No. C 743
February
2023

Underwater noise from fairways

– policies, incentives and measures to reduce the environmental impact

Torbjörn Johansson, Sara Sköld, Carl Andersson, Anna-Sara Krång, Hulda Winnes, Cecilia Andersson and Sabina Hoppe

In cooperation with Swedish Maritime Administration

Authors: Torbjörn Johansson, Sara Sköld, Carl Andersson, Anna-Sara Krång, Hulda Winnes, Cecilia Andersson and Sabina Hoppe
Funded by: Formas - a Swedish research council for sustainable development
Photographer: Click and add text
Report number C 743
ISBN 978-91-7883-477-8
Edition Only available as PDF for individual printing

IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // www.ivl.se

Terminology

Directional	A source that radiates more sound to some directions than others
Omnidirectional	A source that radiates sound equally in all directions
Monopole	A point source that radiates sound omnidirectionally
Hydrophone	Underwater sound sensor, typically based on a piezoceramic element
Cavitation	The creation of vapour bubbles in a liquid when the pressure is low enough. Cavitation is often caused by a ship's propeller and is often the dominant source of ship underwater noise.
Sound pressure level (SPL)	A common measure of loudness. The sound pressure level is a measure of the amplitude of the sound pressure at a certain point. It is expressed on the logarithmic decibel (dB) scale using $SPL = 20\log_{10} {}^{p}/_{p_{ref}}$, where p is the root-mean-square amplitude of the sound pressure and p_{ref} is a reference sound pressure, which is 1 μPa in water.
Narrowband	A signal that has its power concentrated in a narrow band of frequencies, e.g., a tone.
Broadband	A signal that has its power distributed over a broad band of frequencies.
Spectrum	A signal's distribution of power or amplitude at different frequencies
Octave band	A set of standard frequency bands where the upper frequency is approximately double the lower frequency.
Third octave band	A set of frequency bands derived from octave bands. Three third octave bands fit into one octave band.
Power spectral density (PSD)	A common way to express the spectrum of broadband signals. The PSD is calculated by dividing the noise power in a certain frequency band by the width of that band. The unit is dB re $1\mu Pa^2/Hz$ but can also be expressed as dB re $1\mu Pa/\sqrt{Hz}$,
Transmission loss	The attenuation of sound on its way from a source to a receiver
Lloyd-Mirror effect	The interference of noise from an underwater source with its reflection in the sea surface
Source level	An equivalent sound pressure level that would be measured at 1 m from a monopole source, if that were possible. Source levels are used to compare sound pressure levels measured at different distances. They can be expressed as dB re $1\mu Pa\ @1m$ or simply dB re $1\mu Pa\ m$.

Table of contents

Summary

Underwater noise and its negative impact on marine life is a growing environmental concern where scientific knowledge is increasing but mitigation is scarce. This report is the outcome of a joint effort of the IVL Swedish Environmental Research Institute and the Swedish Maritime Administration that addresses this challenge. Motivated by environmental concerns and coming EU legislation, our vision is that Sweden should become the first country to implement national incentives for underwater noise mitigation.

The technical aspects of ship underwater noise are relatively well known. At cruise speed, cavitation at the propeller is typically the dominant source of underwater noise, but this is not true for all ships. Standardised measurement methods exist but are costly to implement. Prediction models are useful for noise mapping and fleet-wide estimates but not sufficiently accurate for individual ships.

The environmental impact of underwater noise from shipping has gained increased scientific attention in recent years. While many studies have been made, dose-response relationships and thresholds for different effects are largely unknown. Behavioural effects, including escape reactions, difficulty to avoid predators and masking of important communication calls, have been observed across a large number of species upon exposure to ship noise.

There are no national or international binding rules on ship underwater noise emissions. The International Maritime Organisation is currently updating its voluntary guidelines on ship underwater noise. The EU is introducing legislation on permissible levels of ship underwater noise in the environment, which is expected to come into force in member states within a few years. Technical methods for mitigation of underwater noise are known but not independently validated. Ship speed reductions may reduce underwater noise but may incur increased operational costs at the ship owners.

Stakeholders in ship underwater noise mitigation are found across ship owners, the ship design and technology industry, research bodies and authorities. Through interviews and workshops a network of relevant stakeholders in Sweden has been established. A stakeholder analysis showed that there is a need for more knowledge on ship underwater noise and its environmental impacts as well as its mitigation.

Fairway design for reduced transmission of underwater noise to the environment was investigated by long-term measurements at different sections of the fairway leading to Västerås in lake Mälaren. Neither depth nor a turn could be demonstrated to have an effect on the radiated noise. A more detailed experiment would be required to clarify if fairway design is a viable alternative for noise mitigation.

Six different ways of designing a financial incentive for ship underwater noise reduction were described. Rewarding speed reductions or technical measures for noise mitigation is feasible but the scientific basis is not clear. An incentive may be based on a silent ship notation from a classification society, but these are not commonly issued. A noise inquiry may be performed, but it may be difficult to identify the most relevant mitigations without underwater noise measurement. Bespoke measurement stations at or near port inlets may be a cost-effective way to collect measurement data, but the accuracy of such opportunistic measurements would need to be improved if the data is to be used for a financial incentive.

Sammanfattning

Undervattensbuller och dess negativa inverkan på det marina livet är ett växande miljöproblem där den vetenskapliga kunskapen ökar men effektiva åtgärder saknas. Denna rapport är resultatet av en gemensam insats av IVL Svenska Miljöinstitutet och Sjöfartsverket som adresserar denna utmaning. Motiverade av miljöhänsyn och kommande EU-lagstiftning är vår vision att Sverige ska bli det första landet som genomför nationella incitament för att minska undervattensbuller.

De tekniska aspekterna av fartygsbuller under vatten är relativt välkända. I marschfart är kavitation vid propellern vanligtvis den dominerande källan till undervattensbuller, men detta gäller inte för alla fartyg. Standardiserade mätmetoder finns men är kostsamma att genomföra. Prediktionsmodeller är användbara för bullerkartläggning och uppskattningar över en hel flotta, men inte tillräckligt exakta för enskilda fartyg.

Miljöpåverkan av undervattensbuller från fartyg har fått ökad vetenskaplig uppmärksamhet de senaste åren. Många studier har gjorts men dos-respons samband och trösklar för olika effekter är i stort sett okända. Beteendeeffekter, inklusive flyktreaktioner, svårigheter att undvika rovdjur och maskering av viktig kommunikation, har observerats hos ett stort antal arter vid exponering för fartygsbuller.

Det finns inga nationella eller internationella bindande regler för undervattensbuller från fartyg. FN:s internationella sjöfartsorgan IMO håller för närvarande på att uppdatera sina frivilliga riktlinjer om fartygsbuller under vatten. EU inför lagstiftning om tillåtna nivåer av undervattensbuller från fartyg i miljön, som förväntas träda i kraft i medlemsländerna inom några år. Tekniska metoder för att minska undervattensbuller är kända men inte vetenskapligt validerade. Hastighetssänkningar kan minska undervattensbuller men kan medföra ökade driftskostnader för fartygsägarna.

Intressenter inom reduktion av fartygs undervattensbuller finns hos fartygsägare, fartygsdesigners och teknikindustri, forskningsorgan och myndigheter. Genom intervjuer och workshops har ett nätverk av relevanta intressenter i Sverige etablerats. En intressentanalys visar att det finns ett behov av mer kunskap om fartygs undervattensbuller och dess miljöpåverkan samt dess begränsning.

