conclusions and recommendations of this workshop was published in 2014[829].

Techniques to reduce noise from pile driving mainly consist of placing a barrier around the pile to attenuate sound from hammering. The barrier can be a solid casing that is drained or filled with a layer of bubbles or other absorptive materials, or a curtain of bubbles. There has been considerable progress in the development of a range of methods to mitigate pile driving noise. The most commonly used techniques are cofferdams and bubble curtains. Techniques that alter the duration of the noise pulse and the design of the piling hammer are also at the early stages of development (Table 7a).

There have been numerous studies of the effectiveness of bubble curtains for wind turbine foundations, docks and other coastal construction projects and pile driving activities (See CSA Ocean Sciences Inc., 2013[830] for a list of published studies). Big bubble curtains are currently regarded as the best-tested and

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[821] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[822] Nash, P. and Strudley, A.V. 2010. Fibre optic receivers and their effect on source requirements. In: Weilgart, L.S (ed.), 2010. Report of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals. Monterey, California, 2009. Okeanos – Foundation for the Sea. 29+iii pp

[823] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[824] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.

[825] ACCOBAMS 2013. Methodological Guide: Guidance on underwater noise mitigation measures. ACCOBAMS-MOPS/2013/Doc24

[826] OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic. 2014. Draft Inventory of noise mitigation measures for pile driving. Meeting of the Intersessional Correspondence Group on noise (ICG Noise), Gothenburg (Sweden): 29-30 January 2014. ICG Noise 14/6/2-E.

[827] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[828] Quieting technologies for reducing noise during seismic surveying and pile driving workshop. 25-27 February 2013. Silver Spring, Maryland. Bureau of Ocean Energy Management (BOEM).

[829]

[830] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

most proven noise mitigation technique for the foundations of offshore wind farms[831]. Their suitability has been shown through modelling, field testing and practical application. Additionally, using a double layer of bubbles can be considerably more effective for noise mitigation than a single bubble curtain, Little bubble curtains also have considerable potential and more recent designs of using a ring of vertical hoses or casings are able to prevent bubble drift in tidal currents[832]. Of the three designs mentioned (Table 7a) the curtain of vertical hoses is at the most advanced stage of development. Little bubble curtains have the potential to be applied in commercial offshore settings once the components are adapted to offshore conditions[833]. To date bubble curtains have been shown to result in noise reductions that can meet objectives including meeting regulatory noise criteria [834], reducing behavioural disturbance of marine mammals[835] and avoiding fish kills[836].

A variation on the bubble curtain is the Hydro Sound Damper (HSD) which uses a net embedded with small elastic, gas filled balloons and foam to enclose the pile. By varying the balloon size the HSD can be adjusted to achieve maximum noise reduction at particular frequencies. Other advantages over bubble curtains are that the HSD system is very flexible in terms of assembly design to suit different applications, does not rely on compressed air and is not affected by currents or tides[837].

The known effectiveness and current development status of two recent designs for complex isolation casings (IHC Noise Mitigation System and BEKA Shells) are summarised in Table 7a. These combine the effects of a reflective casing and confined bubble curtains with the principle of cofferdams to reduce noise by absorption, scattering and dissipation[838]. Both systems have been designed primarily for offshore developments and in theory will achieve greater noise reduction than bubble curtains or cofferdams individually. However, both systems require further testing in an offshore setting to provide actual emission reduction data that can confirm the modelling predictions.

The potential for technical noise mitigation from pile driving is currently limited by the multipath transmission of the emitted sound waves. Modelling of the relative contribution of propagation pathways (air, water and seismic paths) indicates that the water path propagates the greatest amount of noise and mitigation techniques have therefore focussed on reducing the sound radiation into the water[839]. However, the seismic contribution through the seabed is usually the limiting factor for the effectiveness of mitigating the water path[840] as a considerable amount of sound energy can re-enter the water column via the seismic path. The seismic contribution to overall sound transmission in water is 10-30 dB less than the three paths combined[841]. Therefore, the maximum achievable noise reduction for current mitigation techniques is limited to 30 dB unless the seismic path is also attenuated[842].

[831] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.
[832] Ibid
[833] Ibid
[834] Wilke, F., Kloske, K. and Bellman, M. 2012. ESRa – Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl. May 2012 (In German with extended abstract in English)
[835] Nehls, G. 2012. Impacts of pile driving on harbour porpoises and options for noise mitigation. In: Symposium on protecting the Dutch whale, Amsterdam, 18 October 2012.
[836] Reyff, J.A. 2009. Reducing underwater sounds with air bubble curtains. TR News 262. P. 31-33.
[837] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp
[838] Nehls, G., Betke, K, Eckelmann, S. and Ros, M. 2007. Assessments and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from construction of offshore wind farms. BioConsult SH report, Husum, Germany.
[839] OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic. 2014. Draft Inventory of noise mitigation measures for pile driving. Meeting of the Intersessional Correspondence Group on noise (ICG Noise), Gothenburg (Sweden): 29-30 January 2014. ICG Noise 14/6/2-E.
[840] Applied Physical Sciences. 2010. Mitigation of underwater pile driving noise during offshore construction. Final report. Report No. M09PC00019-8
[841] Ibid
[842] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.

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Table 7: **Summary of Noise Limitation Techniques for pile driving (7a) and seismic surveys (7b) and their development status in 2014**

7a. Pile driving and associated marine construction activities (dredging and drilling)

Mitigation Technology	**Description**	**Emission Reduction**	**Development Status[1] / Comments**
Big air bubble curtain	A large bubble curtain that usually consists of a pipe with drilled holes placed on the seabed around the whole foundation or structure. Compressed air escaping from the holes forms the bubble screen, shielding the environment from the noise source.	Single bubble curtain: 11-15 dB (SEL), 8-14 dB (peak) [2] Double bubble curtain: 17 dB (SEL), 21 dB (peak)	Proven technology and potential for optimisation in terms of handling and system effectiveness (air supply, bubble sizes and distance from source). Double screens reduce emissions more than single ones and are most effective when two separate bubble curtains form. Seismic path propagation may be reduced due to the large diameter of the system.
Little air bubble curtain (several variations)	More customised smaller curtain that is placed around the noise source in a close fit. Can consist of a rigid frame placed around the source but several designs are possible: -Layered ring system – multiple layers of perforated pipes that surround the source in a ring-shaped arrangement; -Confined bubble curtain – additional casing around the area of rising bubbles. Casing can consist of plastic, fabric or a rigid pipe and does not affect the mitigating properties of the system; -Little bubble curtain of vertical hoses – vertical arrangement of a number of perforated pipes or hoses around the source.	Layered ring system: 11-15 dB (SEL), 14 dB (peak) Confined little bubble curtain: 4-5 dB (SEL) Little bubble curtain with vertical hoses: 14 dB (SEL), 20 dB (peak)	Pilot stage with full-scale tests completed. Practical application possible. Tidal currents can cause bubble drift and sound leakage but effect can be minimised in more recent designs. Confined bubble curtains initially designed for shallow waters with strong tidal flow. All designs do not affect seismic path propagation. Vertical hose design prevents sound leakages as there are no horizontal gaps between the hoses.
Hydro Sound Damper (HSD)	HSD consists of fishing nets embedded with small latex balloons filled with gas and foam that surround the source. The resonance frequency of the balloons is adjustable, even to low-frequency ranges.	4-14 dB (SEL); 17-35 dB (SEL)	Independent of compressed air and not influenced by currents. Easily adaptable to different applications. Pilot stage but also commercially applied at one North Sea offshore wind farm. Further development – additional dampers and net layers; tests to reduce seismic propagation.
'encapsulated bubbles'	Same principle as HSD - balloons of 6-12 cm diameter used to reduce low-frequency components of pile driving noise.	Up to 18 dB (singular third octave bands)	Currently under development with a few 'proof of concept' field experiments completed.

Cofferdam	Rigid steel tube that surrounds the pile from seabed to surface, with the water pumped out between the tube and pile. The air space between the pile and the water column attenuates sound – acoustic decoupling of noise of the pile driving noise within the cofferdam.	Up to 22 dB (SEL), 18 dB (peak) Generally expected to match bubble curtains in terms of noise mitigation	Practical application in many commercial projects in shallow waters (<15 m). Currently at the pilot stage for deeper offshore waters and proposed for depths of at least 45 m. Further developments for offshore underway (e.g. free standing system, telescopic system). Installation likely to require more time than lined barriers or bubble curtains and specialist equipment is needed for offshore developments.
Pile-in-Pipe Piling	Particular type of cofferdam where the cofferdams are the four legs of a foundation. Pile driving occurs above the sea level so that acoustic decoupling is enabled by the construction itself. Requires considerably more material than conventional cofferdams.	27 - 43 dB (SEL) – modelled High noise reduction expected	Validated concept stage but is a variation on a proven technique. Complete dewatering of cofferdams will be crucial Cofferdams are not reusable as they are part of the foundation.
IHC Noise Mitigation System (NMS)	Double layered screen filled with air and a multi-level and multi size confined bubble curtain between the pile and the screen.	5-17 dB (SEL)[2] Noise reduction by NMS predicted to exceed that of a bubble curtain	Bubble curtain is fully adjustable. Proven technology to 23 m depth. Tested in a commercial offshore project but insufficient data available to make reliable conclusions for mitigation performance.
BEKA Shells	Double steel casing with a polymer filling combined with an inner and outer bubble curtain and acoustic decoupling (vibration absorber). Multiple layers create shielding, reflection and absorption effects.	6-8 dB (SEL)* Predicted to have the highest noise reduction potential of all techniques presented	Lower end penetrates the seabed to decouple sound transmission along the seismic path. *Available emission reduction data collected in specific problematic circumstances (ESRa Project). Pilot stage completed. Requires full-scale testing in offshore field conditions.
Prolongation of pulse duration	Prolonging the pulse duration of a pile strike will reduce the corresponding sound emission which in principle can be achieved by having an elastic piling cushion between the hammer and pile. Disadvantage of a loss of piling force with the use of cushions increasing the total number of strikes.	Models: 4-11 dB (SEL), 7-13 dB (peak)[2] Piling cushions (various materials): 4-8 dB (SEL)[2]	Modelling and experimental stage for large pile diameters but proven technology for small pile diameters. In tests micarta (bakelite) was identified as the best option for piling cushion material.
Modification of piling hammer	Not specified	Not available	Experimental stage – research results pending

1. With regard to North Sea offshore conditions and water depths to 40 m.
2. Data from several developments or field tests combined

7b. **Seismic surveys** (Source: CSA Ocean Sciences Inc., 2013 and references therein)

Technology	Description	Emission Reduction	Development Status / Comments
Bubble curtains	Evaluation of deploying towed air bubble hoses to reduce lateral noise propagation (BOEM sponsored study).	Initial evaluation; at least 20 dB Second evaluation: bubble curtains were not able to produce the required noise reduction.	Desk-based evaluation - advise in 2010 was to not investigate further as little noise, if any, would be attenuated. Not practical for deep water and does not block sound when there is a direct line of sight to the source.
Parabolic reflectors	Evaluation of the potential to make airgun arrays more vertically directional by towing a parabolic reflector over the array.	Potential for large reductions in sound, especially at vertical angles > 70°.	Not recommended for further investigation in 2009 due to a number of limitations (elevated risk in towing and deployment, not effective in shallow water because of bottom reflections).
Airgun silencer	Consists of acoustically absorptive foam rubber on metal plates mounted radially around the airgun.	Tests: 0-6 dB (SPL) above 700 Hz but overall increase in SPL of 3 dB due to an increase in sound near 100 Hz.	Modest reduction achieved in tests but thought to have potential to improve. Regarded as a 'proof of concept' that would require further development in 2007 but later, in 2009, as 'impractical'.
Modification of airguns	Possibility of redesigning airguns to reduce high-frequency sound considered. E-source airgun – reduces high-frequency output.	Not available Not available	Initially regarded as unfeasible as would require development and testing of a completely new product. E-source airgun currently under development.

Damping of the seismic path from the embedded section of the pile is currently difficult[843] but needs to be considered if noise mitigation systems are to be improved further[844]. The application of big bubble curtains may enable noise reduction from the seismic path as the large diameter of the mitigation system can extend beyond the distance where seismic path noise re-enters the water column. BEKA shells are also designed to mitigate the noise propagated through the seismic path by penetrating into the seabed and decoupling the sound transmission via this route[845].

A key logistical challenge is minimising the installation time for the noise mitigation system so that the application of such a system is economically feasible[846]. As not all of the available systems have been routinely applied yet, it is difficult to predict the length of the installation process with certainty, particularly in offshore settings. Further work is currently aiming to efficiently integrate noise mitigation into the operations[847].

Noise mitigation techniques for seismic surveys have been recently reviewed by the U.S. Government's Bureau of Ocean Energy Management (BOEM)[848]. A number of techniques to reduce lateral noise emissions from airguns have been investigated including the use of bubble curtains and parabolic reflectors, and the development of an airgun silencer or re-designed quieter airguns (Table 7b). However, none of the techniques have been taken much further than the early developmental stages and some have been discontinued. Both bubble curtains and parabolic reflectors were regarded as impractical and ineffective after initial evaluation. Airgun silencers were first thought to have potential as modest levels of noise reduction were measured during tests[849] but then were also later considered to be impractical[850]. Efforts to re-design airguns for the reduction of high-frequency emissions have made more progress than other noise mitigation technique but are still under development. The E-source airgun is currently being developed by Bolt Technology Corporation and WesternGeco[851] but there is no information publicly available to report on current progress[852].

Continuous Sound Mitigation

Long-term measurements of ocean ambient sound have indicated that low frequency anthropogenic noise has been increasing and this has been primarily attributed to commercial shipping noise[853] [854]. The global merchant fleet is through to be the greatest contributor to the doubling in background noise levels

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[843] Ibid

[844] OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic. 2014. Draft Inventory of noise mitigation measures for pile driving. Meeting of the Intersessional Correspondence Group on noise (ICG Noise), Gothenburg (Sweden): 29-30 January 2014. ICG Noise 14/6/2-E.

[845] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.

[846] Ibid

[847] Ibid

[848] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[849] Nedwell, J. and Edwards, B.E. 2005. Initial tests of an airgun silencer for reducing environmental impact. Subacoustech report reference: 644 R 0108. Submitted to Exploration and Production Technology Group, BP Exploration.

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[851] Weilgart, 2012. Alternative quieter technologies to seismic airguns for collecting geophysical data. In: Abstracts, 3rd International Conference on Progress in Marine Conservation in Europe 2012. Straslund, Germany. Pp. 17-18

[852] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[853] Andrew RK, Howe BM, Mercer JA, Dzieciuch MA (2002) Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoust Res Lett Online 3:65–70

[854] McDonald MA, Hildebrand JA, Wiggins SM, Ross D (2008) A fifty year comparison of ambient ocean noise near San Clemente Island: a bathymetrically complex coastal region off southern California. J Acoust Soc Am 124:1985–1992

in the marine environment in every decade over the last 50 years[855]. In some areas, there is clear evidence that shipping noise is increasing as the level of ship traffic increases[856].

The main noise sources from ships are those caused by the propeller, by machinery including sea-connected systems (e.g., pumps) and the noise caused by the movement of the hull through the water[857] [858]. Propeller cavitation is usually the dominant source for large commercial vessels.

Reducing noise production by ships can be achieved through design or operational solutions and a wide range of these are available[859] [860]. Design alterations are briefly summarised below (Table 8), and considerable further detail for these can be found in the source references. Many of the alterations are designed to improve the propulsive efficiency of the ship. It is thought that existing technology can be used to quieten the noisiest ships which are also currently operating at sub-optimal efficiencies[861]. The main techniques available are improving propeller design to reduce cavitation and match actual operating conditions, and improving the wake flow into the propeller for existing ships or for new-builds. The latter is achievable with relatively little additional cost to the overall price of a vessel[862] and may result in reduced running costs once operational[863]. Retro-fitting existing ships to improve wake flow is also relatively cheap compared to other more substantial design changes. A flow chart sets out the activities required to reduce underwater noise from commercial shipping[864] (Figure 9).

Another option that has had a small level of uptake by the shipping industry is the use of a large computer-controlled towing kite that helps to pull the ship through the water. This can reduce fuel usage and decrease the operational load on the propeller[865]. There are also quieter alternatives to conventional propulsion systems which are not a solution for existing vessels but can be considered when designing new ships for particular uses[866]. Examples are drop thrusters, Z-drives and podded propulsion systems (azipods), waterjets, rim drive propulsion and Voith-Schneider systems[867].

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[855] Wright, A.J. (ed.) 2008. International Workshop on Shipping Noise and Marine Mammals, Hamburg, Germany, 21st-24th April 2008. Okeanos - Foundation for the Sea, Auf der Marienhohe 15, D-64297 Darmstadt. 33+v p

[856] Frisk, G.V. 2012. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. Sci. Rep. 2:437. doi: 10.1038/srep00437

[857] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[858] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.

[859] Wright, A.J. (ed.) 2008. International Workshop on Shipping Noise and Marine Mammals, Hamburg, Germany, 21st-24th April 2008. Okeanos - Foundation for the Sea, Auf der Marienhohe 15, D-64297 Darmstadt. 33+v p

[860] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.

[861] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[862] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[863] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[864] Ibid

[865] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[866] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp.

[867] Ibid

Many of the technologies available to reduce noise from the engine and associated machinery are not currently scalable to the sizes needed for commercial shipping. Research programmes are needed to resolve this issue, which has been regarded as a priority for investment[868].

Table 8. A Summary of Design Noise Reduction Methods for Commercial Ships (after CSA Ocean Sciences Inc. 2013; Leaper and Renilson, 2012)

Source	Technique	Notes
Propeller	Reduced vessel speed	Simple method to reduce the ship's acoustic footprint, but may result in sub-optimal propeller performance –see below
	Modify propeller to match actual use	Most propellers are designed for modelled and not actual, variable operating conditions
	Foul release coating – non-toxic, antifouling coating that improves efficiency	Mixed evidence that there is noise reduction
	Routine maintenance	Repair minor damage / remove marine growth to maintain efficiency and minimise cavitation
	Specially designed propellers and thrusters	Delay and reduce cavitation but effects not independently verified for all designs
	Wake inflow devices and ducted propellers	Improve the wake to reduce cavitation and improve the flow into the propeller
	Propeller hub caps	Reduce hub vortex cavitation and hydroacoustic noise, and improve propeller efficiency
	Altering propeller/rudder interactions	Propeller/rudder interaction has a significant impact on propulsive efficiency. Various concepts
	Anti-singing edge	Modify the propellers trailing edge
	Twin-screw ships – better working conditions for propellers	Reduce propeller cavitation
Machinery	Resilient isolation of equipment	Reduce vibration
	Isolated deck / larger structure	Resiliently mount equipment on one floating deck
	Damping tiles / Spray-on damping	Reduce vibration energy in structures
	Ballast-Crete – pre-blended commercial ballast material	Provides additional damping of structures in contact
	Decoupling materials (e.g. foam rubber or similar)	Applied to hull exterior to reduce radiation efficiency
	Selection of low-noise equipment	Variation between manufacturers
Hull	Well-designed hull form	Good designs require less power for a given speed and provide a more uniform flow into the propeller, increasing its efficiency and improving wake flow
	Asymmetrical afterbody	Improves flow into single screw propellers
	Air bubble system (curtain) along a portion of the hull	Blocks sound transmission from hull (but also from propeller or machinery)

[868] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

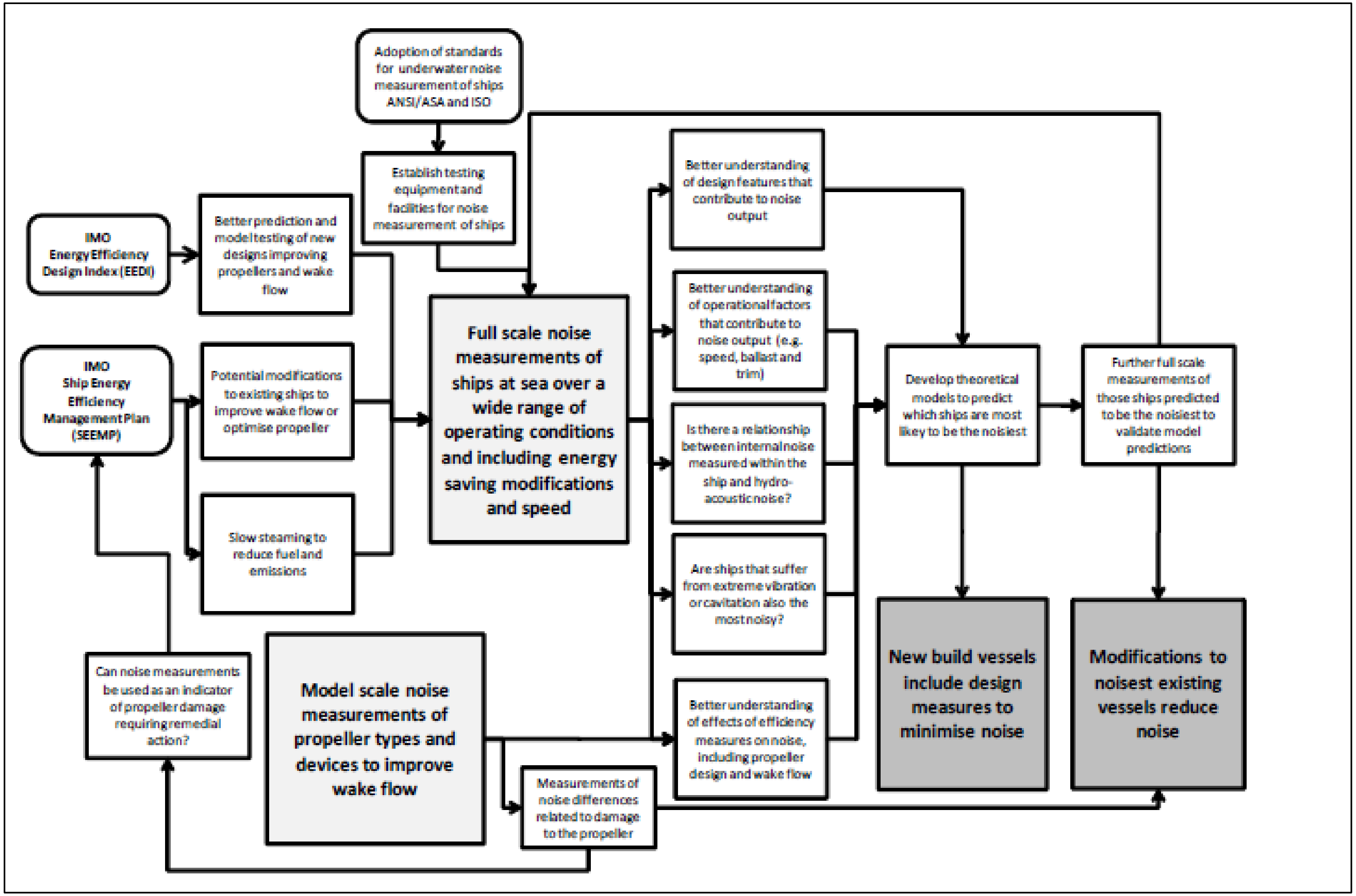

Figure 9. Flow chart of activities required to reduce underwater noise emissions from conventional merchant ships (Leaper and Renilson, 2012)

Operational procedures to reduce noise emissions are mainly concerned with travelling at slower speeds or ensuring there is routine maintenance of equipment such as propellers. Although slower steaming will require more ships to be operated to carry the same amount of cargo, there should be a large reduction in total acoustic emissions associated with slow steaming[869]. Slow steaming can also reduce fuel costs for individual vessels.

Regulating vessel routing and scheduling[870] may also achieve reductions in ambient noise levels by reducing the density of shipping traffic in certain areas and/or times, such as sensitive habitats or seasons for marine taxa[871]. Re-routing vessels has been suggested to avoid operation in environments that favour long-range transmission[872] such as locations where sound will propagate into the deep sound channel[873]. These locations are where the sound channel intersects bathymetric features such as the continental slope or at high latitudes where it is very close to the surface[874]. Avoiding such areas can be achieved by vessels moving further offshore in some cases but such re-routing will need careful consideration if there is an associated increase in speed or distance travelled[875] (and fuel usage).

Guidelines for minimising underwater noise from commercial ships have been developed by the International Maritime Organisation's (IMO) Design and Equipment Subcommittee[876]. The guidelines mainly focus on considering noise in the design of propellers and hulls, and in the selection of on-board machinery. They also encourage model testing during the design phase and maintenance during operation. The draft guidelines were adopted by the IMO's Marine Environment Protection Committee at their meeting (MEPC 66) in 2014. The guidelines are voluntary and are intended to provide general advice about the reduction of underwater noise to designers, shipbuilders and ship operators. It has been stated that the adoption of these guidelines will represent acknowledgement of the severity of the issue and represent a substantial step forward in reducing ship noise[877]. Guidelines for commercial shipping have also been developed by the AQUO and SONIC projects in Europe[878].

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[869] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[870] Southall, B.L. and Scholik-Schlomer, A. 2008. Final report of the NOAA International Conference: 'Potential application of vessel-quieting technology on large commercial vessels.' 1-2 May, 2007, Silver Spring, MD.

[871] CSA Ocean Sciences Inc., 2013. Quieting Technologies for reducing noise during seismic surveying and pile driving. Information Synthesis. BOEM. 53 pp

[872] Southall, B.L. and Scholik-Schlomer, A. 2008. Final report of the NOAA International Conference: 'Potential application of vessel-quieting technology on large commercial vessels.' 1-2 May, 2007, Silver Spring, MD.

[873] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[874] McDonald, M.A., Hildebrand, J.A. and Wiggins, S.M. 2006. Increases in deep ambient noise in the Northeast Pacific west of San Nicholas Island, California. J. Acoust. Soc. Am. 120:711-718.

[875] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

[876] International Maritime Organisation. 2014. Document MEPC. 1/Circ. 833. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life.

[877] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[878] Audoly, C. Flikeema, M, Baudin, M. and Mumm, H. 2015. Guidelines for Regulation on Underwater Noise from Commercial Shipping. Technical report, AQUO/SONIC, Nov 2015.

Monitoring and Mapping Tools

This section outlines the monitoring and mapping tools currently available or in development to enable the production of acoustic and marine species population maps for a given area. Data needs and the current availability of acoustic and mapping tools are discussed. Monitoring tools include passive acoustic monitoring (PAM), habitat models for marine mammals and real-time marine mammal detection. New monitoring techniques such as the use of thermal imaging are also highlighted.

Acoustic monitoring and modelling is an essential element of noise mitigation for the marine environment both for the assessment of impulsive and continuous sound levels in an area but also for predicting and determining the presence of marine species in the vicinity of noise generating activities.

Acoustic and Species Distribution Mapping

The development of acoustic mapping tools has made considerable progress in recent years, with a number of tools currently being developed by researchers, mainly for government agencies. These tools are being put together to describe average human induced noise fields over extended periods of time or over large areas of coastline or open ocean. They can provide powerful visualizations of low frequency contributions from anthropogenic sources and their extent, and also begin to address the scales at which many marine animals actually operate. In combination with tools to characterize the distribution and density of marine animals as well as important management jurisdictions, they can provide important information for risk assessment and for understanding what tools are available to address those risks[879]. Two important tools were developed in the United States are 'SoundMap' and 'CetSound' by working groups convened by NOAA: the underwater sound-field mapping working group and the cetacean density and distribution mapping working group. SoundMap aims to create mapping methods to depict the temporal, spatial and spectral characteristics of underwater noise. The specific objective of CetMap is to create regional cetacean density maps that are time- and species-specific for U.S. waters using survey and models that estimate density using predictive environmental factors. Cetmap is also identifying known areas of specific importance for cetaceans such as feeding and reproductive areas, migratory corridors, and areas in which small or residential populations are concentrated[880]. The SoundMap product will enable predicted chronic noise levels to be mapped for an area over a specific timeframe and facilitate the management of cumulative noise impacts for cetaceans and other taxa. Mapping of more transient and localised noise events from acute sources such as military sonar or seismic surveys can also be undertaken.

Both tools were presented to a range of stakeholders from government and industry as well as research scientists, environmental consultancies and conservation advocacy groups at a symposium in 2012[881]. Discussions at the meeting provided feedback for the working groups on the utility of the products to support planning and management, and also suggested ways to improve the tools such as integrating them with other mapping products to assess risk from multiple stressors and determine cumulative impacts. The use of equivalent, unweighted sound pressures levels (L_{eq}) which are averages of aggregated sound levels was also questioned in that it does not provide sufficient detail to show the acoustic conditions experienced by individual animals[882]. However, it was generally agreed that the products were a useful first step in developing practical tools to map both noise and cetaceans in the marine environment and have great potential as they are further improved. Regular updates of the products are also required to keep them up to date and usable.

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[879] Leila Hatch pers. comm.

[880] Van Parijs S.M., Curtice C., Ferguson M.C. (eds). 2015. Biologically Important Areas for cetaceans within U.S. waters. Aquat Mamm 41(Spec Issue): 1−128.

[881] National Ocean and Atmospheric Administration. 2012. Mapping Cetaceans and Sound: Modern Tools for Ocean Management. Final Symposium Report of a Technical Workshop held May 23-24 in Washington, D.C. 83 pp.

[882] Ibid

In Europe, acoustic mapping approaches are also being developed to define and demonstrate risk-based noise-exposure indicators that can be used by managers to quantify and reduce the exposure of a population to noise pollution[883]. Two case studies of cumulative impulsive noise activity in the North Sea and the associated risk of effects on herring spawning and the harbour porpoise were recently published[884]. The approach has the flexibility to map and quantify risk at the population level or be applied in place-based management for specific habitats or managed areas such as MPAs. The methodology is also compatible with risk mapping approaches used in cumulative assessment[885], which enables noise to be incorporated as a stressor in such assessments[886].

The European Union project called "Achieve Quieter Oceans by shipping noise footprint reduction" (AQUO) was a four-year programme between 2012 and 2015[887]. It consisted of experts from shipbuilding, underwater acoustics and bioacoustics working on a multidisciplinary approach to develop guidelines for controlling the underwater radiated noise (URN) from commercial shipping. Both technical and operational solutions were evaluated by considering the impact on marine life, feasibility in terms of ship design, and cost-effectiveness, including fuel efficiency[888]. For impacts on marine life, three species were selected for assessment: the harbour porpoise, Atlantic cod and the common cuttlefish. For two of these species, scenarios related to masking by shipping noise were used: i. masking of communication signals of male cod during spawning; and ii. masking of killer whale predator sounds for a harbour porpoise. The corresponding risk using adapted zones of influence concept[889] was calculated and mapped spatially. With sufficient computational power, it is also possible to run the predictive model in real time, using AIS[890] information, to provide the capability for real time underwater noise monitoring and ship traffic management[891].

Another product that was developed for Europe was the Subsea Environmental Acoustic Noise Assessment Tool (SEANAT) which provides a range of tools for modelling sound fields associated with underwater noise sources[892]. SEANAT has been developed by the Centre for Marine Science and Technology at Curtin University for use in the German Economic Exclusion Zone (EEZ) waters. The product can configure model scenarios, run underwater sound propagation models in realistic acoustic environments, compute received levels and visualise the resulting sound fields. Sound propagation modelling uses two models: RAMGeo, a modified version of the Range-dependent Acoustic Model (RAM) is used for lower frequencies up to 2 kHz, whereas for higher frequencies (>2 kHz), the Bellhop model is used.

Habitat modelling of cetaceans can also help to inform marine spatial management and planning. Cetacean modelling has considerably advanced in the last decade[893], and near real-time forecasts of distribution[894] are now possible providing highly useful information that can assist in the planning of anthropogenic noise generating activities. Cetacean habitat modelling techniques are also able to predict

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883 Merchant, N.D. Faulkner, R.C. and Martinez, R. 2018. Marine noise budgets in practise. Cons. Lett. 11: 1-8.
884 Ibid
885 Halpern, B.S., Walbridge, S., Selkoe, K. & Kappel, C. 2008. A global map of human impact on marine ecosystems. Science, 319, 948-952.
886 Merchant, N.D. Faulkner, R.C. and Martinez, R. 2018. Marine noise budgets in practise. Cons. Lett. 11: 1-8.
887 www.aquo.eu
888 Audoly, C. et al 2017. Mitigation of Underwater Radiated Noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO Project. IEEE Journal of Ocean Engineering 42: 373-387.
889 Dooling, R.J. and S. H. Blumenrath. 2013. Effects of noise on acoustic signal production in marine mammals. In: Animal Communication and Noise, Vol. 2. New York, NY, USA: Springer-Verlag.
890 The automatic identification system (AIS) is an automatic tracking system used on ships
891 Audoly, C. et al 2017. Mitigation of Underwater Radiated Noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO Project. IEEE Journal of Ocean Engineering 42: 373-387.
892 Subsea Environmental Acoustic Noise Assessment Tool (SEANAT) V3-Draft. 2014. SEANAT Manual. 4 January 2014.
893 Gregr, E.J, Baumgartner, M.F., Laidre, K.L. and Palacios, D.M. 2013. Marine mammal habitat models come of age: the emergence of ecological and management relevance. Endangered Species Research 22: 205-212.
894 Becker, E.A. and others. 2012. Forecasting cetacean abundance patterns to enhance management decisions. Endangered Species Research 16: 97-112.

cetacean densities at fine spatial scales to match the size of operational areas[895]. Densities are estimated as continuous functions of habitat variables such as sea surface temperature, seafloor depth, distance from shore or prey density[896]. Model results have also been collaboratively incorporated into an online mapping portal that uses OBIS-SEAMAP geo-datasets and a spatial decision support system (SDSS) that allows for easy navigation of models by taxon, region or season[897]. The SDSS displays model outputs as colour-coded maps of cetacean density for an area of interest along with a table of densities and measures of precision. This user-friendly online system enables the application of these habitat models to real world conservation and management issues[898].

There are also considerations to develop confirmatory or mechanistic models that will provide more robust and accurate predictions of species distributions that are based on greater ecological understanding[899]. However, mechanistic models do currently have a number of limitations[900], and an incremental iterative process from simple to complex formulations is recommended before spatially explicit models of marine mammal population dynamics incorporating prey abundance and environmental variability can be successfully built[901].