Farledsutformning för minskad transmission av undervattensbuller till miljön undersöks genom långtidsmätningar vid olika delar av farleden som leder till Västerås i Mälaren. Varken djup eller gir kunde påvisas ha någon effekt på det utstrålade bruset. Ett mer detaljerat försök skulle krävas för att klargöra om farledsdesign är ett genomförbart alternativ för bullerdämpning.

Sex olika sätt att utforma ett ekonomiskt incitament för att minska fartygs undervattensbuller beskrivs. Det är möjligt att belöna hastighetssänkningar eller tekniska åtgärder för bullerdämpning, men det är inte utrett hur effektivt detta skulle vara. Ett incitament kan baseras på en tyst fartygsnotation från ett klassificeringssällskap, men dessa utfärdas relativt sällan. En bullerutredning kan utföras, men det kan vara svårt att identifiera de mest relevanta åtgärderna utan mätning av undervattensbuller. Skräddarsydda mätstationer vid eller nära hamninlopp kan vara ett kostnadseffektivt sätt att samla in mätdata, men noggrannheten i sådana opportunistiska mätningar skulle behöva förbättras om data ska kunna användas för ett ekonomiskt incitament.

Introduction

Underwater noise (UWN) is an environmental pollutant that increasingly impacts marine life, but emission control and incentives are missing. Ships are the dominating source of underwater noise but the existing policy instruments for ships are voluntary and abatement measures are seldom implemented. Environmental quality standards for underwater noise are currently being developed in order to address this problem. IVL Swedish Environmental Research Institute and the Swedish Maritime Administration have a vision that Sweden, as the first country in the world, introduces incentives and measures to reduce underwater noise from ships in fairways. This report describes the results of a joint effort with a vision to implement a management strategy including control, follow-up and mitigating measures. Funding was provided by Formas – a Swedish research council for sustainable development. Ships often travel in fairways, in particular in shallow and coastal areas, so in order to understand underwater noise from fairways it is vital to understand ship underwater noise. The study of underwater noise from fairways encompasses the study of ship underwater noise and the study of the effect that fairways have on the ships that use them, as well as the impact of underwater noise on the environment. All of these aspects are treated here. The present report describes the state of the art in ship underwater noise including its sources, measurement, environmental impact and mitigation, as well as stakeholders in Sweden who are relevant to ship underwater noise mitigation. It also investigates fairway design for reduced transmission of underwater noise to the environment and discusses alternative ways to implement a financial incentive for mitigation of ship underwater noise in Swedish waters.

The commonly used metrics for noise in acoustics are all measured on the logarithmic decibel (dB) scale. This is due to the large range of values that are spanned by the physical quantities. A ten-fold increase in sound intensity corresponds to an increase of 10 decibel, which is abbreviated as dB. Conversely, a 100-fold increase in intensity corresponds to 20 dB. An increase of 3 dB corresponds to a doubled intensity. The decibel is also a relative unit, meaning that it expresses the relation between a certain sound pressure and a reference value. In air, this reference value is 20 μPa, which is the lower limit of hearing of a healthy young person. In water, the reference value is 1 μPa. It is common to present decibel levels without the reference value, which should then be assumed to be 1 μPa in water. Sound levels can be expressed either as sound pressure levels (SPL) or particle motion. In a propagating sound wave far from any reflecting interfaces such as the surface or seabed, these quantities are proportional to each other. Underwater noise is typically measured as sound pressure, which is acceptable in many cases but e.g., not when studying impact on animals that live on the seabed. Here, measurement of both sound pressure and particle motion is important to be able to accurately assess the impact of underwater noise (Nedelec et al. 2016).

The ocean is full of noise and the ocean underwater soundscape is a complex mixture of sounds from various natural and anthropogenic sources, with different frequencies, sound levels and duration (Hildebrand 2009; Duarte et al. 2021; Chahouri et al. 2022). Natural sounds are produced by for example wave motions, wind, rain and ice but also different organisms, including sound signals for biological communication. Human activities and infrastructure in and near the ocean add anthropogenic (man-made) underwater noise to the ocean soundscape. A major contributing factor to underwater noise pollution in the sea is transportation (Hildebrand 2009; Mustonen et al. 2019; Duarte et al. 2021). It has been estimated that the increased shipping over the past 50 years has contributed to a 12 dB increase in low-frequency noise along high-traffic shipping lanes (Hildebrand, 2009). In areas with dense shipping, marine organisms are likely to be chronically exposed to noise all year round. The frequent use of recreational boats during spring and summer means that noise exposure can become enduring during the boating season even in areas away from shipping lanes (Haviland-Howell et al. 2007; Hermannsen et al. 2019; Moksnes et al. 2019).

When a ship moves through the water, underwater noise is generated by the propeller, the engines, gears, vibrating machines that are connected to the hull, and also by the hull itself as it moves through the water and creates flow noise. The propeller and the engines are generally the two loudest sources of ship underwater noise, and of these the propeller is usually dominant at typical operating speeds. Propeller noise is mainly caused by cavitation. Ship design for quiet operation is established for military and research vessels, but for merchant vessels there is a lack of scientifically proven noise mitigation methods that do not have a negative impact on carbon dioxide emissions. It has been estimated that at the design phase, with an increase of 1% of the total costs of the vessel, a 10 dB noise reduction is possible (Spence and Fischer 2016) and if the total cost is increased 10-15 % this could entail a 20-40 dB noise reduction (Southall 2005). These substantial cost expenditures need to be motivated by a firm knowledge base on the environmental effects of ship underwater noise and financial incentives that offset the costs.

A good environmental status with respect to underwater noise pollution requires that the level and distribution of anthropogenic sounds should not cause negative impacts on marine life (HELCOM 2013). In order for underwater noise to have an environmental impact, the sound has to spread from the source through the environment and reach an organism, where it may cause a response or an effect. Sound propagation is highly dependent on the environment, including depth, currents and seabed properties as well as water temperature and salinity (Hildebrand 2009; Urick, 1983). Generally, sound propagates four to five times faster and much further in water than in air (Slabbekoorn et al. 2010; Urick, 1983). Sound also propagates the farthest in water compared to other sensory cues used by marine animals. Indeed, many marine animals use acoustic cues for a wide range of behaviours essential for their life, including communication, recognition of conspecifics, orientation, navigation, locating food, avoiding predators and other dangers, finding and choosing reproductive partners, and locating suitable habitats for settling (Popper et al. 2001; Kasumyan 2009; Slabbekoorn et al. 2010; Erbe et al. 2016). Both continuous and temporary anthropogenic noise may disturb or disrupt the ability of marine animals to perform these sound-dependent behaviours, for example by masking sounds used for communication. Noise pollution may also affect animals' physiology and induce general stress responses, and in extreme cases loud noise may induce temporary or permanent physical damage and hearing loss, or even be lethal (Slabbekoorn et al. 2010; de Soto 2016; Shannon et al. 2016; Erbe et al. 2019; Popper and Hawkins 2019; Duarte et al. 2021; Wale et al. 2021). Although the impact of underwater noise on marine animals has received more attention in recent times (Shannon et al. 2016), there is still much we do not know about how marine animals perceive sound and what effect noise can have on them.

This report commences by describing sources, characteristics, measurement, prediction, mapping and monitoring of ship UWN. Then follows a chapter on the environmental impact of ship UWN on different marine animals, focusing on species from coastal, Swedish waters. Subsequently a chapter on the mitigation of this impact describes technical and operational mitigation methods, discusses the potential of fairway design of reduced noise transmission, and then describes policies and incentives that are applicable to ship UWN and aim to reduce it. The stakeholders involved in UWN impact mitigation are described in the following chapter. This chapter covers needs, resources and requirements. The report concludes with two chapters about innovations that were developed and investigated; fairway design for reduced noise transmission and development of a financial incentive for reduced ship environmental impact in Swedish waters.

Underwater noise from ships

The environmental impact of the underwater noise from ships is a relatively recent area of research and mitigation. Knowledge of underwater noise is scarce among the general public, perhaps because few have experienced it, but also because until recently it received little media attention. Concerns about the impact of underwater noise on marine life were raised during the 1990-s due to mass marine mammal strandings in connection with naval warfare exercises (Frantzis, 1998; Freitas et al, 2004). It was later agreed that the primary cause of these strandings was the use of active sonar, which emits loud bursts of noise into the sea. The impact of ship noise is less evident; the noise of a single ship is not nearly as loud as the active sonars that caused marine mammals to strand, but there are hundreds of thousands of ships that emit a nearly continuous drone of underwater noise into the seas.

There are multiple sources of underwater noise that contribute to the overall noise profile of a certain vessel. The main contributors to ship underwater noise in general are the propeller and the engines and onboard machinery (Abrahamsen (2012), Wittekind (2014)). This holds as an average across all ships but is not necessarily true for any given ship. Understanding what the dominant noise sources are is the first step to achieving a quieter ship, otherwise any measures taken to reduce the noise might not have a significant impact. It is important to understand that the total noise can only be meaningfully reduced by targeting the components that have the highest levels. An example of ship noise measurement and identification of dominant noise sources is shown in Figure 1, where underwater and airborne noise as well as onboard vibrations were measured simultaneously in order to ease identification of sources of radiated noise.

Figure 1. Simultaneous measurement of airborne and underwater noise as well as onboard vibrations of the Styrsöbolaget ship "Elvy", May 2022.

Propeller noise

Leaper and Renilson (2012) state that cavitation is the main driving mechanism for the dominant noise from the propeller. All propellers will cavitate above some certain cavitation inception speed (CIS), which depends on the specific design of the propeller. If noise levels are the primary consideration, it is possible to reduce the noise by designing the propeller with a high CIS, thus reducing or removing the cavitation noise altogether. This will however reduce the fuel efficiency of the vessel, since an efficient propeller will cavitate at least to some extent. For merchant ships, fuel efficiency and climate impact are very important, which puts non-cavitating propeller designs in a less favourable position. For this reason, it is important to understand the specifics of the cavitation: what types of cavitation are there, how do they radiate noise, etc. The hydrodynamics of cavitation are generally understood, see e.g., Wijngaarden (2011), but difficult to model in practice. This means that the noise effects of cavitation are often treated empirically but linked to an understanding of the different types of cavitation.

A large noise effect of the cavitation comes from gas cavities formed at the leading edge of the propeller blades as they pass the low-pressure region at the top of the propeller. As explained by Wales and Heitmeyer (2002), this volume fluctuation will act as a source operating at the blade passing frequency. While this source does not have a distinct location in space, it is often modelled as a monopole source at a location between the propeller hub and the top position of the blades during rotation. This will radiate acoustical noise at the blade passing frequency and its harmonics. The propeller is typically rotating at a frequency which is at the lower end of the acoustical spectrum, usually below 100 Hz. This means that this noise will appear as low frequency tones, i.e., tonal, and is easily related to the rotation rate of the propeller.

The other strong cavitation noise generating mechanism is the collapse of smaller gas bubbles generated by e.g., blade tip vortex cavitation or hub vortex cavitation. Abrahamsen (2012) states that due to the differing sizes of these bubbles, they have different lifetimes, which in turn creates a noise which is distributed both in time and space. This therefore behaves as a broadband source, potentially with a varying spatial distribution in the water behind the propeller. The properties of the propeller design that influence this noise source are generally not well understood.

A third common noise effect is called "propeller singing" and is due to interactions between the tip vortices and the propeller blades themselves. The forces created by the vortices will cause the blades to vibrate at their natural resonance frequencies, which can generate high-frequency tonal noise. According to Leaper and Renilson (2012) this is easily remedied by designing the propeller with a so called "anti-singing trailing edge".

Machine noise

Machine noise typically refers to all types of noise that is generated by vibrating machinery on the ship, the propeller excluded. This is very dependent on what machines are present on a given ship, how they are mounted, and how they are operating. The noise is radiated into the water through vibrations of the ship hull, which is excited by vibrations of the machines onboard. According to Wittekind (2014) the dominant machine sources are often diesel engines, used either for the propulsion of the ship or for power generation. These sources are almost exclusively tonal, with tones relating to the engine ignition rate and the engine shaft rotation rate. Merchant ships often use low-speed direct-drive diesel propulsion because of its high energy efficiency.

Other types of machines that can create underwater noise are compressors, hydraulics, and various pumps. These sources are rarely as strong as the diesel engines, and often operate intermittently rather than continuously. However, these sources can still appear in measurements of the underwater noise, and it is thus important to be aware of them when analysing measured data, especially if the ship has electric propulsion.

Figure 2. One of two main engines on a diesel-powered car ferry.

Ship noise characteristics

To quantify how noisy a ship is, typically from a measurement, it is important to compensate for measurement conditions such as distance between ship and sensor, bathymetry etc. To enable comparison of noise level measured at different distances, the underwater acoustics community have converged to reporting so called “source levels”. They are the theoretical sound pressure that would be created at a one-meter distance if the entire ship was replaced by a simple point source. These levels are typically reported either as sound pressure levels in third octave bands or as sound power spectral densities in narrow bands. It is important to note that while these two representations carry the same information, the numerical values are not directly comparable without a conversion.

Based on measurements done in the Haro Strait in 2017, MacGillivray and de Jong (2021) presented curves for typical source spectra in six different ship categories. All six categories show a decreasing level at high frequencies, and the behaviour above 1 kHz is very similar for all categories. The source level is typically around 155-165 dB re. 1 µPa m at 1 kHz, decreasing to around 150-155 dB re. 1 µPa m at 20 kHz. The four categories bulker, containership, tanker, and vehicle carrier show a characteristic peak at 40 Hz to 60 Hz, with levels around 175-180 dB re. 1 µPa m. The other two categories, cruise and tug, show a less pronounced peak at 100 Hz and 300 Hz respectively. Measurements done in this project show similar overall tendencies, see Figure 10.

There are two main contributors to low frequency tonal noise: the propeller cavitation and the engine(s) revolution and ignition rates. These frequencies can overlap to some extent depending on the gearing ratio between the engine and the propeller, as demonstrated by Johansson et al (2015). This complicates a characterization of the ship as a noise source with respect to understanding where the noise is generated. This means that it is often difficult to quantify how much noise stems from the engine and the propeller respectively, since only the combined effect can be measured.

In the frequency range above a few hundred hertz the broadband cavitation noise is the dominating source. This noise generally decreases slowly with frequency and is a weak contributor to the total noise levels. However, certain species of marine life cannot hear the low frequency noise at all. Hermannsen et al (2014) presents a study on high frequency noise levels in the Danish waters, demonstrating a reduction in the communication ability of harbour porpoises.

Ship noise measurement

Direct measurement is the most accurate method of obtaining information on the level of radiated underwater noise from a certain ship. Opportunistic measurements collect data from non-collaborating vessels, typically at autonomous measurement stations that operate for weeks, months or years, collecting many ship noise signatures. If a greater accuracy is desired, one resorts to a dedicated measurement with a collaborating ship that moves in a controlled manner. Typically, measurement staff are present during a dedicated measurement, monitoring data and controlling the trial. Dedicated measurements typically use more hydrophones and spend more effort on understanding local sound propagation, which both contribute to a greater accuracy as compared to opportunistic measurements. However, dedicated measurements are expensive and the ship under study may need to be taken out of its operating route.