Mapping the distributions of marine mammals other than cetaceans is required as well as important species from other taxa such as fishes, turtles and invertebrates. Fisheries data is a key source of information to produce species distribution and habitat maps for many marine fishes. These data should be combined with products such as SoundMap to enable spatio-temporal risk assessments that can feed into the marine spatial planning process. Ecosystem-level modelling frameworks for the marine environment that permit the inclusion of human activities should also be considered[902].

Continuous noise pollution has the potential to mask the vocalisations or hearing of marine animals during important activities such as navigating, feeding or breeding. These chronic effects may be more substantial than short-term acute effects over the spatial and temporal extents relevant to marine animals that rely on acoustic communication[903]. There is increasing recognition that sub-lethal impacts such as communication masking or behavioural responses from chronic exposure to sounds are perhaps one of the most important considerations for populations[904]. Communication masking is particularly an issue for baleen whales that rely on low-frequency sounds for major life functions as their communication frequencies overlap with most chronic noise producing activities, particularly from large commercial vessels. It is therefore important to be able to measure chronic noise levels and determine the extent of communication masking for marine fauna such as baleen whales.

Studies in the Mediterranean Sea of Cuvier's beaked whale distribution indicate that modelling tools can be employed for a preliminary risk assessment of 'unsurveyed' areas[905]. *A priori* predictions of beaked whale presence in the Alboran Sea were evaluated using models developed in the Ligurian Sea

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[895] Forney, K.A. and others. 2012. Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. Endangered Species Research 16: 113-133.
[896] Redfern , J.V. and others. 2006. Techniques for cetacean-habitat modeling. Marine Ecology Progress Series 310: 271-295.
[897] Best, B.D. and others. 2012. Online cetacean habitat modelling system for the U.S. east coast and Gulf of Mexico. Endangered Species Research 18: 1-15.
[898] Ibid
[899] Palacios, D.M., Baumgartner, M.F., Laidre, K.L. and Gregr, E.J. 2013. Beyond correlation: integrating environmentally and behaviourally mediated processes in models of marine mammal distributions. Endangered Species Research 22: 191-203.
[900] Ibid
[901] International Whaling Commission 2013. Report of the scientific committee. Annex K1: Report of the working group on ecosystems modelling. J. Cetacean Res Manag. 14(Suppl.): 268-272.
[902] Plaganyi, É.E. and others. 2012. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. Fish Fish, doi: 10.1111/j.1467-2979.2012.00488.x .
[903] Hatch, L. T., et al. 2012. Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. Conservation Biology 26: 983-994
[904] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. Literature Synthesis. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management
[905] Azzellino, A. et al., 2011. Risk mapping for sensitive species to underwater anthropogenic sound emissions: Model development and validation in two Mediterranean areas. Marine Pollution Bulletin 63: 56-70.

that use bathymetric and chlorophyll features as predictors. The accuracy of predictions was found to be adequate suggesting that the habitat model was transferable for use in an area different from the calibration site[906]. This study indicates that initial risk assessments may be feasible in data-poor areas if a regional habitat model for a particular species is available for transfer into the ‘unsurveyed’ site. Tools have been developed to measure communication masking in the marine environment. One example is the assessment of communication space and masking for the endangered North Atlantic right whales in an ecologically relevant area during their peak feeding season on the east coast of the United States[907] [908]. Modelling techniques were used to predict received sound levels from vessel and whale sound sources for the area within the frequency band that contains most of the sound energy in whale contact calls. As well as providing techniques to measure and predict the degree of communication masking the tools can be used to support the development of management guidelines, as they provide a method for integrating different quantitative evaluations into a management framework.

Further development of tools to assess masking in other marine taxa such as fishes is required. The potential for communication masking in marine fishes is considerable[909], which overlaps with low frequency shipping noise. There is a need to develop techniques to translate the effects of masking on ecosystem services[910] for marine taxa, especially marine mammals and fishes. Integration of masking effects into assessments of cumulative impacts from multiple stressors is also required.

Passive and Active Acoustic Monitoring

Passive acoustic monitoring (PAM) can be an effective tool for cetacean detection if used properly and should be a mandatory requirement for mitigation procedures during operations. PAM is also a useful tool for the collection of baseline data before a project starts and once operations have been completed to monitor long-term patterns of cetacean distribution in the project area. PAM has become a fundamental tool, not only for researching the behaviour of whales, but for designing real time mitigation protocols that may minimise the potential impacts of anthropogenic activities[911]. The ability to conduct detailed real-time mitigation and monitoring has improved considerably in recent years with the availability of GIS-based data collection tools such as PAMGUARD[912], SEAPRO and PAM Workstation[913], LOGGER[914] and WILD[915]. Further information for these PAM tools has been summarised in a report by the ACCOBAMS/ASCOBANS joint noise working group (Table 19)[916]. Most PAM systems still require human operators to assess incoming sounds although automated detection systems are becoming increasingly viable for some species[917]. Advances in electronics, computers, and numerical analysis have made PAM technology more accessible and affordable to researchers[918]. Various systems are in use, including radio-linked systems, drifting buoys, and arrays of

[906] Ibid

[907] Clark, C.W., Ellison, W.T., Southall, B.L., Hatch L., van Parijs, S.M., Frankel, A. and Ponirakis, D. 2009. Acoustic masking in marine ecosystems: intuitions, analyses, and implication. Marine Ecology Progress Series, 395: 201 – 222

[908] Hatch, L. T., et al. 2012. Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. Conservation Biology 26: 983-994

[909] CBD Secretariat 2012. Scientific Synthesis on the impacts of underwater noise on marine and coastal biodiversity and habitats. 93 pp.

[910] Hatch, L. T., et al. 2012. Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. Conservation Biology 26: 983-994

[911] Przeslawski, R. et al. 2018. An integrated approach to assessing marine seismic impacts: Lessons learnt from the Gippsland Marine Environmental Monitoring project. Ocean Coast. Manag.160: 117-123.

[912] PAMGUARD. 2006. PAMGUARD: Open-sourced software for passive acoustic monitoring. www.pamguard.org.

[913] http://www-3.unipv.it/cibra/seapro.html

[914] International Fund for Animal Welfare (IFAW). 2000. Logger: Field data logging software (Version 2000). http://www.marineconservationresearch.co.uk/downloads/logger-2000-rainbowclick-software-downloads.

[915] D’Amico, A., Kyburg, C. and Carlson, R. 2010. Software tools for visual and acoustic real-time tracking of marine mammals. The Journal of the Acoustical Society of America, 128 (4), 237.

[916] Maglio, A. 2013. Anthropogenic noise and marine mammals. Review of the effort in addressing the impact of anthropogenic underwater noise in the ACCOBAMS and ASCOBANS areas. Prepared for the Joint ACCOBAMS-ASCOBANS noise working group. Sinay, Caen, France.

[917] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland.

[918] Andre, M. 2018. Ocean noise: Making sense of sounds. Social Science Information. doi:10.1177/0539018418793052

autonomous recorders for versatile and long-term deployments. However, PAM does have a number of limitations[919][920], although some of these can be addressed[921]. Specifically PAM is unable to:

- Accurately measure animal abundance as passive acoustics cannot independently verify the number of animals from which vocalisations originate. Several techniques have been used by field-based researchers to accommodate for this;
- Identify to the species level in some cases – especially for odontocetes. This can be overcome by collecting simultaneous visual observations;
- Determine whether a lack of acoustic communication is associated with the absence of animals that might otherwise be vocalising. Visual observers can confirm the presence of marine mammals in favourable conditions. At night or in adverse weather conditions, marine mammal presence may be detected by thermal imaging of blows[922].

In addition, subtle variations in marine mammal sounds produced between different populations of the same species can reduce the accuracy of automated detection systems[923]. The orientation of the sound-producing animal in relation to the PAM system can also influence the levels received and therefore the estimated distance to the animal[924]. Although there are issues with using PAM, the technology is developing rapidly and becoming a more efficient tool for mitigation.

The correct use of PAM is important so that acoustic detection is as accurate and effective as possible. In the past, there has been a lack of guidance for PAM implementation and a lack of training programmes for its use[925]. As PAM use has become more widespread, there has been the development of accredited training programmes for industry. Detailed guidance on the qualifications, training standards and conduct of PAM operators and MMOs are available as a series of Marine Mammal Observer Association (MMOA) position statements[926]. High quality standardised training of MMOs/PAM is offered by ACCOBAMS through the ACCOBAMS school with accredited trainer organisations[927]. National governing bodies have also approved MMO/PAM training courses offered by private contractors, for example the Joint Nature Conservation Committee in the UK[928] or the Department of Conservation in New Zealand[929].

The use of PAM to detect non-mammal marine fauna is questionable as vocalisations by fishes and invertebrates are quieter than those of marine mammals. Specific PAM systems used in noise mitigation

[919] Bingham, G. 2011. Status and applications of acoustic mitigation and monitoring systems for marine mammals: Workshop Proceedings; November 17-19, 2009, Boston, Massachusetts. U.S. Dept. of the Interior, Bureau of Energy Management, Regulation, and Enforcement, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEMRE 2011-002. 384 pp.

[920] Gill, A. et al. 2012. Marine Mammal Observer Association: Position Statements. The key issues that should be addressed when developing mitigation plans to minimise the effects of anthropogenic sound on species of concern. Version 1 (Consultation document). 32 pp. Marine Mammal Observer Association, London, U.K. http://www.mmo-association.org/position-statements

[921] Carduner, J. 2013. Best Practises for baseline passive acoustic monitoring of offshore wind energy development. Research Thesis. Duke University. 41 pp.

[922] Zitterbart, D.P., Kindermann, L., Burkhardt, E. and Boebel, O. 2013. Automatic round-the-clock detection of whales for mitigation from underwater noise impacts. PLoS ONE 8(8): e71217. doi: 10.1371/journal.pone.0071217. 6 pp.

[923] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland.

[924] Ibid

[925] Weir, C. R. and Dolman, S.J. 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy. 10: 1-27.

[926] Ibid

[927] http://www.accobams.org/main-activites/mmo-certificate-school/

[928] http://jncc.defra.gov.uk/page-4703

[929] https://www.doc.govt.nz/our-work/seismic-surveys-code-of-conduct/observer-standards-and-training/

procedures that can detect the presence of fishes have not yet been developed[930], although the use of passive acoustics for fisheries monitoring and assessment is an active and growing research field[931][932]. Active acoustic monitoring (AAM) techniques are more applicable for non-vocalising marine fauna such as fish, turtles and invertebrates and also for non-vocalising marine mammals. However, AAM systems can often only detect animals at closer ranges than passive monitoring but is able to estimate the range of targets more easily. The use of active acoustic systems will, however, add sound energy to the marine environment, which may have behavioural effects on some taxa, particularly marine mammals, and increase the occurrence of stress and masking responses. The use of AAM is not recommended for marine mammals, except in the case of mitigating single loud sounds such as explosives where they can be used simultaneously as an alarming device[933]. The potential effects of AAM on other marine taxa also need to be investigated.

Real-time Automated Monitoring

Large-scale real-time passive monitoring of the marine acoustic environment can provide information on both continuous and impulsive noise production as well as detecting the presence and location of vocalising marine taxa such as marine mammals. 'Listening to the Deep Ocean Environment' (LIDO) is an international project that can monitor marine ambient noise in real-time over large spatial and temporal scales[934]. Acoustic information is collected at cabled deep sea platforms and moored stations in multiple sites associated with national or regional observatories. The software has several dedicated modules for noise assessment, detection, classification and localisation[935]. Data is processed to produce outputs that can characterise an acoustic event as well as spectrograms for quick visualisation and compressed audio. The outputs are publicly available via a website[936] and can be viewed with a specific application.

The main approach is to divide the recording bandwidth into frequency bands that cover the acoustic niche of most cetacean species and apply a set of detectors and classifiers. This information is then used by localisation and tracking algorithms to monitor the presence and activity of cetaceans. This acoustic detection, classification and localization (DCL) system has the potential to be used as a mitigation tool for some offshore noise generating activities and has the advantages of being a fully automated system that can operate in all conditions (sea state, day/night) with no specialist operators required. The technology has been adapted to offer internet-based tools to ocean users, such as oil and gas and renewable energy (windfarm) companies[937].

Management Frameworks and International Agreements

This section provides information on a range of management frameworks currently in use or proposed to manage underwater noise pollution. These include the use of spatio-temporal restrictions (STRs) to protect marine fauna from noise pollution as part of a wider marine spatial planning approach and the use of impact or risk assessment frameworks. The progress made by various agreements at the regional and international level (e.g., ACCOBAMS/ASCOBANS/CMS, OSPAR, HELCOM, EU MSFD, IMO) to address underwater noise pollution is also summarised.

[930] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. Workshop Report. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management
[931] Gannon, D.P. 2008. Passive acoustic techniques in fisheries science: a review and prospectus. Transactions of the American Fisheries Society 137: 638-656.
[932] Luczkovich, J.J., Mann, D.A. and Rountree, R.A. 2008. Passive acoustics as a tool in fisheries science. Transactions of the American Fisheries Society 137: 533-541
[933] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland.
[934] Andre, M., ven der Schaar, M., Zaugg, S., Houegnigan, L., Sanchez, A.M. and Castell, J.V. 2011. Listening to the Deep: live monitoring of ocean noise and cetacean acoustic signals. Mar Poll Bull 63:18-26
[935] Ibid
[936] http://listentothedeep.com/acoustics/index.html
[937] Andre, M. 2018. Ocean noise: Making sense of sounds. Social Science Information. doi:10.1177/0539018418793052

Spatio-temporal restrictions, including marine protected areas, are regarded as one of the most effective ways of protecting cetaceans and their habitat from the cumulative and synergistic effects of noise and other anthropogenic stressors[938] [939]. Avoiding sound production when vulnerable marine fishes or invertebrates are present has also been recommended[940]. The use of spatio-temporal restrictions (STRs) to protect marine mammals and other taxa from noise pollution and other stressors has been strongly endorsed with the proposal of a conceptual framework for STR implementation[941]. However, the size of marine areas to be protected from noise is a major concern as sound can propagate great distances in the marine environment, especially at low frequencies[942]. For example, for intense mid-frequency sounds to be excluded from areas tens of kilometres away from critical cetacean habitats would require an STR of 100-1000 km^2 while protection from intense low frequency sounds could require distances of hundreds of kilometres and STR areas of at least 10 000 to 100 000 km^2[943]. The use of noise-based STRs as part of marine spatial planning frameworks requires that managers have a certain level of background information for the species of concern and their preferred habitats for activities such as breeding/spawning or feeding. Information on the timing, location, type and intensity of proposed noise generating activities is also needed to evaluate the level of risk to marine fauna in the region if spatial restrictions are not permanent.

Management Frameworks

Management frameworks for the marine environment include underwater noise management and mitigation as part of a broader approach to control the impacts of anthropogenic stressors on marine biodiversity, often within an ecosystem-based management approach. These frameworks include marine spatial planning approaches and assessments of the level of risk or impact for species. Risk and impact assessments are also moving to estimating effects on species at the population level rather than the individual level.

A framework for the systematic prioritisation of noise mitigation for cetaceans was developed and proposed during the global scientific workshop on spatio-temporal management of noise[944] (Table 8). The framework consists of six steps and draws heavily on the general principles identified in the conservation planning and adaptive management literature[945]. Although published in 2007, it is still valid for use in noise mitigation today and contains some similar recommendations for mitigation practises provided in recent publications[946]. The six-step process could also be tailored to suit other marine taxa such as vulnerable species of fishes, turtle or invertebrate.

Table 8: A Framework for systematic prioritisation of noise mitigation (for cetaceans) (adapted from Agardy et al., 2007)

Step	Notes

[938] Weilgart, L.S. 2006. Managing Noise through Marine Protected Areas around Global Hot Spots. IWC Scientific Committee (SC/58/E25).

[939] Agardy, T., Aguilar, N., Cañadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E., Martin, V., Notarbartolo di Sciara, G., Pavan, G., Servidio, A., Smith, B., Wang, J., Weilgart, L., Wintle, B. and Wright, A. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages.

[940] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. Literature Synthesis. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management

[941] Agardy, T., et al., 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages

[942] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[943] Agardy, T., et al., 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages

[944] Ibid

[945] Ibid

[946] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377.

1. Define the goal(s), constraints and geographic scope of the planning process	Key requirements of the goal on which prioritisation can be structured are: clear geographic scope, a measurable conservation target, the desired degree of confidence, and a measure of social opportunity costs. Crucial to the transparency of the project and helps engage all stakeholders.
2. Identify relevant data and data gaps	Spatial information on species habitat distributions, threats (e.g., areas of seismic exploration) and socio-economic information (e.g., current jurisdictional boundaries). Sufficient data is seldom available for all species and all social aspects). Urgent data collection may be needed but usually preferable to proceed with data that is available and use expertise and modelling to make decisions.
3. Synthesise habitat and threat data to generate exposure ranking maps	Identify areas of overlap between biodiversity value and threats to those values e.g., Threat maps may be species-specific or general. Weighting of particular species of concern or interest can be applied.
4. Generate map of mitigation priority areas	Integrate exposure maps from 3. With spatial data on existing opportunities and impediments, opportunity costs and any other relevant spatial information. Commonly associated with systematic conservation planning algorithms that can be used to produce an 'optimal' solution e.g., the most effective protection for a species or habitat for the least cost. Committee processes (Delphi methods) can be used instead of algorithms for less complicated situations.
5. Identify and prioritise actions for priority conservation zones	Action prioritisation is necessary as conservation budgets are finite. Use a coherent and transparent approach with a respected prioritisation protocol that incorporates the concepts of conservation benefit, feasibility and cost efficiency, to prioritise actions.
6. Implement and monitor	Ensure that monitoring data is integrated back into the decision making process to enable adaptive management. This requires good coordination between managers and scientists. Monitoring is central to the success of the adaptive prioritisation framework. Design monitoring programme in advance to allow monitoring prior to implementation.