Opportunistic measurements

This type of measurement typically employs a relatively simple instrumentation, where a mostly autonomous system records the noise from ships passing by a fixed recording station. The ship traffic in the area is often monitored by use of the Automatic Identification System (AIS), mandatory for all vessels over 300 gross tonnage, which sends out information about the vessel location, speed, and some limited ship particulars. One of the large uncertainties in opportunistic measurements is in the acoustic propagation conditions, which makes these methods unsuited for detailed investigations of individual vessels. However, the sheer number of ships capture still enable some quantitative and statistical conclusions about the current fleet of ships.

Opportunistic measurements of ship underwater noise have contributed greatly to the understanding of ship noise levels and have been used to develop ship noise prediction models (see below). McKenna et al (2012) presented noise levels and spectra of 29 different merchant vessels, recorded using a bottom-mounted hydrophone at a depth of 580 m. Karasalo et al (2017) presented results from source level estimation based on opportunistic recordings of over 2000 vessels from a single hydrophone logger south of the Öland island in the Baltic Sea. Recently, MacGillivray et al (2022) reported statistics of ship noise based on opportunistic measurements of 9880 passes of 3188 different ships.

One common trait in most reported opportunistic measurement campagns is a large spread in the UWN radiated from ships, uptowards of 30 dB. This spread remains even after grouping ships after type (e.g. containers, tankers, bulkers), and compensating for ship speed and size. This consistent spread indicates both that the noise radiated from individual ships is very difficult to predict without a lot of knowledge, but also that there is a large potential for reducing the noise from the noisiest vessels.

Dedicated measurements

Dedicated measurements have contributed to the understanding of how different noise sources contribute to ship underwater noise and to establishing incentives for ship noise mitigation via the different notations for silent vessels that have been implemented by ship classification societies.

They are the go-to alternative for accurate estimation of the noise radiated by a particular ship. Arveson and Vendittis (2000) described the radiated noise characteristics of a cargo ship based on dedicated measurements using a single bottom-mounted hydrophone. The ship position was tracked using a radar system.

Compliance with standardised measurement and reporting protocols is important for quality assurance and comparability of results. There are several international standards for measurement, analysis and reporting of ship UWN using dedicated measurements. These include the ISO 17208, which describes ship underwater radiated noise measurement in deep water (at least 150 m). There are no international standards for UWN measurement in shallow water.

A recent overview by Ainslie et al (2022) listed five classification societies that have implemented classification rules for underwater noise and associated standards that describe how ship UWN should be measured. Recently, Korean Register of Shipping published its rule for underwater noise, bringing the total number of classification societies with underwater noise rules to six:

- American Bureau of Shipping (ABS),
- Bureau Veritas (BV),
- Det Norske Veritas (DNV),
- Korean Register of Shipping (KR),
- Lloyd’s Register (LR) and
- Registro Italiano Navale (RINA)

Broadly, the procedures of the different classification societies differ in complexity and, as a result, expected accuracy. The ABS, DNV and RINA procedures estimate the radiated noise level, which is an approximation that makes a simplified correction for sound propagation from source to receiver. As a result, these procedures will produce results that are less comparable between different sites than the procedures of BV and LR. These latter estimate the monopole source level, which is a hypothetical noise power at a range of 1 m assuming that the source is a monopole i.e., radiates equally in all directions. They include a detailed modelling and correction for propagation effects. The KR procedure proposes on-site measurement of transmission loss using a controlled underwater loudspeaker, but also permits using a simplified law. Propagation modelling can be accurate but depends on accurate data on the water column and seabed, which are rarely available. Sound propagation therefore typically accounts for the largest uncertainties in ship underwater radiated noise determination.

The Bureau Veritas method (BV, 2019), based on research conducted in the EU FP7 AQUO project, is arguably one of the most detailed among the classification society UWN guidelines. It prescribes that for each operating condition, a ship under study should be measured at three different ranges, typically between 100 and 400 m depending on the ship length. At each range, the ship should make two passages at constant speed and travelling in a straight line. This adds up to six passages and takes several hours to complete. The ship should be equipped with a GPS receiver at a known location, which tracks the ship’s movements. Noise is assumed to originate at a single point called the acoustic centre. It is located halfway between the propeller and the main engine and along the centre line. Data analysis is detailed and can be summarized as shown in Table 1.

Table 1. Underwater radiated noise signature determination according to Bureau Veritas.

Step	Action
1	Divide each ship passage into 19 analysis windows, centred at aspect angles of -45, -40, …, 40, 45 degrees to the hydrophone. An aspect angle of 0 implies broadside incidence, which occurs at the closest point of approach. The window duration should be such that it matches the ship length at the studied speed.
2	Calculate the power spectral density for each analysis window.
3	Convert the power spectral density to 1/3 octave bands.
4	Adjust the power spectral densities for the influence of background noise. This uses a background noise sample measured before or after the trials.
5	Estimate transmission losses from the centre point of each analysis window to each hydrophone.
6	Compensate the power spectral densities of the received noise for transmission loss. We have now arrived at an estimate of the source level as a function of aspect angle.
7	Average the analysis windows into one source level estimate for the entire passage.
8	Average the three hydrophone channels.
9	Average multiple passages at the same condition.

Ship noise prediction

Ship noise levels in the environment can be modelled by combining data from measurements of ship source spectra and models for the noise propagation. One important component in this is estimating the source spectrum of ships without requiring an acoustical measurement of each individual ship, i.e., using some predictive model. These prediction models can be categorized into physically motivated and statistical ensemble models. Physical models mainly rely on a physical understanding of how noise is generated and are supported by thorough measurements of a few ships. Statistical ensemble models mainly rely on statistics of measured ensembles of ships and aim to provide a model that is correct on average across a fleet of ships. Models derived by the two approaches often have similar input parameters, e.g., ship speed, but it is important to interpret these parameters correctly. A relation between ship speed and noise levels as derived by operating a single ship under different conditions is very different from how the designed cruise speed of multiple ships relate to their noise levels. This indicates that the models can inform decisions in different ways.

Physically informed models attempt to model the noise spectrum of a ship as accurately as possible, based on knowledge of the properties of the ship. These models are difficult to obtain since they require thorough acoustical measurements of ships as well as a detailed description of the ships in question. This makes these models able to predict how noise levels would change if the physical properties or operative conditions of a ship is changed, although only with certainty for the specific parameters and ships that were included in the study. If this behaviour, often derived from a small sample of ships, generalizes over an entire fleet, it can be used to predict how fleet-wide actions can impact the overall noise level. However, such a generalization is a source of uncertainty and possible errors. It can also be difficult to apply physical models in practice since they may rely on ship properties which are not easily available.

Statistical ensemble models on the other hand are by design meant to represent an entire fleet and can as such accurately predict the average noise levels present due to a large number of ships. Most statistical models do not, however, attempt to describe anything but the current ensemble of ships. This means that they are not good predictors of the effects of any changes to ship design or operating conditions that are not represented in the current ensemble of ships. E.g., if a statistical model is derived from measurements of ships at cruise speed, it cannot be used to estimate the effect of operating the ships at speeds lower than their respective cruise speeds.

The following two sections treat a handful of models, either often cited in the literature, or of particularly interesting methodology. Note that there are other models also presented in recent years, which have not been included due to similarity in approach to the presented models. Table 2 lists characteristics of some commonly used ship noise prediction models.

Table 2. Ship noise prediction models.

Model name	Reference	Year publ.	Number of data points	Parameters	Complexity
RANDI	Breeding et al (1996)	1996	12	Length, speed	A typical ship noise spectrum is compensated for length and speed.
Wales-Heitmeyer	Wales and Heitmeyer (2002)	2002	approx. 40	None	Ship independent. Adjusted for low frequency Lloyd mirror effects.
Wittekind	Wittekind (2014)	2014	unclear	Speed, CIS, block coefficient, displacement, engine mass, number of engines, engine mounting	Three components: propeller, broadband cavitation, and engine. Each component has the same frequency dependence for all ships. Adjusted for low frequency Lloyd mirror effects.
AQUO	Audoly et al (2014)	2014	6-20	Length, speed, ship type	Three components: propeller, broadband cavitation, and engine. Separate coefficients for each component and ship type. Limited speed interval. Adjusted for low frequency Lloyd mirror effects.
ECHO-JOMOPANS	MacGillivray and de Jong (2021)	2021	approx. 1800	Length, speed, ship type	A typical ship noise spectrum for each class is compensated for length and speed.

Physically motivated source models

The oldest empirical model is a model from the *Research Ambient Noise Directionality* (RANDI) project, which is based on measurements of ships taken shortly after the second world war. This model, described by Breeding et al (1996), uses only the ship speed and length to shift a certain baseline spectrum. This baseline spectrum has been updated since the original measurements to account for the changes in ship construction and overall fleet composition during the latter half of the 20th century. This model is often used as a reference benchmark for new models.

Wittekind (2014) developed a model based on various measurements of a low number of new ships, as well as an analysis done by Arveson and Vendettis (2000) of an extensive measurement done in 1980 of a small bulk carrier. This model estimates the noise of a ship as a combination of low frequency propeller noise, high frequency propeller noise, and high frequency machinery noise. These three components were modeled by fitting curves to the measured results, often fitting different parts of the model to different source measurements. Many of the details on how the coefficients in the model were derived are omitted in the original text, which complicates evaluation of the model validity. One important parameter in the model is the cavitation inception speed, which has to be measured or predicted for each ship the model is used for.

Statistical ensemble source models

Wales and Heitmeyer (2002) did a survey of 272 ships measured between 1986 and 1992 in the Mediterranean Sea and the Eastern Atlantic Ocean. The measured data had low correlation between ship size, speed, and measured noise levels. This motivated the creation of an empirical source model depending on only the frequency. This model is essentially a curve fit of a specific type of function to the mean spectrum of the entire ensemble of measured ship spectra. Averaging of multiple source spectra will smooth out the tones from the propeller and engines of the ships and distribute that energy over all the tonal frequencies from all the ships. This is stated as one of the goals of the authors of the article and is a viable way to estimate the overall power level radiated from ships. However, it will remove the tonal character of the noise, which may be influence the impact on marine life. Such procedures should be used with care if investigating the impact of underwater noise on marine life.

Simard et al (2016) measured the source levels from 255 ships, this time outside Quebec in St. Lawrence Seaway. In this study the ships were initially categorized in two different ways, based on either type (cargo & container vs. tanker) or length (50 m brackets from 100 m up to 250). Source levels were determined for each of the groups in both of these categorizations. The spread among all the ships was around 30 dB in each third octave band. Considering the different groupings of the vessels, the general trends are the same and the spread within each group is too high to make any statistical predictions, with the medians for individual groups mostly within the quartiles of the other groups. A clustering algorithm and a principal component analysis was also done on the spectral data. This resulted in three reasonably large clusters, and several small ones. These large clusters were mainly separated by the first principal component, which was said to account for the overall noise level. A closer inspection of the median levels in the different frequency bands shows that this level difference is the most apparent in the higher frequencies, which are overall much quieter than the low frequency bands. The clusters showed no statistically significant correlation with the available physical properties of the ships, e.g., length, age, and speed. The two dominant principal components were analysed for correlation with physical ship properties. Many properties were found correlated with the principal components of the spectra, but none of them could explain more than 22% of the variance of said components. An empirical model was also developed as part of this work. The ship parameters used included length, breadth, speed, and draughts, with various combinations of logarithms and powers. These models had a coefficient of determination of between 72% and 79% when used on the full data set, with less errors for models with more parameters. Additional models were fitted and evaluated for the largest class of ships only, which reached a coefficient of determination of 88%. The clustering and principal component analysis done in the same work were not used in any modeling approaches.

Based on measurements of 1862 source spectra, MacGillivray and de Jong (2021) developed a source spectra model similar to the RANDI model, but with additional variations of the baseline spectrum depending on the ship class. The measured source spectra included larger variations in ship speed, as a result of a slowdown trial performed during the measurements. This data showed that both the ship speed and the ship length were correlated with the ship noise levels, contrary to the data presented by Wales and Heitmeyer. This new model was compared to the most recent RANDI model and the model developed by Wales and Heitmeyer (2002). In this comparison, the authors note that the differences between the models are larger than their claimed statistical accuracy. This is ascribed to the difference in measurement methodology, environmental conditions, and sampled ensemble. They highlight the lack of consistency and cross-validation as a large issue within the field.

Karasalo et al (2017) performed a comparison of various empirical source models to measured data of a large ensemble of ships. Their results indicate that the spread of the levels in the ensemble are smaller at frequencies above 200 Hz, both measured and predicted by models. Most of the ship passages were from either cargo ships or tankers, where the typical values predicted by the models agree reasonably well with the measured results. However, in the lower frequencies, the variability among the measured values is much larger, and the differences between the models is also larger. All the models used in said study do not agree as well with the measured data as in the articles where they were originally developed, especially in the lower frequency range. Some of the input parameters to these previously developed models are not directly available, and sometimes not even known by the ship manufacturer or owner. These parameters were estimated based on other known parameters and logs over the ship activity, essentially working as a nested estimation model for the noise characteristics. Using such estimation models increases the risk that the relation between input and output parameters is only valid for the ships included in the study and could create a model based more on correlation than causation.

Ship noise mapping

Noise mapping is the process of determining some quantitative metric of how much noise is present in a location based on the nearby ship traffic. Ship noise mapping typically uses AIS data to obtain ship locations and speeds. It then extracts ship design information from AIS data and/or ship information databases. Despite the accuracy concerns outlined above, statistical ensemble models are used to predict ship source level spectra. A numerical model that estimates sound propagation from each ship within a certain given range is then applied to estimate the contribution from each ship to the received levels at a certain point in space and time. This procedure is repeated for all ships and at different time steps across a geographical grid. There are few commercially available underwater noise mapping tools. One example is Quonops by French company Quiet Oceans. Quonops is a noise management and forecasting system for natural and anthropogenic noise which maps the spatio-temporal distribution of noise levels generated by combined human marine activity. Large EU-financed projects have been successful in producing soundscape maps based on measurement data and modelling. One example is the Joint Monitoring Programme for Ambient noise in the North Sea (JOMOPANS) (JOMOPANS, 2021). Another is Baltic Sea information on the Acoustic Soundscape (BIAS) initiated in 2012 (BIAS, 2016).

Erbe et al (2012) presents a study of the shipping-related underwater noise levels at the west coast of Canada during 2008. The shipping traffic was logged and the noise contribution from each ship was predicted for a spatial grid of 5 km resolution. This was represented as an exposure level, i.e., the received sound power times the duration that it was present, accumulated for all the ships in the area of interest. Their results show that the noise levels do not have a one-to-one relation with the shipping traffic. This can be seen by comparing the two major lanes northward from

Vancouver and Seattle, the one along the coast towards Prince Rupert and the one further out in the sea. Both these lanes have around the same amount of traffic, but the noise levels are much higher near the coast. It is also clear that the noise can spread up to 100 km from the main shipping lane.