In the United States, a national policy[947] was signed in 2010 to strengthen ocean governance and coordination, establish guiding principles for ocean management and adopt a flexible framework for effective coastal and marine spatial planning (CMSP) to address conservation, economic activity, user conflict and sustainable use of the marine environment in U.S. waters[948]. The National Ocean Policy recommends the development of regional assessments that include descriptions of the existing biological, chemical, physical and historic characteristics; identification of sensitive habitats and areas; identification of areas of human activities; analyses of ecosystem conditions, and assessments, forecasts and modelling of cumulative impacts[949].

To inform marine spatial planning and other processes such as environmental impact assessments, several national-scale systems were developed including Ocean.Data.Gov and the NOAA CMSP Data Registry. The Ocean.Data.Gov system is dedicated to coastal and marine scientific data and aims to build capacity in the development of spatial data, data standards, mapping products and decision support tools. These information platforms feed into NOAA's Integrated Ecosystem Assessment (IEA) framework which is regarded as a promising approach to ecosystem-based management and a leading example of a comprehensive ecosystem-based assessment[950]. The IEA framework consists of five components: 1. Scoping, 2. Identifying indicators and reference levels, 3. Performing risk analyses, 4.

[947] National Policy for the Stewardship of the Oceans, Coasts and Great Lakes.
[948] National Ocean and Atmospheric Administration. 2012. Mapping Cetaceans and Sound: Modern Tools for Ocean Management. Final Symposium Report of a Technical Workshop held May 23-24 in Washington, D.C. 83 pp.
[949] Interagency Ocean Policy Task Force. 2010. Final recommendations of the Interagency Ocean Policy Task Force. White House Council on Environmental Quality.
[950] Foley et al., 2013. Improving ocean management through the use of ecological principles and integrated ecosystem assessments. BioScience 63:619-631.

Evaluating management strategies and, 5. Monitoring and evaluating progress towards management goals. The framework has been widely implemented in U.S. waters[951] and also in the North Sea[952].

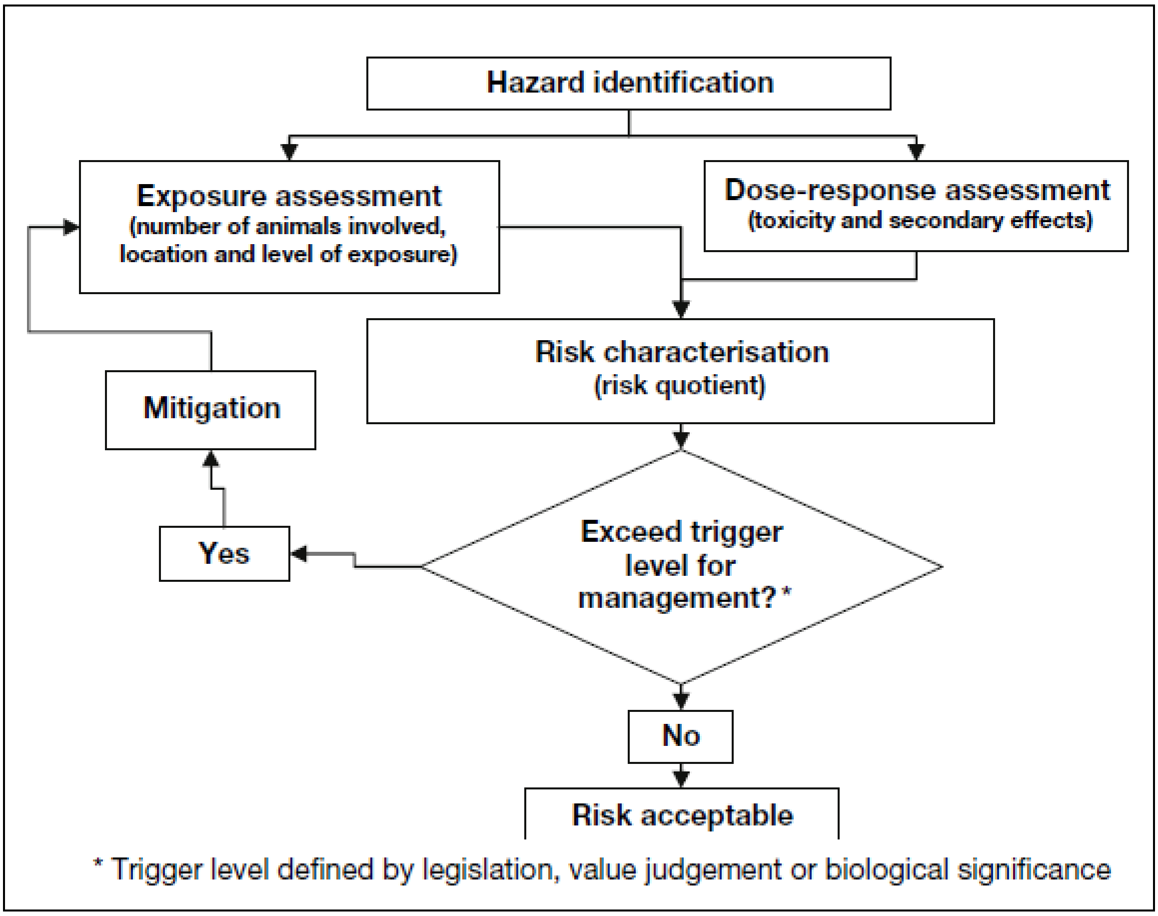
Undertaking risk or impact assessments is a key part of ecosystem-based management and conservation planning. Quantitative risk assessment techniques that could be applicable for the assessment of underwater noise effects in combination with other impacts include the use of population viability analysis (PVA). This technique is commonly used to quantify the probability that a species will decline to an unacceptably low population size within a particular timeframe[953]. To date PVA has not been widely used to assess noise impacts and the viability of populations of marine fauna under a range of management scenarios.

A framework to assess risk to indicator species in coastal ecosystems has been tested in Puget Sound, WA, USA[954]. The framework can identify land- or sea-based activities that pose the greatest risk to key species of marine ecosystems, including marine mammals, fishes and invertebrates. Ecosystem-based risk is scored according to two main factors: the exposure of a population to an activity and the sensitivity of the population to that activity, given a particular level of exposure. The framework is scalable, transparent and repeatable and can be used to facilitate the implementation of EBM, including integrated ecosystem assessments and coastal and marine spatial planning[955]. In the Puget Sound case study, the combined effects of four human activities – coastal development, industry, fishing and residential land use – were assessed for seven indicator species: two marine mammals, four fishes and one invertebrate. The framework offers a rigorous yet straightforward way to describe how the exposure of marine species to human stressors interacts with their potential to respond under current and future management scenarios[956]. The applicability of this framework to assess the risk of noise effects for marine species requires consideration.

A risk assessment framework specifically addressing underwater noise impacts for marine mammals is also available[957] and could be adapted for other marine taxa. The framework consists of a four-step analytical process: 1. Hazard Identification, 2. Dose-response assessment, 3. Exposure assessment, and 4. Risk characterisation. A fifth step, risk management, involves the design and application of mitigation measures to reduce, eliminate or rectify risks[958]. A decision flow and information pathway for the framework is presented in Figure 10. The decision pathway contains a feedback loop involving mitigation when the risk exceeds the trigger level indicating that an adaptive approach to managing risk is taken.

Figure 10. Illustration of the information flow and decision pathway for a risk assessment process (Boyd et al., 2008).

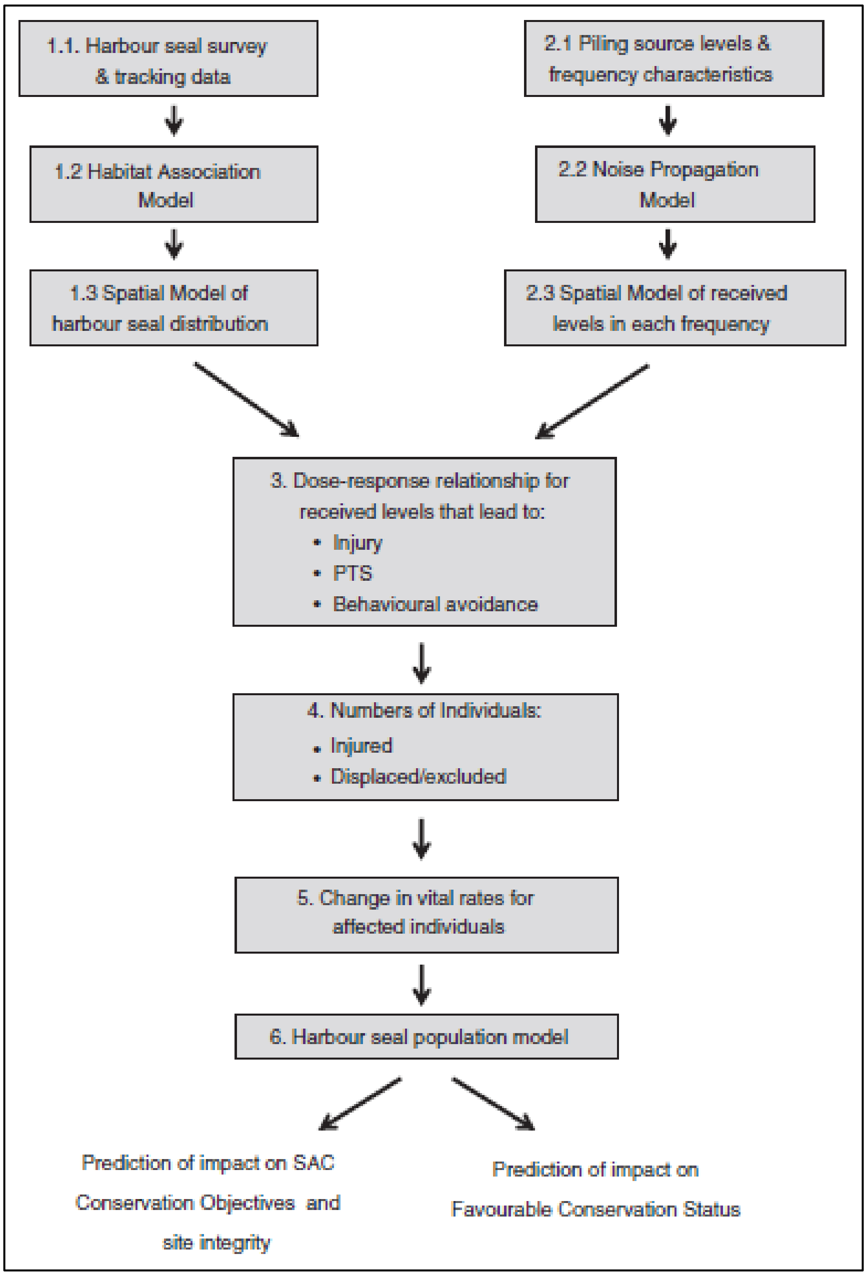
[951] www.noaa.gov.iea
[952] International Council for the Exploration of the Sea. 2011. Report of the working group on integrated assessments of the North Sea (WGINOSE). ICES Report no. ICES CM 2011/SSGRSP:02.
[953] Burgman, M.A., Ferson, S. and Akçakaya, H.R. 1993 Risk assessment in conservation biology. Chapman and Hall, London.
[954] Samhouri, J.F. and Levin, P.S. 2012. Linking land- and sea-based activities to risk in coastal ecosystems. Biological Conservation. 145: 118-129
[955] Ibid.
[956] Ibid
[957] Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005.
[958] Ibid.



An example of an assessment framework to explore the long-term impact of a noise generating activity on a marine mammal[959] is summarised in Figure 10. In this case, it is the impact of pile-driving from wind farm construction on a harbour seal population within a Special Area of Conservation (SAC) under the EC Habitats Directive. Spatial patterns of seal distribution and received noise levels were integrated with available data on the potential impacts of noise to predict the number of individuals that would be displaced or experience auditory injury. Then expert judgement was used to link these impacts to changes in vital rates (fecundity and survival) and applied to population models that compare population changes under baseline and construction scenarios over a 25-year period[960]. A schematic of the approach taken is provided below (Figure 11):

Figure 11. Schematic of the approach used to assess the impact of wind farm construction on the harbour seal in a Special Area of Conservation (SAC) and with Favourable Conservation Status (FCS). (after Thompson et al., 2013)

[959] Thompson, P.M. et al., 2013. Framework for assessing the impacts of pile-driving noise from offshore wind farm construction on a harbour seal population. Environmental Impact Assessment Review 43: 73-85.
[960] Ibid.



The framework can be used to provide preliminary guidance on how developers should assess the population consequences of acoustic disturbance from construction activities in the marine environment. There was considerable uncertainty for some parts of the analysis, particularly for the number of animals that were displaced from the area or experienced Permanent Threshold Shift (PTS) and how this affected individual fitness[961]. The latter was completely dependent on expert judgement. It was deemed most appropriate to use expert judgement in the short-term for certain parameters, but in the long-term, use of the Population Consequences of Acoustic Disturbance (PCAD) framework[962] is recommended as more information becomes available and uncertainty is reduced. Development of the framework relied heavily on the availability of detailed information on harbour seal populations in the locality which also makes the case study a suitable opportunity to develop detailed PCAD studies in the future[963].

[961] Ibid
[962] NRC, 2003. Ocean Noise and Marine Mammals. Washington, DC. National Academies, 2003.
[963] Thompson, P.M. et al., 2013. Framework for assessing the impacts of pile-driving noise from offshore wind farm construction on a harbour seal population. Environmental Impact Assessment Review 43: 73-85.

The modelling framework could also suitable for use on other less studied harbour seal populations, although it may be necessary to 'borrow' data such as fecundity estimates from better studied populations or possibly other seal species[964]. It is important to recognise that, due to the level of uncertainty and the use of conservative estimates for some individual parameters, this assessment framework is assessing worst-case impacts. Conservatism accumulates through the framework leading to more significant short-term impacts than is thought to be likely[965]. However, the framework does offer an alternative interim approach that can provide regulators with confidence that proposed developments will not significantly affect the long-term integrity of marine mammal populations, in this case the harbour seal. The use of mitigation and management frameworks over the whole lifetime of a proposed noise generating activity was discussed previously.

International Agreements and Processes

This section provides a brief overview of the current progress regarding the regulation, mitigation and management of underwater noise governed by a number of regional and international agreements. It should be noted that underwater noise is not comprehensively regulated by international or national law[966]. However, there is growing recognition that anthropogenic underwater noise should be regarded as a form of marine pollution and covered by the United Nations Convention on the Law of the Sea (UNCLOS), mainly under articles 1 and 94[967] [968]. Moreover, the declaration "Our ocean, our future: call for action", adopted at the United Nations Conference to Support the Implementation of SDG 14 ("Ocean Conference") in June 2017, includes a specific reference to addressing underwater noise (see General Assembly resolution 71/312, para. 13 (g))[969].

CMS/ASCOBANS/ACCOBAMS – Joint Noise Working Group

The Joint CMS/ASCOBANS/ACCOBAMS Noise Working Group (Joint NWG) consists of members and observers of the scientific and advisory bodies of the Convention on Migratory Species (CMS), the Agreement on the Conservation of Cetaceans of the Black Sea. Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) and Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS). External experts also participate in the Joint NWG to ensure the best possible advice can be generated for Parties.

The Joint NWG presents reports on progress and new information to each meeting of the CMS Scientific Council, ACCOBAMS Scientific Committee and ASCOBANS Advisory Committee. It addresses the mandates of relevant resolutions for all three organisations including CMS Res 9.19, CMS Res. 10.24, ACCOBAMS Res 3.10, ACCOBAMS Res. 4.17, ASCOBANS Res. 6.2 and ASCOBANS Res 7.2 and any new relevant resolutions not yet passed.

In 2013, the Joint NWG produced three main reports as part of its 2012- 2014 work programme:

1. Anthropogenic noise and marine mammals. Review of the effort in addressing the impact of underwater noise in the European Union

This document reviews the political effort from international bodies (resolutions, regional agreements etc.), existing guidelines from these bodies and implementation by countries, and existing mitigation technologies. Future actions to strengthen the effectiveness of mitigation measures are also provided.

964 Caswell, H., Brault, S., Read, A.J. and Smith, T.D. 1998. Harbor porpoise and fisheries: an uncertainty analysis of incidental mortality. Ecol. Appl. 8: 1226-1238.
965 Thompson, P.M. et al., 2013. Framework for assessing the impacts of pile-driving noise from offshore wind farm construction on a harbour seal population. Environmental Impact Assessment Review 43: 73-85.
966 Markus T., Sánchez P.P.S. 2018. Managing and Regulating Underwater Noise Pollution. In: Salomon M., Markus T. (eds.) Handbook on Marine Environment Protection. Springer, Cham.
967 Ibid
968 Report on the 19th Meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea: https://undocs.org/A/73/124
969 https://undocs.org/A/RES/71/312

2. Implementation of underwater noise mitigation measures by industries: operational and economical constraints

A report on consultations with industries and military authorities within the French Maritime Cluster which involved discussions on five main topics: marine renewable energies, sonar and seismic, marine traffic and dredging, fisheries, and marine protected areas. The consultations provided a better understanding of the mitigation procedures that are actually implemented and which measures have technical and economic constraints.