Merchant et. Al (2016) reports on the typical noise levels in the seas around the UK. The results are presented as statistics of the probability distributions of the levels in selected third octave bands. These bands were the two bands selected for monitoring under the EU Marine Strategy Framework Directive, 63 Hz and 125 Hz, and two higher bands, 250 Hz and 500 Hz. The results show that the lower two frequency bands cannot be used to predict the levels in the higher two bands. It is also clear that the different metrics can vary a lot, and in particular that the mean energy level, the *RMS level*, is often larger than the 90th percentile of the levels, see Table 3. This indicates that the RMS level is dominated by loud noise bursts and highlights the importance of clearly communicating how analyses have been done when presenting statistical measures. Furthermore, until there is an understanding of which statistical metrics are relevant for the marine life, the safest option is likely to avoid single value metrics in favour of presenting as much of the underlying level distributions as possible.

Table 3 Statistics of measured underwater noise levels in the UK. Reproduced from Merchant et al (2016).

	Region	63 Hz	125 Hz	250 Hz	500 Hz
Mode	Celtic Sea	75.8	83.2	88.4	91.5
	North Sea	90.0	92.0	94.5	94.3
	Southern North Sea	94.0	87.0	72.7	82.3
Median	Celtic Sea	82.0	83.3	87.1	89.7
	North Sea	90.5	93.6	95.5	94.6
	Southern North Sea	94.7	86.0	78.9	83.5
90th percentile	Celtic Sea	93.2	93.3	96.0	96.9
	North Sea	100.3	103.5	103.9	103.3
	Southern North Sea	102.0	96.5	94.3	93.3
RMS level	Celtic Sea	101.6	102.3	102.9	99.9
	North Sea	101.8	103.8	104.5	104.2
	Southern North Sea	110.8	113.1	113.3	104.9

Mustonen et al. (2019) reports on the noise levels at several measurement sites in the Baltic Sea, measured during the entire year of 2014. This study targeted the EU Marine Strategy Framework Directive third octave bands at 63 Hz and 125 Hz, as well as the third octave band at 2 kHz. The results are presented as estimated probability density functions of the recorded levels for each site, which allows further interpretation of the results as new knowledge on the environmental impact become available in the future. They also find that the 63 Hz band and the 125 Hz band are strongly correlated between the measurement sites, while the 2 kHz band is less correlated with the two lower bands.

Putland et. Al (2022) reported noise mapping of the North Sea performed as part of the JOMOPANS project and compared the results to measurements at a few sites. In general, their results are that the prediction underestimates the levels at low frequencies (below 50 Hz), is somewhat spread in the middle frequencies (between 50 Hz and 2 kHz), and more reliable at higher frequencies. The errors were in many cases more than 10 dB, with varied results for the different comparison sites.

Environmental impacts of underwater noise from shipping

The environmental impact of noise pollution is a research field that has grown rapidly in recent years. When it comes to understanding how anthropogenic underwater noise affects different animal groups and species, our knowledge is still scarce, although more and more studies show negative effects on different marine species. Initially, research on the hazards of anthropogenic underwater noise focused on marine mammals known to use sound for communication and orientation. Today however, there is a predominance of new studies on fish, and over the last 10 years, also studies on invertebrates have increased. The majority of the invertebrate studies focus on commercially important crustaceans, bivalves and cephalopods, although invertebrates still only represent a small proportion of the studies made so far (Wale et al. 2021; Chahouri et al. 2022). Studies on birds and reptiles are still very scarce (Duarte et al. 2021; Chahouri et al. 2022). In a recent article, (Duarte et al. 2021) reviewed over 500 published studies that attempted to quantify the effects of anthropogenic noise on marine animals and found strong evidence of significant impact on mammals (85-94% of all studies), fishes and invertebrates (>80% of studies). It should be noted however, that there may be a bias because it is likely that studies showing significant effects are published to a greater extent than those presenting no effects.

Noise pollution may affect any level of biological organisation, although behavioural studies dominate the field (Duarte et al. 2021; Wale et al. 2021). Anthropogenic noise may mask, i.e., overpower or disturb the perception of natural sounds that animals use to find food, avoid predators, navigate or communicate (Erbe et al. 2019; Hawkins et al. 2015). Other effects range from temporary reactions and minor cellular changes to permanent physical damage to hearing organs, or even death at very high energy levels that occur close to sources, such as explosions, seismic air guns and piling (McCauley et al. 2003; Popper and Hastings 2009b). To the best of our knowledge, there are no reports of animal death or permanent hearing damage due to ship underwater noise.

There are a number of recent and comprehensive review articles summarising the current state of knowledge on impacts of noise pollution (e.g., Shannon et al. 2016; Duarte et al. 2021; Chahouri et al. 2022) and some more specific on marine mammals (Erbe et al. 2019), fish (Slabbekoorn et al. 2010; Popper and Hawkins 2019) and invertebrates (de Soto 2016; Wale et al. 2021).

Hearing abilities and vulnerability of marine mammals, fish and invertebrates

It is problematic to generalise regarding vulnerability to noise pollution since different species perceive sounds differently and vary in sensitivity and auditory range and are thus sensitive to different kinds of noise (Ladich and Fay 2013; Popper et al. 2019; Duarte et al. 2021; Wale et al. 2021). The vulnerability depends on whether the sound overlaps in frequency with the hearing ability of the animal and whether the noise reaches levels above the animal's detection threshold (Slabbekoorn et al. 2010; Popper and Hawkins 2019; Duarte et al. 2021). This detection threshold varies depending on the level of background noise and sounds must be more intense at higher levels of background noise in order to be detected (Popper and Hastings 2009b). Thus, it is important to also measure the amount of background noise when examining the effects of noise.

Underwater noise produced by ships is primarily of relatively low frequency (typically less than 1000 Hz) but may range from below 10 Hz to over 10 000 Hz (Hildebrand 2009; Popper and Hawkins 2019). This overlaps with the hearing range of a wide range of taxa, including mammals, fish and invertebrates. In contrast, high-frequency sounds from for example sonars and echo-sounders mainly affect mammals, such as harbour porpoises and seals (Popper and Hastings 2009a; Slabbekoorn et al. 2010; Erbe et al. 2019). In general, **fish** hear mainly low-frequency sounds below 500 Hz or sometimes up to a few thousands of Hz and also hear these frequencies better than marine mammals (Popper et al. 2019). For example, for Atlantic cod the hearing range is 30-500 Hz, herring can detect frequencies up to ca. 4000 Hz, while the Eurasian minnow can detect up to 6000 Hz (Enger 1967; Kasumyan 2005). Also, a few species like European eel are sensitivity to infrasound (<20 Hz). **Mammals** have broader hearing ranges. Pinniped grey seals for example hear sounds between ca. 75-75000 Hz, while cetaceans may hear sounds over 100 000 Hz (Erbe et al. 2019). The harbour porpoise is among the animals with the broadest hearing range and specialises in detecting high rather than low frequency sounds with an estimated hearing range of 100-160 000 Hz (Au 2000; Hermannsen et al. 2019). Sound waves can be registered both as pressure changes and particle motion/vibration and marine animals have different organs to register these. Mammals perceive sound pressure (Erbe et al. 2019), while all fish species studied can perceive sound through particle motion/vibration either via the inner ear or via the lateral line (Popper et al. 2019). Some fish species can also perceive sound pressure via the swim bladder (Popper et al. 2019). There is, however, a lack of threshold studies for many marine species and most threshold studies report sound pressure but not particle motion.