3. Guidance on Underwater Noise Mitigation Measures

A working document that provides guidance to industries and country authorities for the application of noise mitigation measures. It outlines noise mitigation practises and technologies that should be used for dealing with major sources of impulsive noise as identified by the European Commission's Technical Subgroup on underwater noise (TSG Noise)[970].

Since 2013, the Joint NWG has recently been addressing the development of guidance for the whole duration of impulsive noise generating operations (pre-operation assessment and planning, implementation and post-operation evaluation) with an emphasis on seismic surveys and the need for a more rigorous assessment stage as part of EIAs or SEAs.

In 2014, the Joint NWG worked with the ACCOBANS Secretariat to: a) identify anthropogenic noise/cetacean interaction hot spots in the ACCOBANS area and to map and develop monitoring of ambient noise, particularly in critical habitats; and b) develop monitoring guidance on marine noise for Ecological Objective (EO)11. In late 2014, the Joint NWG developed a Statement of Concern relating to activities in the Adriatic Sea. Guidelines for offshore exploration activities in the Adriatic Sea were also developed in early 2015. Also, that year the Joint NWG began to identify further area statements, modelled on the Adriatic Statement, which were then developed in 2015/2016.

In 2017, the Joint NWG developed an advisory statement on offshore exploration activities in sensitive areas in the Mediterranean Sea. The statement overlays information about the current Mediterranean Sea EBSA areas with ACCOBAMS science vulnerability and provides recommendations for offshore exploration activities. Also in 2017, the Joint NWG contributed to the "Overview of the noise hotspots in the ACCOBAMS area" project. This produced a first inventory of noise-producing human activities, identified areas where such activities are carried out, obtained cumulative maps of noise-producing human activities and proposed a first identification of noise-cetacean interaction hotspots. A methodology for implementing an international noise registry was also proposed.

The Joint NWG also contributed to an ACCOBAMS investigation into the Mediterranean noise monitoring strategy, based on MSFD TG-Noise guidance for Descriptor11. Two indicators have been proposed, one for impulsive noise and one for ambient noise. The recommendations from ACCOBAMS are to have an inventory of impulsive noises to understand their distribution in space and time, with a spatial grid of 20 x 20 km to locate and count noise events during a calendar year. Environmental status can be assessed after establishing a spatial and a temporal threshold for impulsive noise distribution. For ambient noise the proposal is to monitor levels and trends in selected 1/3 octave bands, and to identify and use a threshold in dB for environmental status assessment.

OSPAR Commission

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) has set up an Intersessional Correspondence Group on Noise (ICG Noise) under the OSPAR Committee of the Environmental Impact of Human Activities (EIHA). The ICG Noise initially

[970] Van der Graaf, S. et al. 2012. European Marine Strategy Framework Directive – Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy.

focussed on the monitoring of impulsive and ambient noise but also on primary and secondary noise mitigation measures. For the latter the group is currently developing an inventory of noise mitigation measures with priority given to pile driving, seismic activities and explosions. Other sources and activities that will be considered within the inventory are high frequency impulsive noise from echosounders, dredging activities, sonar and shipping. The inventory will provide an overview of the effectiveness and feasibility of mitigation options and help to support OSPAR EU member states in establishing programmes of measures in relation to underwater noise under the European Marine Strategy Framework Directive (MSFD).

OSPAR recently had a meeting of the Intersessional Correspondence Group on Underwater Noise (ICG Noise) in Gothenburg, Sweden (January 2014) where mitigation was on the agenda. A draft document on mitigation of pile driving noise was presented and discussed, which will be part of the OSPAR Inventory of noise mitigation strategies. The draft inventory of noise mitigation measures for pile driving is based upon a longer report compiled by Germany[971]. Outcomes of the meeting are available on the OSPAR website[972]. Work on other areas of noise mitigation to be included in the inventory was being developed from 2014.

At the ICG Noise meeting in London (November 2014), it was reported that Germany had held a national workshop on noise mitigation in October 2014. The workshop had also looked into the costs of implementing the techniques for mitigation of pile driving noise and had concluded that there was now the possibility to meet the government requirement for mitigation with current techniques. One area that did need further work, however, was mitigation from pile driving noise at deeper water depths. There had been little progress in completing additional chapters in the OSPAR Inventory of Mitigation techniques following the development of the overall document and chapter on pile driving. It was agreed that CEDA should be approached in relation to drafting the dredging chapter and that the OSPAR Offshore Industry Committee (OIC) approached to identify a lead to for the chapter on seismic noise.

Also in London, the ICG Noise meeting in November 2016 included mitigation on the agenda. A potential Regional Action Plan (RAP) on underwater noise was introduced. Contracting Parties were generally in favour of exploring a potential RAP further. Having an overarching framework under which Parties can coordinate actions taken to achieve the goals of the North-East Atlantic Strategy (NEAS) and the MSFD was considered useful. There was little progress on the further development of the Inventory of Mitigation Techniques with no update of the remaining chapters by Parties.

At the next meeting of the ICG Noise (Gothenburg, October 2017) it was agreed to prioritise the work on the remaining chapters of the Inventory of Mitigation Techniques for explosions and shipping with a lower priority for the other chapters. The chapter on seismic noise was close to publication subject to final agreement. . The outcome of the discussion with the Environmental Impacts of Human Activities (EIHA) Committee on the need for a Regional Action Plan (RAP) on underwater noise was presented. EIHA considered that it was too early to start the development of a RAP but requested the ICG consider future technical work to help inform policy direction for the implementation of the North East Atlantic Environment Strategy (NEAES).

HELCOM

The Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention or HELCOM) stipulates (under Regulation 2 of Annex VI) that parties must use the best available technology and best environmental practise to prevent and eliminate pollution, including noise, from offshore activities.

[971] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp.
[972] http://www.ospar.org/v_meetings

At the HELCOM Ministerial Meeting in Moscow in 2010, the parties agreed to "develop common methodologies and appropriate indicators, to facilitate national and coordinated monitoring of noise and identification of sources of noise and to further investigate the potential harmful impacts to wildlife from noise"[973].

In its capacity as the coordinating platform for the regional implementation of the EU MSFD in the Baltic Sea for those Contracting Parties that are also EU members, HELCOM initiated work to develop HELCOM core indicators which are harmonized with MSFD Descriptors under the HELCOM-CORESET project.

In October 2013, at the HELCOM Ministerial Meeting in Copenhagen[974] the parties agreed that "the level of ambient and distribution of impulsive sounds in the Baltic Sea should not have negative impact on marine life and that human activities that are assessed to result in negative impacts on marine life should be carried out only if relevant mitigation measures are in place, and accordingly as soon as possible and by the end of 2016, using mainly already on-going activities, to:

- Establish a set of indicators including technical standards which may be used for monitoring ambient and impulsive underwater noise in the Baltic Sea;
- Encourage research on the cause and effects of underwater noise on biota;
- map the levels of ambient underwater noise across the Baltic Sea;
- Set up a register of the occurrence of impulsive sounds;
- Consider regular monitoring on ambient and impulsive underwater noise as well as possible options for mitigation measures related to noise taking into account the on-going work in IMO on non-mandatory draft guidelines for reducing underwater noise from commercial ships and in CBD context."

At the meeting of the HELCOM Monitoring and Assessment Group in November 2013, the parties shared information about their national activities and projects dealing with underwater noise. There was discussion about how to carry out further regional work on development of an underwater noise indicator and monitoring. It was agreed that as a first step for establishing a foundation for monitoring of noise, HELCOM should make use of the outcomes of the Baltic Sea Information on Acoustic Soundscape project (BIAS), in which several HELCOM countries are involved. An intersessional activity has been initiated with the view that there will be a thematic session on underwater noise (based on preparations by and material from the intersessional activity) at the meeting of the HELCOM Monitoring and Assessment Group (Oslo, Norway; 8-10 April 2014).

BIAS is an EU LIFE+ funded project with the ultimate goal to secure that the introduction of underwater noise is at levels that do not adversely affect the marine environment of the Baltic Sea. BIAS will work towards this goal by bridging the gap between the MSFD descriptor 11 and actual management of human-induced underwater noise. Objectives of the project include:

- Demonstration of national and regional advantages of a transnational approach for management of underwater noise;
- Initial assessment of underwater noise in the Baltic Sea;
- Implementation of a planning tool for straightforward management of intermittent underwater noise sources;
- Establishment of draft Baltic Sea standards and tools for management of underwater noise.

In 2015, a regional registry of licenced impulsive events such as pile driving, controlled explosions from naval operations and other activities that release energy was established by HELCOM, working

[973] HELCOM 2010 Moscow Ministerial Declaration
[974] HELCOM Copenhagen Ministerial Declaration

with OSPAR, and member countries are providing national data to ICES. HELCOM is in the process of adopting regional monitoring guidelines for continuous noise and monitoring programme of continuous noise, to be implemented by the Baltic Sea countries. The programme proposal includes measurements and modelling, as well as data arrangements to compile and visualize regional monitoring data.

HELCOM published a report in 2017 presenting the rationale for selecting Baltic species with the potential to be impacted by noise together with a preliminary identification of biologically sensitive areas. The report includes a prioritized list of seven noise sensitive species: harbour porpoise, harbour seal, ringed seal, grey seal, cod, herring and sprat. The species have been identified based on the following criteria: hearing sensitivity, known (or suspected) noise impact on the species, threat status, commercial value, and data availability. For each species their distribution and biologically sensitive areas is presented based on available data. HELCOM has also produced an overview report of underwater noise mitigation measures including country specific information, to provide background information what type of measures already exist in the Baltic Sea region. Based on the new knowledge and information gathered, HELCOM has included underwater noise in its newest assessment the ‘State of the Baltic Sea report, June 2017’ for the first time.

HELCOM continues to work on the operationalization of underwater noise indicators. The indicators will enable the evaluation of progress towards the goal of achieving good status with respect to underwater noise in the Baltic Sea. Tthe work has mainly focused on pressure indicators. Further research is needed to close knowledge gaps on the impact of anthropogenic noise on sensitive species at the population level.

EU Marine Strategy Framework Directive (MSFD)

There have been several pieces of relevant work conducted in the context of the EU Marine Strategy Framework Directive (Dir. 2008/56/EC):

1. Report on Underwater noise and other forms of energy (2010)[975]

This document takes stock of the (limited) knowledge on the effects of underwater energy, particularly noise, and especially at any scale greater than the individual/group level. The report contains much scientific background information and has suggestions for possible indicators for noise, as well as on the assessment of the effects of electromagnetic fields and heat on the marine environment.

2. Report of the Technical Subgroup on Underwater Noise and other forms of energy (2012)[976]

This is the report of an expert group (TSG Noise) established to help EU Member States implement relevant indicators determined by Commission Decision 2010/477/EU. The Group focussed on clarifying the purpose, use and limitation of these indicators and on the description of a methodology that would be unambiguous, effective and practicable.

3. Monitoring guidance for underwater noise in European Seas (2014) [977]

This document provides guidance on how to monitor loud impulsive noise and ambient noise on a (sub-) regional basis in European waters. In the Baltic Sea, the EU-sponsored project BIAS has analysed this

[975] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[976] Van der Graaf, S. et al. 2012. European Marine Strategy Framework Directive – Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy

[977] Dekeling, R.P.A. et al. 2014. Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications, JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/27158.

approach further. The report consists of three parts: Part 1, Executive summary and Recommendations; Part 2, Monitoring Guidance Specifications; and Part 3, Background Information and Annexes.

The monitoring guidance for impulsive noise provides details on the requirements to meet EU MSFD indicator 11.1.1 to determine the spatio-temporal distribution of loud, low and mid frequency impulsive sounds. This involves setting up a register of the occurrence of impulsive sounds to establish the current level and trends at a Regional Sea level. The indicator is designed to address the cumulative impact of sound generating activities and possible associated displacement that is 'considerable'[978] and may lead to population effects. All sources that have the potential to cause a significant population level effect are to be included in the register, including explosives and military activities. A series of minimum thresholds were derived for each of the sound generating activities over which the sound emission must be recorded in the register (except for pile driving where all activities are recorded). The register will provide member states with a quantified assessment of the spatial and temporal distribution of impulsive noise sources, throughout the year in regional seas. This will enable States to establish baselines for current levels and then use the register to help manage impulsive noise levels, assist in marine spatial planning and mitigation requirements to minimise displacement.

The monitoring of ambient noise is covered by indicator 11.2.1 which requires the monitoring of trends in ambient noise in two 1/3 octave bands centred at 63 and 125 Hz. Levels and trends will be derived from a combined use of measurements, models and sound maps to enable cost-effective and reliable trend estimation. Guidance is also provided to member states on monitoring strategy and for the reporting of results.

Since the publication of the guidance document significant progress has been made with implementation of monitoring of underwater sound, making use of regional scale registers for impulsive noise-generating activities and setting up joint monitoring programmes for continuous noise. Ongoing work of the TSG Noise includes ensuring consistency between monitoring programmes, both inside and outside Europe, and developing common methodology for assessment of the data obtained in these programmes.

Relevant work also emerges from the context of EU conservation law, in particular the Habitats Directive (Dir. 92/43/EEC). In this context, Guidelines for the establishment of the Natura 2000 network in the marine environment have been developed which, inter alia, address the issue of noise pollution (pp. 94-96) in relation to provisions in Articles 6 and 12 of the Directive.

There are also several completed or on-going EU-based research projects that are addressing issues relevant to underwater noise which were summarised in a report by TG Noise in 2017[979]. These included:

- BIAS - Baltic Sea Information on the Acoustic Soundscape[980] (2013-2016);
- AQUO – Achieve Quieter Oceans by shipping noise footprint reduction (2012-2015)
- SONIC – Suppression of Underwater noise Induced by Cavitation (2012-2015)
- MaRVEN -Environmental Impact of Noise, Vibrations and Electromagnetic Emissions from Marine Renewables (2013-2015)[981]
- Impacts of noise and use of propagation models to predict the recipient side of noise[982]
- UNAC-LOW – Underwater Acoustic Calibration Standards for frequencies below 1 kHz
- DEPONS – Disturbance effects on the Harbour Porpoise Population in the North Sea

[978] Displacement of a significant proportion of individuals for a relevant period and at a relevant spatial scale
[979] Management and monitoring of underwater noise in European Seas - Overview of main European-funded projects and other relevant initiatives. Communication Report. MSFD Common Implementation Strategy Technical Group on Underwater Noise (TG-NOISE). April, 2017.
[980] http://biasproject.wordpress.com/
[981] https://publications.europa.eu/en/publication-detail/-/publication/01443de6-effa-11e5-8529-01aa75ed71a1/language-en
[982] http://ec.europa.eu/environment/marine/

- SHEBA – Sustainable shiiping and the environment of the Baltic Sea region
- CMEMS – Copernicus Marine Environment Monitoring Service
- Quiet-Oceans Initiative on Underwater Noise Mapping
- QUIETMED – Joint programme on noise for the implementation of the second cycle of the MSFD in the Mediterranean Sea

International Maritime Organization (IMO)

In 2008 following a submission on ‘the development of non-mandatory technical guidelines to minimize the introduction of incidental noise from commercial shipping operations into the marine environment to reduce potential adverse impacts on marine life’ to the Marine Environment Protection Committee (MEPC) of the International Maritime Organisation (IMO), it was suggested that the issues should be discussed by the IMO. Given this suggestion, the MEPC agreed to commence the work programme on “Noise from commercial shipping and its adverse impacts on marine life” and to establish an intersessional correspondence group, with a view to identifying and addressing ways to minimize the introduction of incidental noise into the marine environment from commercial shipping to reduce the potential adverse impact on marine life. More in particular, the MEPC agreed to develop voluntary technical guidelines for lower noise technologies as well as potential navigation and operational practices. After thorough discussions at the MEPC over four years, the guidelines, i.e., “Guidelines for the reduction of underwater noise from commercial shipping”, were finalised in early 2014 and adopted at the 66th MEPC held in March/April 2014.

Setting Standards and Guidelines at the National / International level

This section provides information on the current status of efforts to set global standards (ISO) for acoustic measurements of anthropogenic noise in the marine environment. The need for standards, limits and guidelines for a range of noise-related procedures that concern the marine environment is also highlighted. These include the setting of international standards for environmental impact assessments (EIAs) and for mitigation procedures undertaken by Government and/or Industry regarding noise generating activities such as seismic surveys or naval sonar. International harmonisation of ways to define underwater noise exposure criteria is also included.

National and International Standards

The development of standards for the measurement and assessment of underwater noise only began quite recently. Previously measurements were made by a number of organisations using different techniques and with different methods of extrapolation to determine the source level[983]. In 2009, a voluntary consensus standard for the measurement of underwater noise from ships was developed by the American National Standards Institute (ANSI) and the Acoustical Society of America (ASA). The standard describes measurement procedures and data analysis methods to quantify the underwater-radiated noise level from a vessel referenced to a normalised distance of 1m. Three different standards are specified according to the level of precision needed.

In December 2011, The International Standards Organisation's (ISO) Technical Management Board established a new subcommittee: TC 43/SC 3, underwater acoustics. The Secretariat of the subcommittee is provided by the ASA acting on behalf of the ANSI. The scope of the subcommittee is:

'*Standardization in the field of underwater acoustics (including natural, biological, and anthropogenic sound), including methods of measurement and assessment of the generation, propagation and reception of underwater sound and its reflection and scattering in the underwater environment including the seabed, sea surface and biological organisms, and also including all aspects of the effects of underwater sound on the underwater environment, humans and aquatic life'.*

ISO standards are of a voluntary nature for use by industry as appropriate, and developed based on the demand of industry. The ISO underwater acoustics subcommittee contains three working groups (WG) that are predominantly working on the following subjects:

WG1 Measurement of noise from ships
WG2 Underwater acoustic terminology
WG3 Measurement of radiated noise from marine pile driving

Under a separate subcommittee ISO TC8/SC2, Marine Environment Protection, the standard ISO 16554 – Ship and marine technology – Measurement and reporting of underwater sound radiated from merchant ships – deep-water measurement, was published in 2013. The standard provides shipyards, ship owners and ship surveyors with an easy to use and technically sound measurement method for underwater sound radiated from merchant ships for use at the final delivery stage of ships. The measurement method should be carried out in a short duration (within a few hours) possibly during the official sea trial of the target ship after the completion of construction and before delivery. Classification societies may issue a notation on the underwater sound level radiated from the ship under survey using the measurement results conducted according to ISO 16554.

A 'sister' standard, ISO 16554-2 Ship and marine technology – Measurement and reporting of underwater sound radiated from merchant ships – shallow-water measurement, is currently under development.

[983] Leaper, R. and Renilson, M. 2012. A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227

The ISO underwater acoustics subcommittee has also developed the standard ISO 17208-1:2016, Acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes. ISO 17208-1:2016 describes the general measurement systems, procedures and methodologies to be used to measure underwater sound pressure levels from ships at a prescribed operating condition. Two 'sister' standards are in development: ISO/DIS 17208-2 Underwater acoustics – Quantities and procedures for description and measurement of underwater noise from ships – Part 2: Determination of source levels from deep water measurements; and ISO/NP 17208-3 Underwater acoustics – Quantities and procedures for description and measurement of underwater noise from ships – Part 3: Requirements for measurements in shallow water. Other standards that are under the direct responsibility of the acoustics subcommittee are ISO 18405, Underwater acoustics – Terminology, and ISO 18406, Underwater acoustics – Measurement of radiated noise from marine impact pile driving. Both standards were published in 2017. Also published that year was ISO 20154:2017: Ships and marine technology – Guidelines on vibration isolation design methods for shipboard auxiliary machinery. The purpose of ISO 20154:2017 is to provide general guidelines on the design of ship vibration isolation based on the basic methodology of vibration isolation for shipboard machinery. A well-designed vibration isolation system can significantly reduce the vibration transmission from shipboard machinery to ship structures lowering the noise level onboard the ship or the underwater noise radiated from the ship.

A number of other subjects have been discussed by the acoustics subcommittee including a standard for measuring ambient noise, measurement standards for explosions or air gun pulses, and other potential future work items including the measurement of underwater sound from active sonars, underwater sound propagation modelling, measurement of the underwater sound field and underwater noise mapping.

Work on the development of acoustic standards is also being carried out in Europe with a focus on acoustic monitoring in relation to the environmental impact of offshore wind farms in the North Sea. European countries that border this sea are collaborating to develop standards and definitions of quantities and units related to underwater sound[984]. These metrics were then used for the development of standardised measurement and reporting procedures, aimed specifically at acquiring the relevant acoustic data for assessing the impact of the construction, operation and decommissioning of offshore wind farms on marine life[985].

Setting other forms of standards for the mitigation and management of underwater noise has been proposed. These include the:

- Mandatory use of comprehensive Environmental Impact Assessments [986] (or Strategic Environmental Assessments) for any proposed impulsive noise generating activity in the marine environment;
- Setting of measurement standards for particle motion, of sound in the near field, and of ground transmission of sound[987];
- Standardisation of the design of behavioural data collection to make results comparable[988];

[984] Anon. 2011. Ainslie, M.A. (ed.). The Hague: TNO report TNO-DV 2011 C235. Standard for measurement and monitoring of underwater noise, Part I: Physical Quantities and their units. 67 pp.
[985] de Jong, C.A.F., et al. 2011. The Hague: TNO report TNO-DV 2011 C251. Standard for measurement and monitoring of underwater noise, Part II: Procedures for measuring underwater noise in connection with offshore wind farm licensing. 56 pp.
[986] Prideaux, G. and Prideaux, M. 2013. Seismic Seas: Understanding the impact of offshore seismic petroleum exploration surveys on marine species. Wild Migration technical and policy review #3. Wild Migration, Australia.
[987] Lucke, K. et al. 2013. Report of the Workshop on International Harmonisation of Approaches to Define Underwater Noise Exposure Criteria. Budapest, Hungary, August 2013. IMARES –Institute for Marine Resources and Ecosystem Studies. Report No. C197.13
[988] Ibid.

- Standardisation of monitoring data formats to improve data quality and robustness for use in research and evaluation[989];
- Generic standardisation of the main phases of impulsive noise generating activities – pre-operation planning and assessment, implementation and mitigation, post-operation evaluation and reporting;
- International standardisation of mitigation procedures and measures for naval exercises using active sonar[990];
- Use of training standards for operational activities e.g., MMOs or PAM operators[991];
- Setting of regional standards for cumulative noise mapping and marine spatial planning[992];
- Uptake of transparency and accountability standards by noise generating operators to ensure best practised is followed and information that is not commercially sensitive is made available to inform management[993];
- Setting of data sharing standards for online data banks of acoustic, environmental and ecological information[994].

Summary

Considerable progress has been made in the last decade to mitigate the effects of underwater noise produced by industry, particularly for seismic surveys and offshore construction techniques such as pile driving. Detailed mitigation measures and procedures have been developed for use by these industries, which are on the whole designed for marine mammals. Particular examples of best practise are the mitigation and monitoring plans and procedures implemented to protect Gray whales from the effects of seismic surveys[995] and the use of mandatory exposure levels for pile driving in Germany which catalysed the production of new mitigation technologies by the offshore energy industry[996].

However, although best practise exists, it is often non-mandatory and not used to a standard level by industry or the military. For example, although mitigation measures for active sonar are taken during non-strategic exercises by navies, in some cases, no measures apart from MMO and PAM protocols are taken in strategic exercises[997]. The debate between national security needs versus the welfare and security of vulnerable marine fauna continues. There is a need for a minimum level of mitigation by navies on all military exercises that can be verified by independent observers.

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[989] Ibid.
[990] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477
[991] Gill, A. et al. 2012. Marine Mammal Observer Association: Position Statements. The key issues that should be addressed when developing mitigation plans to minimise the effects of anthropogenic sound on species of concern. Version 1 (Consultation document). 32 pp. Marine Mammal Observer Association, London, U.K.
[992] Lucke, K. et al. 2013. Report of the Workshop on International Harmonisation of Approaches to Define Underwater Noise Exposure Criteria. Budapest, Hungary, August 2013. IMARES –Institute for Marine Resources and Ecosystem Studies. Report No. C197.13
[993] Prideaux, G. and Prideaux, M. 2013. Seismic Seas: Understanding the impact of offshore seismic petroleum exploration surveys on marine species. Wild Migration technical and policy review #3. Wild Migration, Australia.
[994] Lucke, K. et al. 2013. Report of the Workshop on International Harmonisation of Approaches to Define Underwater Noise Exposure Criteria. Budapest, Hungary, August 2013. IMARES –Institute for Marine Resources and Ecosystem Studies. Report No. C197.13
[995] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377.
[996] Koschinski, S. and Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Federal Agency for Nature Conservation / Bundesamdt für Naturschutz (BfN). 97 pp
[997] Maglio, A. 2013. Implementation of underwater noise mitigation measures by industries: operational and economic constraints. Prepared for the Joint ACCOBAMS-ASCOBANS noise working group. Sinay, Caen, France.

Noise exposure thresholds and management measures are beginning to move away from a reliance on received level (RL) thresholds to a broader ecosystem-level assessment of the cumulative impacts of both multiple impulsive noise sources and increased levels of ambient noise. However most mitigation measures are not very effective in reducing the aggregate impact of underwater noise on marine mammals[998], let alone on other marine taxa. Further development of techniques to assess cumulative impacts of underwater noise is required and this 'overall noise impact' also needs to be considered alongside other multiple stressors affecting marine taxa[999].

There have been some advances made in considering how noise affects animal behaviour and whether a proposed noise generating activity will have an impact on a population. Researchers, working together with regulators and industry are developing and testing new monitoring and mitigation practises that take into consideration some of the more obvious behavioural effects on marine mammals such as displacement[1000]. These assessment frameworks are still at a relatively early stage and have to rely on a number of assumptions to determine behavioural effects as there is often insufficient data available for populations to use more quantitative techniques. Considerable data gathering is needed, particularly for the measurement and recognition of behavioural effects on marine taxa and the determination of noise impacts at the population level. In particular, a far greater understanding of the more subtle behavioural effects (e.g., communication masking, stress responses, cognitive bias, fear conditioning, and attention and distraction) on marine taxa and how these influence populations is needed[1001]. Such knowledge can then feed into the development of improved mitigation practises to minimise or prevent chronic impacts on marine fauna at the population level.

Improvements in technology and processing capacity have enabled substantial advances in real-time mitigation and monitoring procedures for impulsive noise generating activities, mainly for marine mammals although this has also highlighted the need for meticulous planning and implementation of mitigation practises facilitated by clear and practical communications protocols. Mapping tools to show acoustic characteristics of a particular area or the presence and distribution of species of concern are becoming more available to assist in marine spatial planning and the development of mitigation frameworks.

Spatio-temporal management of underwater noise at the regional level should focus on eliminating harmful levels of anthropogenic sound from locations and times that are critically important to marine fauna such as feeding, spawning and nursery grounds. If a noise generating activity is permitted within range of a sensitive area then mitigation practises of the highest standard[1002] are required to ensure disturbance to the species of concern is prevented or kept to an acceptable level.

For many of the advances made for improving noise mitigation there has been an ongoing focus on a limited number of marine taxa, notably marine mammals and particularly cetaceans. This can be justified to a certain extent given their often vulnerable conservation status and high sensitivity. However, other taxa such as marine fishes, reptiles and many invertebrate groups all require greater attention in terms of fundamental research on noise effects on individuals and populations and the development of specific mitigation measures and procedures for non-mammal marine fauna. This is especially required for keystone species within marine ecosystems and for those that significantly contribute to providing ecosystem services. Identifying key species that are sensitive and vulnerable to underwater noise and developing best practise to mitigate the impacts of noise for these taxa should be

[998] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[999] Merchant, N.D. Faulkner, R.C. and Martinez, R. 2018. Marine noise budgets in practise. Cons. Lett. 11: 1-8.

[1000] Thompson, P.M. et al., 2013. Framework for assessing the impacts of pile-driving noise from offshore wind farm construction on a harbour seal population. Environmental Impact Assessment Review 43: 73-85.

[1001] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[1002] Nowacek, D. et al., 2013. Responsible practises for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals. Aquatic Mammals 39: 356-377 prioritised. Noise impacts on non-mammal marine fauna are beginning to receive greater attention in terms of research and general recognition but there are still more questions than answers[1003].

The development of internationally accepted standards for the measurement of underwater noise produced by anthropogenic activities started relatively recently. Although progress is quite slow, it is being made and should be encouraged. A range of standards will be required to cover noise emissions for the various anthropogenic activities in the marine environment.

A review of noise mitigation for cetaceans provides a range of recommendations for both the main activities that produce unwanted sound emissions and for regulatory bodies responsible for managing the marine environment[1004]. These are summarised in Table 9 and their applicability to other marine taxa is also highlighted. Numerous recommendations were also made in a recent report by the ACCOBAMS/ASCOBANS joint noise working group[1005] and these have also been incorporated.

The recommendations include specific mitigation measures for the main noise generating activities in the marine environment, acoustic and biological research priorities and measures to improve the sharing of information to facilitate best practise for mitigation planning and implementation. The vast majority of the recommendations are applicable to marine taxa other than mammals. However, in some cases, there is insufficient knowledge to effectively implement a particular measure, even though it is likely to reduce noise levels for species of marine fishes or invertebrates. Further research is required to determine acceptable levels for many non-mammal species for both impulsive and continuous noise.

[1003] Normandeau Associates Inc. 2012. Effects of noise on fish, fisheries, and invertebrates in the U.S. Atlantic and Arctic from energy industry sound generating activities. Literature Synthesis. Prepared for the U.S. Department of the Interior, Bureau of Ocean Energy Management

[1004] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland.

[1005] Maglio, A. 2013. Anthropogenic noise and marine mammals. Review of the effort in addressing the impact of anthropogenic underwater noise in the ACCOBAMS and ASCOBANS areas. Prepared for the Joint ACCOBAMS-ASCOBANS noise working group. Sinay, Caen, France.

Table 9. Recommendations to improve the mitigation and management of underwater noise for marine mammals, but also relevant for other marine taxa (adapted from Wright, 2014; Maglio, 2013).

Domain	Recommendation / Action	Applicable to Non-Mammal taxa?
General	Implement proactive area-based management efforts where sufficient data is available (e.g., time-area closures, MPA establishment)	Yes
	Include environmental considerations at the very early stages of project planning	Yes
	Prioritise the collection of necessary biological data to support area-based determinations in data-deficient regions.	Yes
	Noise generating activities in data-deficient areas are to be undertaken with extreme caution	Yes
	Implement buffer zones around established protected areas to ensure noise levels with these areas do not go beyond acceptable levels	Yes
	Address cumulative impacts from multiple stressors through appropriate cumulative impact assessment and management	Yes
	Adopt protocols that encourage cooperation within industry in the preparation of cumulative impact assessments so that all potential impacts are known in advance	Yes
	Identify ways to limit the combined impacts of human activity on marine mammal populations to prevent population decline	Yes
	Incorporate the level of uncertainty into any established legal noise thresholds	Yes
	Identify and quantify understudied noise sources such as high powered active transducers (Echosounders, various sonars)	Yes
	Improve knowledge of acoustic biology and of the distribution, abundance and life history of marine mammal species, especially endangered and data-deficient species	Yes
	Quantify noise effects on marine mammals at the population level	Yes
	Establish or enhance direct linkages between the scientific community and the private sector to exchange information on best available practises and technologies and also the effectiveness of mitigation measures during operations	Yes -
Oil and Gas Industry (seismic surveys and other activities)	Implement technology-forcing, scientifically based noise limits for all types of oil and gas activities (e.g., exploration, extraction and decommissioning) that can be phased in over a period of not more than 10 years. Set noise limits according to area characteristics e.g., lower limits for biologically sensitive areas	Yes
	Determine the effectiveness of soft start / ramp-up procedures for marine mammal species in ‘real world’ conditions	Yes
	Conduct research into the long-term effects of exposure to seismic activity on marine mammals, such as non-injurious impacts that may occur outside the prescribed safety zone	Yes
	Assess the noise-related impacts of other aspects of the industry – drilling rigs, drill ships, offshore terminals etc. – and conduct research to reduce the noise levels from these aspects	Yes
	Use risk assessment software tools to improve mitigation measures during an operation	Yes – if available
	Promote the use of national, regional or global public web platforms to industry that contain data / maps on species presence/abundance and distribution and the location of maritime protection zones, biologically important areas etc.	Yes
Shipping	Encourage Port Authorities to develop regional port partnerships and adopt noise-related certification standards for low noise propulsion technologies and/or operational mitigation measures	Yes
	‘Green’ Certification programmes to include noise-related criteria in their standards	Yes
	Governments to actively support the efforts of the International Maritime Organisation to address noise from ships	Yes

	Regulators to mandate and incentivise compliance with the pending IMO guidelines	Yes
	Assess the feasibility of operational measures for shipping such as route and speed management	Yes
	Develop indicators for quantifying ship noise and use on-board monitoring systems to indicate the need for maintenance or repair	Yes
Pile driving and other coastal offshore operations	Determine acoustic emissions during the installation of gravity-based or suction foundations and of vibratory pile drivers	Yes
	Encourage the adaptation of screw pile technology for use in offshore settings (low noise emissions)	Yes
	Recognise the limitations of noise mitigating measures for pile driving and gradually introduce more restrictive standards	Yes
	Include a shutdown safety zone appropriate to the noise source which is monitored by visual observers and/or PAM	Yes- turtles (visual)
	Improve the knowledge and understanding of cumulative impacts of noise generated by construction activities	Yes
	Further test the effectiveness of source-based and target-based technologies	Yes (source-based)
Naval activities	Take efforts over the long-term to refine military sonars to produce signals that are less damaging to marine mammals	Yes
	Encourage the use of risk assessment software by all Navies	Yes
	Encourage the use of national, regional or global public web platforms by Navies, that contain data / maps on species presence/abundance and distribution and the location of maritime protection zones, biologically important areas etc.	Yes – if available
	Avoid conducting sonar exercises in locations with topographical characteristics thought to be important in leading to strandings	No
	Use of pre-survey scans, safety zones, ramp-ups and the lowest possible source levels	Yes (lowest source)
	Include lower-level pings between sonar pulses if modelling shows that there is time for animals to approach too close to the source	No
	Restrict sonar exercises to daylight hours and use experienced MMOs instead of lookouts	No

6. FUTURE RESEARCH NEEDS

This assessment of anthropogenic noise and its effect on marine organisms has highlighted the extent of knowledge gaps and uncertainties for this issue. The current status of scientific knowledge (in terms of the level and types of sound that will result in a specific effect) often results in estimates of potential adverse impacts that contain a high degree of uncertainty[1006]. These uncertainties need to be addressed in a systematic manner to fully understand the effects of increased noise from human activities in the marine environment. There are a suite of research needs that have to be addressed to both better characterise and quantify anthropogenic noise in the marine environment and the impact it has on marine organisms. However, the extensive knowledge gaps also mean that prioritisation will be required. Detailed research programmes of noise effects on species, populations, habitats and ecosystems as well as cumulative effects with other stressors need to be put in place or consolidated where they already exist. Current knowledge for some faunal groups such as elasmobranch fishes, marine turtles, seabirds and invertebrates is particularly lacking. Other priorities for acoustic research are endangered or threatened marine species and critical habitats they depend upon for important activities such as foraging or spawning. Marine species that support commercial or subsistence fisheries should also be assessed for susceptibility to noise pollution and the issue of anthropogenic noise considered for fisheries management plans. Existing or proposed management frameworks also need to be tested and refined accordingly in a range of scenarios. A number of current or proposed large-scale research programmes are addressing a range of issues with a focus on marine mammals. However, there is a need to scale up the level of research and management efforts to significantly improve our understanding of the issue and minimise our noise impacts on marine biodiversity.