Relatively few studies have examined the hearing ability of marine **invertebrates** and we know relatively little about how invertebrates perceive sound, but they seem to perceive sound through particle motion/vibrations, also via the seabed (Popper et al. 2001; Zhadan 2005; Lovell et al. 2005; Kaifu et al. 2008; Roberts et al. 2016; Charifi et al. 2017; Popper and Hawkins 2018). A few recent audiogram studies investigating sound-detection abilities in invertebrates like cephalopods (Mooney et al. 2010) and decapod crustaceans like crabs, prawns and lobsters (Lovell et al. 2005; Hughes et al. 2014; Radford et al. 2016; Jezequel et al. 2021), have shown that they mainly detect low frequencies below 1000 Hz (up to 3000 Hz in crabs and prawn), with best sensitivity around 100 Hz. Behavioural experiments have shown that scallops can detect water-born vibrations in the range of 30-1000 Hz (Zhadan 2005) and recently, even jellyfish were described to possess sensitivity to low frequency sound (Sole et al. 2016). Marine invertebrates show a great variety of sensory organs and hydrodynamic receptors (mechanoreceptors) supposedly able to detect particle motion, including hair-like cells on the body or antennae and chordotonal organs on appendages. Moreover, octopuses and some crustaceans, echinoderms and mussels have ear-like statocyst organs (Popper et al. 2001; Breithaupt 2002; Andre et al. 2016; Edmonds et al. 2016; Roberts et al. 2016) although their role for sound detection has recently been questioned (Jezequel et al. 2021). Some invertebrates produce and may use sound and vibration to communicate with conspecifics (Staaterman et al. 2011). Thus, also animals that cannot hear sounds in the classical manner may detect and/or be disturbed by noise.

Noise levels and noise sources in experimental studies

Most studies on noise impacts aim to investigate whether a certain noise elicits a response in the test organism or not, rather than establishing exact values regarding the test organism's sensitivity to noise and noise levels. Hence, test organisms have often been exposed to a test sound comprised of a wide range of sound levels and frequencies, rather than testing exact sound levels at specific frequencies within the test organisms' hearing ability. Lowest-detectable effect level as well as dose-response relationship describing the magnitude of a response as a function of exposure levels have seldom been established.

Most studies on invertebrates and many on fish are performed in laboratory tanks and/or by use of playback of noise recordings. This enables good experimental control and permits detailed monitoring of the animals' responses to the applied stimuli. However, it can be problematic to extrapolate results from noise experiments to natural systems. In playback studies, the sound from a speaker may change character compared to natural sound sources. This can be compensated for by measuring the resulting noise spectrum and adjusting the playback until the noise in the water is sufficiently close to what is desired. Furter, in closed spaces like tanks or aquaria, the acoustic field an organism experiences can vary rapidly due to the acoustic resonances, an effect that is not present in natural environments. The acoustic field and the relationship between the sound pressure component and the particle motion component changes in the vicinity of materials with acoustic properties other than water, which also causes differences between tank and natural environments (Adamatsu et al. 2002; Duncan et al. 2016; Nedelec et al. 2016; Popper et al. 2019). Most studies have used short-term noise exposures, although the use of continuous noise exposures have increased over the last 10 years.

Effects on marine species in Swedish coastal waters

This part of the report aims to compile the state of knowledge regarding the biological impact of underwater noise from shipping on marine animals living in, or with relevance to, Swedish waters. The focus was to summarise the different kinds of effects that have been found in different species, but also what kind of sound sources, frequencies and levels that have been used to identify negative effects in the different studies. When possible, the impacts are related to what is known about the sound perception ability of the animals. However, due to the limited number of studies found, and since noise produced from shipping and other vessels overlap in the (lower) frequency range with relevance to many marine organisms, also studies investigating noise from smaller motor-derived boats were included to make a more comprehensive overview. All together we identified effect studies on four mammal species (one cetacean and three pinniped seals), 10 fish species and 12 invertebrate species occurring in Swedish waters. However, for both fish and in particular invertebrates, additional closely related species have been included when species occurring in Swedish waters have not been studied.

Effects on mammals

Harbour porpoise

The harbour porpoise (*Phocoena phocoena*) is the most common cetacean in Swedish waters and is considered one of the species most sensitive to noise pollution. It has a unique, highly sensitive hearing ability (hearing range 1–0 Hz - 160 000 Hz), detecting mainly high frequency sounds (Au 2000; Hermannsen et al. 2019). The relevant research studies on cetaceans and shipping noise were performed with adult individuals and include endpoints such as foraging disruption, triggering of specific swimming/escape behaviour (so called porpoising) and temporary hearing loss. Tested underwater shipping noise ranged between frequencies 500-31 500 Hz and levels 70 to 140 dB re 1 μPa.

Disrupted foraging with a significant decrease in prey capture attempts has been identified after exposure to live vessel noise, with estimated threshold at 96 dB re 1 μPa in the 16 kHz octave band (Wisniewska et al. 2018). Unfortunately, the study did not record the total noise level, so it is difficult to use their results. Harbour porpoises, like other toothed whales, rely on echolocation for foraging, communication and navigation. Shipping noise may affect the species negatively by disturbing (masking) the perception of echolocation, also from distances several km from the source. In porpoises, noise is considered more likely to cause negative response than the physical presence of vessels (Wisniewska et al. 2018).

Porpoising relates to specific swimming behaviour of mammals like porpoises, dolphins and pinnipeds (but also birds like penguins), where long jumps are alternated with swimming near the sea surface to maintain respiration and energy efficiency. The behaviour can be referred to as the marine mammal equivalent of running and is used when in pursuit of prey or escaping from a threat. Porpoising behaviour was triggered by vessel noise from passing vessels also from a distance as far as 1 km from the source with an estimated threshold of ca. 110-140 dB re 1 μPa. Furthermore, no clear habituation to the noise exposure was found over longer periods of time (Dyndo et al. 2015).

Temporary hearing loss, or temporary threshold shifts (TTS), may be caused by moderate to high levels of noise for longer periods of time. Data on relationships between noise levels and TTS in marine mammals are scarce and most of the exposure studies focus on short-duration noise e.g., from pile driving, but generally, TTS increases with increasing exposure durations and sound levels. In many cases however, a complete recovery occurred within 15 minutes of noise cessation. Results from TTS experiments and field studies of behavioural reactions to noise have shown harbour porpoises to be more sensitive to sound compared to other smaller toothed whales like dolphins, and response thresholds critically depend on the stimulus sound frequency (reviewed by Tougaard et al. 2015). After exposure to noise of varying source, intensity and duration, the estimated threshold levels were 124-150 dB re 1 μPa (Kastelein et al. 2012, 2014). At exposures to pure tones (i.e., not from vessels), the TTS-inducing sound levels were often at 100 dB above the hearing threshold and avoidance reactions were generally induced at 40-50 dB above hearing threshold (Tougaard et al. 2015).

Pinniped seals

The hearing range of pinnipeds in Swedish waters is estimated to about 100-22 500 Hz for harbour seal (*Phoca vitulina*), 100-25 000 Hz for ringed seal (*Pusa hispida*) and 75-75 000 Hz for grey seal (*Halichoerus grypus*). The relevant research studies on seals and shipping noise were done with adult individuals and included endpoints such as masking of calls, reduced haul-out behaviour and temporary hearing loss. When stated, tested underwater shipping noise frequencies ranged between 10-25 000 Hz and levels between 40-125 dB re 1 μPa.

Seals use vocalisation calls as an important recognition cue between mothers and pups and as complex threat calls between males (Insley et al. 2003). These social calls occur within the frequency range of 100–5000 Hz with considerable overlaps with shipping noise and thus potential **masking** consequences (Bagočius 2014). Noise from vessels can be audible for seals at up to 1 km distance, possibly shortening their communication distance (Blundell and Pendleton 2015).

Haul-out behaviour refers to periods when pinnipeds temporarily leave the water for a range of land-based activities, including reproduction, nursing and tending of pups, predator avoidance, thermoregulation, moulting and resting (London et al. 2012). The peak haul-out season usually occurs during the pupping in the summer months (usually May-June), and mainly at daytime.