There have been a number of reviews of research needs in recent years that have mainly focussed on marine mammals[1007] [1008] [1009] and also specific research needs for other taxa[1010] [1011] [1012] in the literature. The main research priorities recommended by these reviews are summarised in Table 10. Details of these recommendations will be incorporated into the following sections as appropriate.

Research needs can be split into four main areas:

- Further characterisation of underwater noise and properties of emitted sound in a changing marine environment;
- Baseline data on the biology, distribution, abundance and behaviour of marine species;
- Detailed information on the impacts of sound on marine animals at the individual, population and ecosystem level;

[1006] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[1007] MMC (Marine Mammal Commission) 2007. Marine mammals and noise: a sound approach to research and management. Marine Mammal Commission, Bethesda, Maryland. 370pp.

[1008] Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005.

[1009] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[1010] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[1011] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

[1012] Hawkins, A. D., and Popper, A. N. 2016. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES Journal of Marine Science, doi:10.1093/icesjms/fsw205.

- Assessment and improvement of mitigation procedures and measures.

In addition to the previously mentioned reviews of research needs, a gap analysis[1013] has identified a number of research areas that should be highly prioritised:

- Describing Soundscapes;
- Impacts of Particular Sound Sources;
- Effects of man-made sounds on marine animals;
- Mitigation of effects;
- Measurement and decryption of sounds and the conduct of acoustic experiments.

Priority research needs and developments recommended by this gap analysis are also incorporated into Table 10.

Anthropogenic Sources and Ambient Noise

Although there has been considerable previous investment in the collection of underwater sound data for commercial, military or research purposes our knowledge of anthropogenic sound fields in the marine environment is incomplete[1014]. The seas and oceans are also becoming noisier as marine-based human activities increase in diversity and intensity, particularly in coastal and shelf waters. Ambient noise levels for mid and high frequencies are increasing with the greater use of sonar and increased small boat traffic[1015]. Anthropogenic noise sources are also often distributed heterogeneously in time and space which contributes to the complexity of underwater 'soundscapes' that marine organisms inhabit[1016]. In addition, the different components of anthropogenic sound attenuate at different rates depending on their frequency and environmental conditions further increasing complexity and making it difficult to predict the actual sound levels received by marine organisms[1017]. The type of sound is also important in terms of whether it is a continuous emission over a long time period or a series of short intermittent pulses causing different chronic or acute effects even though the power of the sound emitted is the same.

Further quantification of the underwater acoustic environment is therefore required. Increased levels of passive (or active) acoustic monitoring are needed to detect and characterise both natural and anthropogenic sound sources and collect ambient noise information for key areas. Anthropogenic sources considered to be of the highest concern (in the United States) are certain military sonars, ice-breaking, seismic air guns and new classes of large vessels closely followed by wide-azimuth seismic surveys, pile driving, as well as oil drilling and production[1018]. Priorities for action are likely to change somewhat at the national level depending on the key activities and sound sources present or planned within areas under national jurisdiction. Regional or ocean-wide priorities for acoustic research will need to be considered and agreed through regional or global bodies.

Passive acoustic monitoring can also provide real-time information to characterise ambient sound fields and feed into models to predict future trends. To model ambient noise levels a better understanding of the signal characteristics of anthropogenic sources is needed[1019]. For example, further information for the key parameters that make up the noise spectra of ships and also smaller vessels is required. With improved source profiles and an understanding of how the level of activity exactly contributes to the resulting ambient

[1013] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64
[1014] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[1015] Ibid
[1016] Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005
[1017] Ibid
[1018] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.
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noise profile, researchers can extend noise modelling so that better predictions can be made for regions with known anthropogenic activities but are currently lacking in acoustic information[1020].

More detailed information on the location and distribution of anthropogenic noise sources in the oceans can contribute to real-time estimations of regional or global noise levels as part of large-scale ocean monitoring systems. For example the geographic position of commercial vessels or the tracklines for seismic profiling could be used in models along with data on environmental variables (bathymetry, sound speed profiles, wind and wave noise spectra) to provide a more accurate assessment of the relative contribution of natural and anthropogenic noise sources[1021]. Establishing sound monitoring stations and programmes to survey different types of underwater soundscapes are required to build up a greater understanding of the underwater acoustic environment and how this is changing. A long-term aim should be the development of underwater anthropogenic acoustic thresholds for marine ecosystems to determine the amount of anthropogenic sound an ecosystem can tolerate without its status being altered[1022].

There is also a need for further research to predict the effects on declining ocean pH on the properties of underwater sound. As ocean acidity increases, there is a corresponding reduction in the absorption of low frequency sound (100 Hz - 10 kHz)[1023] [1024] and the mechanism for this chemical relaxation-based acoustic energy loss is well known[1025]. More than 50% reduction in the absorption of sound at 200 Hz has been predicted in high latitudes (e.g., North Atlantic) by 2100[1026], although these predictions have recently been disputed by subsequent modelling studies[1027]. If the former predictions are the more likely scenario then there is the potential that marine organisms sensitive to low frequency sound (e.g., baleen whales) will be more susceptible, particularly in acoustic hotspots where high levels of anthropogenic noise (e.g., shipping) coincide with the greatest drop in absorption.

Research programmes such as the International Quiet Ocean Experiment (IQOE)[1028] and the Listening to the Deep Ocean (LIDO) project[1029] are important elements in improving our understanding of underwater sound and anthropogenic noise in our oceans and need to be supported over the long-term.

Baseline Biological Information

To understand how anthropogenic noise is having an impact on marine biodiversity it is important that considerably more biological and ecological information for a particular species is available. Information for species and populations is incomplete for many marine animals, particularly for invertebrates but also for many marine fishes and mammals (e.g., beaked whales). The scale of this task suggests that a system of prioritisation is needed. Marine species that are known or highly likely to be susceptible to the effects of anthropogenic noise but are also threatened by other stressors such as overexploitation, habitat loss or other forms of pollution, are one of the highest priorities. In addition, there is a lack of basic biological information for many threatened species that is relevant to underwater acoustics. For example,

[1020] Ibid.
[1021] Ibid
[1022] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64
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elasmobranch fishes are recognised as highly threatened taxa[1030] but very little is known about their sense of hearing with data available for only a few species[1031]. Research is therefore required for species that are data deficient in terms of auditory biology, hearing sensitivity and how they use sound for communication or for key life processes such as feeding or predator avoidance. Again, due to the number of species involved, research could focus on representative[1032] species as surrogates for less-common or more-difficult-to-test species[1033] or on a wide range of morphologically and taxonomically diverse species of interest[1034]. Representative species could be selected according to trophic group, lifestyle (e.g., pelagic or demersal/benthic) or life history stage. In addition to an improved understanding of the importance of sound to marine organisms it is equally important to collect detailed information on the distribution, behaviour and population size of selected species. Knowing what constitutes normal behaviour and which habitats are preferred by marine species at particular times will enable more effective management and mitigation measures to be made.

Another priority is the use of all reliable biological information currently available for species from a range of sources (e.g., fisheries data for stocks and distribution, marine mammal monitoring data, tagging studies for marine turtles, teleost fishes or elasmobranchs) to help build up a more coherent picture of the life history traits for that organism. The development and maintenance of standardised online databases has been highly prioritised for marine mammals[1035] and could be applied to other groups of marine vertebrates such as teleost and elasmobranch fishes and marine turtles.

Noise Impacts on Marine Biodiversity

The high level of uncertainty for many species also applies to our current knowledge of the impacts of anthropogenic noise. Again, prioritisation of marine species for research will be required and the same criteria mentioned previously for selection should apply. High priority research areas are listed in Table 10 and include anthropogenic noise effects on individuals in terms of physical damage, physiology and behaviour but also the long-term effects on populations and the cumulative effects of noise in combination with other stressors. Studies at the population, community and ecosystem level are all required[1036] and should be linked to the prvision of ecosystem services by marine fauna. Population effects can be predicted from individual responses if there is adequate data on energy budgets, the effect of disturbance and other aspects such as predator-prey dynamics in relation to anthropogenic noise[1037]. The effects of anthropogenic noise on marine mammals are considerably more known than on other taxa. One further prioritisation criterion is to markedly increase the knowledge base for data-deficient groups (e.g., marine fishes, turtles and invertebrates).

An overarching priority is to increase the collection of field-based data for behavioural (and other) long-term responses of individuals to anthropogenic sound rather than relying on data collected in laboratory or enclosed conditions. This is particularly required for teleost fishes where it is not possible to extrapolate

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[1032] those thought to adequately represent related species on which such data are not available

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[1035] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[1036] Williams, R. et al. 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. Ocean & Coastal Management 115: 17-24.

[1037] Ibid.

from studies of caged fishes to wild animals[1038] and only a few studies have observed noise impacts on fishes in their natural environment[1039]. For non-behavioural research new technology may need to be developed to monitor particular noise effects *'in situ'* via devices such as smart' tags e.g., for measurements of hearing loss, metabolism and the production of stress hormones.

The chronic and also cumulative effects of anthropogenic noise on marine organisms and populations have received some attention in recent years, particularly for marine mammals[1040] [1041], but are in need of thorough assessment for other taxa (e.g., teleost and elasmobranch fishes, marine turtles and invertebrates). It is known that chronic disturbance in the coastal environment can lead to reduced reproductive success in some cases[1042] and further research studies are required to investigate whether this is also the case for other marine fauna. Reproductive success may also be compromised by changes in behaviour (e.g., avoidance of spawning sites) or masking of communication between potential mates[1043].

Increasing levels of ambient noise in marine and coastal environments have led to concerns of masking of important biological signals either received or emitted by marine organisms. Although this has theoretically been demonstrated for marine mammals[1044], there is little evidence to confirm masking in other marine taxa. Teleost fishes are one group where acoustic reception and communication can be highly important for survival or reproduction[1045]. Masking of important orientation cues may also occur for both fishes and invertebrate larvae prior to settlement[1046] [1047]. The potential for masking in a range of marine taxa is apparent and the risk of an impact is likely to increase as anthropogenic noise levels rise in shallow seas. This should be regarded as a high priority research need as it has the potential to affect multiple species simultaneously with long-term consequences for populations and communities.

Extensive research on particle motion and seabed vibration is particularly required to better understand effects on a number of taxa. A suite of recomemendations for further research on particle motion and next steps has been provided recently[1048]. Vibration through the substrate is also receiving greater attention with research needs for this subject becoming more apparent, especially for invertebrate fauna living on or in the seabed[1049] and their roles in ecosystem functioning[1050].

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Thus far, the socio-economic consequences of noise-induced impacts on marine populations have not been substantially considered by the research community, although the subject is receiving attention in some regions[1051]. Avoidance of noisy areas or reduced population success may have a significant effect on catches of commercial fishes or invertebrate species. Seismic surveys have previously been linked to short-term reductions in catch levels[1052].

Reviews have also highlighted methodological issues in experimental design and the need for proper controls and pathology (where applicable) as well as careful measurement of sound sources and signals and the use of proper sound metrics[1053] [1054] [1055] [1056]. Early experimental work in the sea confirmed the importance of working under appropriate acoustic conditions[1057]. For laboratory-based work investigating anthropogenic sound effects on marine taxa, it is extremely important that the experimental acoustic conditions accurately depict either natural conditions found in the sea or the sound properties of anthropogenic sources. For example, considerable research has been carried out in small tanks where the acoustic field is considerably different to that found in the natural environment[1058]. The tanks themselves can alter the acoustic field in certain conditions making the determination of meaningful results difficult. Care must also be taken when comparing different types of audiograms used to estimate hearing thresholds[1059]. Standardisation in research studies will help to both define the sound field received but also allow for comparisons of source signals of different types[1060].

Mitigation and Management

The mitigation and management of anthropogenic noise in the marine environment has been extensively covered in the previous chapter. Research needs are mentioned there (e.g., Table 9) with further points provided in Table 10. A number of issues were highlighted that currently exist with commercial and government approved mitigation procedures for marine activities emitting underwater noise. There is a need to critically assess the effectiveness of such mitigation procedures[1061] through an independent peer-reviewed process. Some progress has been made for seismic surveys such as the 'Behavioural Response of Australian Humpback whales to Seismic Surveys' (BRAHSS) project[1062]. Measuring the efficacy of mitigation measures such as 'soft start' in naval sonar exercises is also required. Recommendations can then be made to improve existing guidelines for the relevant practitioners. The long-term aim is the

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[1051] European Commission 2013. Marine Strategy Framework Directive (MSFD) Common Implementation Strategy (CIS). 82 pp. (see Technical Group for Underwater Noise – p. 45): http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/implementation/pdf/MSFD%20CIS%20future%20work%20programme%202014.pdf.

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It is also important to assess the overall noise budgets for the marine environment at a range of scales and how the cumulative effects of multiple sources of anthropogenic noise can be minimised spatially or temporally. Noise budgets are a key part of the EU's MSFD and are in development[1065] but require further research to be applicable for a wider range of taxa and geographic regions. There is also a need to investigate the effectiveness of mitigation measures in terms of their ecological benefit and the recovery of individuals or populations from chronic noise exposure[1066].

As well as improving mitigation procedures and measures, it is important that industry is encouraged to improve existing mitigation tools such as the mechanisms of sound emission by developing quieter noise sources through engineering modifications (e.g., shorter duration, narrower directionality or eliminating unnecessary frequencies)[1067] [1068] [1069]. The development of passive acoustic monitoring (PAM) systems or other remote sensing techniques to detect a range of marine taxa is an important step for improving mitigation[1070]. For example, PAM will become more successful as a mitigation tool if it is able to accurately detect a significant number of vocalising marine mammal species within exclusion zones, identify each marine mammal species and provide a reliable range measurement to the animal[1071].

[1063] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law & Policy 10, 1–27.
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Table 10. Priority research needs for Anthropogenic Noise and its impact on Marine Biodiversity (adapted from Boyd et al., 2008; Southall et al., 2009; Tasker et al., 2010, Hawkins et al., 2015)

Subject Area (s)	Research Priorities	Biodiversity Conservation Priorities
Marine acoustics and monitoring	Long term biological and ambient noise measurements in high-priority areas (e.g., protected areas, critical habitats, commerce hubs,) and more widely at the ocean basin level to record trends. Establish sound monitoring stations and programmes to survey different underwater soundscapes that involve real-time monitoring and storage of raw data.	Migratory corridors; foraging, mating / spawning and nursery habitats. Identification of remaining quiet areas and ambient noise hotspots.
	Determine the characteristics, distribution and abundance of anthropogenic sound sources in the marine environment. Improve knowledge of the propagation of sound (both sound pressure and particle motion). Describe and fully evaluate the effects of sound fields produced by anthropogenic sound sources. Establish a central data repository and standards/protocols for data collection.	Identify 'noisy hotspots' where multiple sources occur or are likely to occur. Propagation of sound and vibration through the seabed – especially relevant to benthic fishes and invertebrates.
	Develop new technologies (*e.g.*, acoustic monitoring) to detect, identify, locate, and track marine vertebrates, in order to increase the effectiveness of detection and mitigation. Determine ecological thresholds for anthropogenic sounds – how much an environment can tolerate without its ecological status being changed.	Monitoring of susceptible groups (e.g., beaked whales) and non-vocal vertebrates (e.g., teleost fishes, elasmobranchs, turtles). Prioritise development of tools for particle motion monitoring.
Baseline Biological Information	Biological research on: • Acoustic sensory organs structure and function • Use of sound by marine organisms; • Species-specific communication maximum ranges; • Basic information on hearing ability, especially for low frequency and high frequency species; • Modelling of the auditory system (to reduce dose response experimental exposure to sound); • Developing new tools to identify unknown biological sound sources and document associated behaviours. • Critical habitats, migration routes and reproductive periods Establish a library of sounds for marine animals to facilitate the use of passive acoustic tools.	Data deficient taxa: Teleost fishes, Elasmobranchs, Marine Turtles, Invertebrates. Marine species that are endangered and/or highly susceptible to multiple stressors (or surrogates for endangered spp.). Taxa that rely on particle motion to detect sounds. Accurate measurement of hearing in field conditions, especially for fishes and invertebrates.
	Expand/improve distribution, abundance, behavioural and habitat data for marine species particularly susceptible to anthropogenic sound.	Beaked whales, threatened cetaceans.

	Expand/improve distribution, abundance, behavioural and habitat data for marine species with high potential susceptibility to anthropogenic sound.	Teleost fishes, invertebrates (Cephalopods).
Baseline Biological Information and Monitoring	Support the development, standardization, and integration of online data archives of marine vertebrate distribution, abundance, and movement for use in assessing potential risk to marine vertebrates from sound-producing activities.	
	Standardize data-collection, reporting, and archive requirements of marine vertebrate monitoring programmes.	Marine mammals, marine turtles, selected fishes (apex predators, threatened keystone species), selected invertebrates.
Sound effects on marine organisms	Data collection, involving controlled exposure experiments, for key species of concern and/or for data deficient taxa for sound effects (where applicable) on: • Hearing loss (TTS/PTS) and auditory damage (e.g., sensory hair cells); • Physiological (e.g., stress effects); • Behavioural – e.g., avoidance / displacement or disruption of normal activity; • Non-auditory injury – barotrauma, embolism, decompression sickness; • Masking – communication and orientation; • Survival and reproductive success; • Particle motion effects for all of the above. Accurate measurement of sound effects in experiments that adequately replicate the sound characteristics of man-made sources. Characteristics of sound that make them more likely to be harmful to fishes and invertebrates.	Key concerns: baleen whales, beaked whales, Arctic & endangered species of marine mammal. Data deficient taxa: Teleost fishes, Elasmobranchs, Marine Turtles, Invertebrates. Prioritise fishes and invertebrates of the greatest ecological and commercial / nutritional importance.
	Investigate cumulative and aggregate effects of noise and stressors on marine organisms for both: • multiple exposures to sound (anthropogenic and natural) • sound in combination with other stressors	Identify noise exposure criteria for cumulative effects. Determine which metrics are most appropriate for expressing the accumulation of sound energy.
	Improve ability to identify and understand biologically-significant effects of sound exposure in order to improve effectiveness and efficiency of efforts to mitigate risk.	
Sound effects on marine populations and communities	Measure changes in vital rates, e.g., fecundity, survival for populations. Measure changes in community composition.	Endangered species with small populations and limited distribution or mobility.

Measurement and description of sounds	Adoption of relevant and universally acceptable metrics that describe sound appropriately and enable comparison of sound effects for different sound types and taxa. Development of a common terminology for sound measurement and exposure understandable to the whole community. Developing inexpensive 'non-specialist' instrumentation for underwater sound measurement in the laboratory and in the field.	Required for both sound pressure and particle motion. Measurement of particle motion is particularly needed for teleost fishes and invertebrates.
The conduct of acoustic experiments	Development of special acoustic facilities to enable investigators to present sounds to animals with full specification of the signals presented both in the laboratory and in the field, and for both sound pressure and particle motion.	
Mitigation	Develop and improve noise exposure criteria and policy guidelines based on periodic reviews of best available science to better predict and regulate potential impacts.	
	Develop and validate mitigation measures to minimize demonstrated adverse effects from anthropogenic noise.	
	Test/validate mitigating technologies to minimize sound output and/or explore alternatives to sound sources with adverse effects (e.g., alternative sonar waveforms).	
	Efficacy of ramp-up, soft start and other aversive techniques for fishes and invertebrates.	
	Application of acoustic monitoring to detect the presence of fishes and invertebrates.	

7. CONCLUSIONS

The levels of anthropogenic noise in the marine environment have increased substantially in the last century[1072] as human activities in coastal and oceanic waters have expanded and diversified. The underwater world is subject to a wide array of man-made noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar[1073]. The level of activity is also predicted to rise over the coming decades as maritime transportation and the exploration and extraction of marine resources continue to grow[1074].

Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators[1075]. From invertebrate larvae[1076] to the largest animals on the planet[1077], the detection and recognition of underwater sound is crucial. The use of sound underwater is particularly important to many marine mammals such as cetaceans and especially the toothed whales which have highly specialised echolocation abilities. Many other marine taxa also rely on sound on a regular basis including teleost fishes and invertebrates such as decapod crustaceans. The importance of sound for many marine taxa is still rather poorly understood and in need of considerable further investigation.

Concerns about the impacts of anthropogenic sound on marine animals have grown steadily over the last four decades. The levels of introduced noise in the marine environment are now considered to be a global issue and a significant stressor for marine life. Noise is listed as one of the impacts that can result in a substantial loss of biodiversity over time in sensitive marine habitats[1078]. In combination with other stressors, underwater noise pollution is likely to contribute to marine defaunation, which is predicted to increase as human use of the oceans industrialises[1079].

A wide range of effects of increased levels of sound on marine fauna have been documented both in laboratory and field conditions. Low levels of sound can be inconsequential for many animals. However, as sound levels increase the elevated background noise can disrupt normal behaviour patterns leading to less efficient feeding for example. Masking of important acoustic signals or cues can reduce communication between conspecifics[1080] and may interfere with larval orientation which could have implications for recruitment. Some marine mammals have tried to compensate for the elevated background noise levels by making changes in their vocalisations[1081].

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Intense levels of sound exposure have caused physical damage to tissues and organs of marine animals[1082] [1083], and even moderate levels of noise can lead to mortality, with lethal injuries of cetaceans documented in stranded individuals caught up in atypical stranding events[1084]. Noise has been shown to cause permanent or temporary loss of hearing in marine mammals and fishes. Behavioural responses such as strong avoidance of the sound source can lead to habitat displacement[1085]. Some marine animals, such as beaked whales are particularly susceptible to anthropogenic sound, and some populations have experienced declines for years after a sonar-induced stranding event[1086]. Short-term effects have been observed in a number of marine mammals and fishes but the long-term consequences of chronic noise pollution for individuals and populations are still mainly unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested[1087]. There is also growing concern of the cumulative effects of anthropogenic sound and other stressors and how this can affect populations and communities[1088].

Research has particularly focussed on cetaceans and other marine mammals such as pinnipeds to a lesser extent but there are still many knowledge gaps that need addressing. Acoustic research for marine fishes and invertebrates is still very much in its infancy and requires considerable investment to set up systematic studies of the effects of marine noise on these animals. Consequently, many sound-induced impacts for less well-studied taxa are currently predicted effects, some of which have been inferred from studies of other faunal groups. Many of the less studied groups rely on particle motion for sensing their acoustic environment and our understanding of this is very limited although gaining more attention. Substantial further research is required in order to better understand the impacts of anthropogenic sound on marine biodiversity. However, a system of prioritisation will also be needed to focus on species that are already highly threatened or endangered through a combination of multiple stressors and intrinsic characteristics, but also representative groups of understudied taxa such as marine fishes and invertebrates, as well as ecologically or commercially important taxa.

There are also additional global factors to consider when assessing the potential of anthropogenic noise to affect marine species. It is known that low frequency sound absorption decreases with increasing acidity in seawater. Modelling of projected changes in acidity caused by ocean acidification has suggested that particularly noisy regions that are also prone to reduced sound absorption should be recognised as hotspots where mitigation and management is probably most needed. Further work is required to verify or refute these predictions.

Previously relatively quiet areas of the oceans such as the Arctic are also highly likely to be exposed to increased levels of anthropogenic sound as the sea ice coverage decreases. The ‘new waters’ will be open to dramatically increased levels of shipping, exploration and exploitation especially by the oil and gas industry (seismic surveys and offshore industry) but also to commercial fishing vessels and possibly naval exercises (active sonar). The effects on marine biodiversity are likely to be significant. Management frameworks for the Arctic need to consider anthropogenic noise as an important stressor in combination with others when deciding the extent of activities permitted in these waters.

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The Arctic and other quieter areas (e.g., Antarctic) are also where naïve populations are likely to occur. These have been highlighted as key sources of baseline information that can be used in mechanistic models to predict impacts before they occur and potentially get ahead of the curve of rapid industrialisation of the ocean[1089]. The quietist sites should be subject to precautionary measures so that they become either acoustic refuges or experimental control sites to improve our understanding of the ecological impact of ocean ensonification[1090].

Long-term strategic recommendations have been made regarding underwater noise mitigation[1091]. Firstly, ways should be found to address and reduce the underlying demand for noise producing activities so that their occurrence can be reduced as much as possible. This involves reducing the need for oil, shipping and (where possible) military sonar, through improved energy efficiency, as well as the development and increased use of alternative technology. It is worth remembering that sound is a form of energy that has the potential to be transferred, converted or stored for later use[1092]. Much of the anthropognic sound in the oceans (e.g., from propulsion systems) is due to inefficiency and has been regarded as wasted energy that could be used more productively[1093]. Secondly, the increasingly strict noise level standards for all noise producing activities are phased in by regulatory bodies in order to drive innovation to reduce noise at the source. This has been evident in Germany where mandatory noise exposure standards for wind farm installation have fuelled technical innovation and the development of mitigation techniques to meet the standards[1094]. Setting lower noise level standards will help to address behavioural and other non-injurious effects of noise on marine fauna, both in proximity to acute sources and at greater distances.

As our use of the oceans increases and becomes more industrialised, anthropogenic sound in the marine environment is an issue that is likely to increase in significance over the next few decades, which could have both short- and long-term negative consequences for marine animals. The increase in the uncontrolled introduction of noise is likely to add significant stress to already-stressed oceanic biota[1095], which will likely contribute to marine biodiversity loss[1096], if not, tackle in combination with other anthropogenic drivers. Protecting marine life from this growing threat will require more effective control of the activities producing sound, which depends on a combination of greater understanding of the impacts and also increased awareness of the issue by decision makers, on a global, regional and national scale, to implement adequate regulatory and management measures.

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ANNEXES

Annex 1: Impacts of low-frequency noise on fishes

	Adult/juvenile fish	Fish eggs/larvae	Elasmobranchs
			
PHYSICAL			
Swim bladder damage	1,2		
Otolith/inner ear damage	3 · 4		
Temporal Threshold Shift	5 · 1a,3a		
Permanent Threshold Shift	5		
Organ/tissue damage	1,2,6		
Mortality	1,2,6-11	12-14 · 13,15	
BEHAVIOURAL			
Startle/alarm response	1,8a · 6,7,8a,9,16,17		
Sound avoidance/migration*	9,18-20 · 7,12,16-18,21-23,24a · 18		
Other changes in swimming	20		
Predator avoidance			
Foraging			
Reproduction			
Intraspecific communication			
PHYSIOLOGICAL			
Metabolic rates			
Stress bio-indicators	16 · 6a · 10a		
Metamorphosis/settlement			
CATCH EFFECTS			
Catch rates /abundance	7,19,25,26 · 21-23 · 12,18,23,27,28		28

1 = Popper et al. 2005⁺, 2 = Popper et al. 2016⁺, 3 = Song et al. 2008⁺, 4 = McCauley et al. 2003, 5 = Hastings and Miksis-Olds 2012, 6 = Santulli et al. 1999, 7 = Hassel et al. 2004, 8 = Boeger et al. 2006, 9 = Wardle et al. 2001, 10 = Radford et al. 2016⁺, 11 = McCauley and Kent 2012, 12 = Dalen and Knutsen 1987, 13 = Booman et al. 1996, 14 = Payne et al. 2009, 15 = Kostyuchenko 1973, 16 = McCauley et al. 2000, 17 = Pearson et al. 1992, 18 = Løkkeborg et al. 2012, 19 = Pickett et al. 1994, 20 = Peña et al. 2013, 21 = Skalskiet al. 1992, 22 = Slotte et al. 2004, 23 = Engås et al. 1996, 24 = Chapman and Hawkins 1969, 25 = Miller and Cripps 2013, 26 = Thomson et al. 2014; 27 = Løkkeborg and Soldal 1993, 28 = Przeslawski et al. in prep.

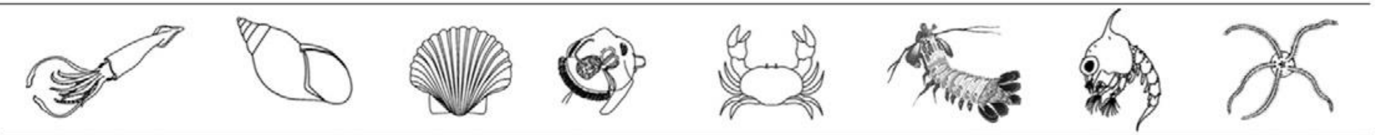
1a: Statistically significant hearing loss immediately upon exposure of freshwater adult Northern Pike to 5 pulses at 400 Hz and exposure of Lake Chub to 5 and 20 pulses at 200, 400 and 1600 Hz. Recovery within 18 hrs. A shift was observed only in adults and not in juvenile Pike.
3a: Adult freshwater Northern Pike and Lake Chub exhibited temporary hearing loss, but no damage to the sensory epithelia studied in any of the otolithic end organs, demonstrating that hearing loss in fishes is not necessarily accompanied by morphological effects on the sensory hair cells.
8a: Repeated exposure to air guns resulted in increasingly less obvious startle responses in effected fish, indicating possible habitation to the disturbance.
10a: Fish exposed to playbacks of pile-driving or seismic noise for 12 weeks no longer responded with an elevated ventilation rate to the same noise type, and showed no differences in stress, growth or mortality compared to those reared with exposure to ambient-noise playback.
24a: Free ranging Whiting school responded to airgun sound by shifting downward, temporary habituation was observed after one hour of continual sound exposure.
* Includes changes in vertical/horizontal distribution.
⁺Freshwater/brackish species.

KEY

Red	Response at realistic exposure levels
Yellow	Response at unrealistic/unknown exposure levels
Green	No response at either realistic or unrealistic exposure levels
Blue	Possible response (conflicting results)
Dark grey	No data, has not been tested
Light grey	Not applicable

Figure reproduced from Carroll et al. 2018. For further detail on effects and reference studies please see **Carroll et al 2017: Supplementary Material B (15 pages)**

Annex 2: Impacts of low-frequency noise on marine invertebrates



	Molluscs				Crustaceans			Echinoderms
	Cephalopod	Gastropod	Bivalve	Larvae	Decapod[a]	Stomatopod	Larvae	Ophiuroid
PHYSICAL								
Air bladder damage								
Otolith/statocyst damage	1-3				4,5; 5			
Organ/tissue damage	6		7,8		9			
Mortality/abnormality	6		7,8,10[c]; 5	11	5,9,12		4,13,14	
BEHAVIOURAL								
Startle response	15-19		5,20		4,21			
Sound avoidance	18				22			
Predator avoidance			5		5,12,23			
Foraging					23			
Reproduction					24			
Bioturbation			25		25			25
PHYSIOLOGICAL								
Metabolic rates[b]	26			11	4,12,27,28		13	
Stress bio-indicators	25		25,29; 5		4,5,12,22,25,27,30			25
Immune response					5			
Energy stores			10					
Metamorphosis/settlement							31; 13	
CATCH EFFECTS								
Catch rates / abundance	29	29	7 10,29	8	4,9,27,29,32,33	29		

1 = André et a; 2011, 2 = Solé et al 2013a, 3 = Solé et al 2013b, 4 = Christian et al 2003, 5 = Day et al 2016a, 6 = Guerra et al 2004, 7 = Harrington et al 2010, 8 = Parry et al 2002, 9 = Courtenay et al 2009, 10 = current study 11 = Aguilar de Soto et al 2013, 12 = Payne et al 2007, 13 = Pearson et al 1994, 14 = Day et al 2016, 15 = Fewtrell and McCauley 2012, 16 = McCauley et al 2000, 17 = Samson et al 2014, 18 = Komak et al 2005, 19 = Mooney et al 2016, 20 = Roberts et al 2015, 21 = Roberts et al 2016, 22 = Celi et al 2013, 23 = Wale et al 2013a, 24 = Lagardere 1982, 25 = Solan et al 2016, 26 = Kaifu et al 2007, 27 = Christian et al 2004, 28 = Wale et al 2013b , 29 = La Bella et al 30 = Filiciotto et al 2014, 31 = Branscomb and Rittschof 1984, 32 = Andriguetto-Filho et al 2005, 33 = Parry and Gason 2006

a DFOC 2004 also examined the effects of various physical and physiological effects of seismic signals on snow crabs but is not included here because no baseline data acquired before seismic survey, and refined experiments in Courtenay et al 2009 supersede these results.

b Includes proxies for metabolic rate such as food consumption, growth, respiration, developmental rate

c Also includes Chalmer (1986), Kosheleva (1992) and Matishov (1992) as cited in Parry et al. (2002)

KEY

- Response at realistic exposure levels
- Response at unrealistic/unknown exposure levels
- No response
- Possible response / conflicting or anecdotal results
- No data, has not been tested
- Not applicable

Figure reproduced from Carroll et al. 2018. For further detail on effects and reference studies please see **Carroll et al 2017: Supplementary Material C (8 pages)**