Presence of vessels, particularly cruise ships and other large vessels (of unknown frequencies and levels) has shown to reduce haul-out behaviour in harbour seals, which may lead to reduced fitness associated with loss of resting-time. Although this does not necessarily relate to underwater noise, it suggests that vessel operators should take special care during the pupping season to avoid disturbing seals during peak haul-out (Blundell and Pendleton 2015).

The noise-induced **temporary hearing loss** of pinnipeds follow similar trends observed in other mammals when tested underwater. For harbour seals exposed to 16 kHz octave band noise the estimated threshold level was 152 dB re 1 µPa (Kastak et al. 2005). Since the pinniped auditory system operates also in air, TTS after exposure to airborne noise would also be of interest.

There are several facilities that perform experiments on mammals in captivity. An example is Seamarco in the Netherlands, who have performed many experiments on harbour porpoises and seals (Figure 3).

Figure 3. A captive common seal (Phoca Vitulina) at the Seamarco facility in the Netherlands.

Effects on fish

Among the fish species considered relevant to Swedish waters (10 Swedish species and 3 additional species), the estimated hearing abilities range from relatively low (up to some 100 Hz) in auditory generalists like the commercially important Atlantic cod (*Gadus morhua*) and European eel (*Anguilla anguilla*), up to 10-4000 Hz in roach (*Rutilus rutilus*) and 16-6000 Hz in common minnow (*Phoxinus phoxinus*) (Kasumyan 2005). The relevant research papers on fish and noise from ships and boats were mainly done with adult individuals but also include a few experiments on larvae/juveniles. Identified effects include numerous behavioural parameters, masking, elevated stress response, developmental or reproductive disturbances and temporary hearing loss. Both naturally occurring vessel noise and playback recordings in the field as well as in laboratory tanks have been used, and effect thresholds are mostly unknown.

Noise pollution from shipping has been shown to affect several important **behaviours** in fish, either by direct disturbance or by masking acoustic signals that fish produce and use in a variety of contexts. Fish can react to the presence of ships by escape or avoidance behaviour (Drastik and Kubecka 2005). For example, schools of tuna (*Thunnus thynnus*) changed swimming direction and tended to disperse when vessels were nearby (Sara 2007) and there was a tendency for cod (*G. morhua*) to change its natural movement pattern when ships passed by, although with high variability between individuals (Andersson et al. 2015). In net-caged Pacific herring (*Clupea pallasii*), avoidance behaviour was induced by noise (0-3000 Hz, 75-112 dB re 1 µPa) from large vessels approaching at a constant speed and smaller vessels approaching at an accelerating speed. In contrast, the herring showed no visible response to sonar, echo sounders, or recordings of natural sounds from rain, gulls, killer whales, sea lions or self-produced chirps and whistles (Schwarz and Greer 1984), indicating higher sensitivity to low frequency noise emitted from ships than high frequency sound from sonar and echo sounders. This agrees with expectations because these high frequency sounds are outside the hearing range of the herring.

Noise can also lead to reduced foraging when fish switch from foraging to other behaviours, as seen in roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) when exposed to noise from a motorboat (50-2500 Hz, 72-150 dB re 1 µPa) in the field (Magnhagen et al. 2017), and in common minnow (*P. phoxinus*) exposed to playback of noise (100-5000 Hz, 60-115 dB re 1 µPa2 Hz^{-1}) originally recorded from ships in an aquarium experiment (Voellmy et al. 2014). Increased noise levels may affect the predator-prey relationship either by disturbing the predators or by making it more difficult for prey to detect predators. This may lead to increased mortality for preys but may also makes it easier for predators to catch their prey. In juvenile European eel (*Anguilla anguilla*), acoustic disturbance by playback of shipping noise (100-5000 Hz at 80-140 dB re 1 µPa) comprised several antipredator behaviours with direct consequences for survival likelihood (Simpson et al. 2015). Decreased foraging efficiency has been shown in aquarium studies with stickleback (*Gasterosteus aculeatus*) that more often failed to catch their prey when exposed to playback of ship noise compared to natural sound conditions (Voellmy et al. 2014). The same species also showed a shift in attention and foraging efficiency by impaired food-handling and decreased discrimination of food items, and more attacks were needed to consume the same amount of prey, when exposed to short-term playback of white noise between 100 and 1000 Hz (Purser and Radford 2011).

Important parental care behaviours may also cease in noisy environments. Largemouth bass (*Micropterus salmoides*) reduced their guarding behaviour and defence of eggs and fry against predators during playback of noise from a passing motorboat (90-2000 Hz, 60-115 dB re 1 µPa) (Bruintjes and Radford 2013). This may lead to lower survival of the offspring. In an aquarium experiment with the common goby (*Pomatoschistus microps*), there was a delay in female nest inspection and spawning as well as reduced mating success under artificially noisy conditions, probably because it became more difficult for females to perceive male sounds correctly (Blom et al. 2019).

Masking of acoustic signals as suggested for the common goby is likely to cause behavioural disruption in many cases. Masking of species-specific signals may decrease the effective sound range for communication, as shown for cod (*G. morhua*) and haddock (*M. aeglefinus*) during times of high vessel activity (Stanley et al. 2017). The peak in acoustic energy for vocalisation in these two species is the 50-260 Hz frequency band which overlaps with frequencies of shipping noise

(Hawkins and Amorim 2000; Finstad et al. 2004). As a consequence, the fish would have to swim closer together to be able to communicate. This raises concerns that communication between conspecifics, and thereby mating success, may be comprised in areas and periods with near constant high levels of low frequency shipping noise, such as near larger shipping lanes.

Noise from vessels may also cause physiological disturbances and increased **general stress responses**, especially if exposure occurs during sensitive life stages. Juvenile eel (*Anguilla anguilla*) have shown stress responses in the form of increased ventilation and metabolism when exposed to playback of ship noise (100-5000 Hz at 80-140 dB re 1 µPa) (Simpson et al. 2015). Anthropogenic noise may influence the endocrine system, leading to an increase in secretion of the stress hormone cortisol (Smith et al 2004; Lara and Vasconcelos 2021). In a study assessing elevated stress response in the gilthead sea bream (*Sparus aurata*) after 10 days playback of shipping noise –62.5 - 16 000 Hz at 96-142 dB re 1 µPa, it was found that all nine stress parameters measured were significantly affected (Celi et al. 2016). These were cortisol, glucose, lactate, haematocrit, ACTH, HSP70, cholesterol, triglycerides and osmolarity. Such stress responses may lead to altered developmental rate, morphological changes, immunological deficiencies or increased mortality (Fakan and McCormick 2019).

Evidence of **disturbed development** has been observed in Atlantic cod larvae (*G. morhua*) after exposure to playback of shipping noise in the laboratory (0-10 000 Hz). Two days exposure to playback of ship noise led to reduced growth and faster yolk sac utilization, while 16 days exposure to regular noise led to reduced body width–length ratio (an indicator for condition) and these larvae were also easier to catch in a predator-avoidance experiment, with possible consequences for survival (Nedelec et al. 2015). Also, **reproductive success** has been shown to be affected, as in a cod broodstock population exposed for two weeks to artificial noise consisting of a repeated 10-second linear sweep from 100 Hz to 1000 Hz (at 132 dB re 1 µPa) during the spawning period. This resulted in reduced egg production and fertilization rates, reducing the total number of viable embryos by over 50% compared to a control (Sierra-Flores et al. 2015).

To our knowledge, **temporary hearing loss** has not been investigated for any Swedish fish species. However, it has been measured in the hearing specialist goldfish (*Carassius auratus*) and the hearing generalist tilapia (*Oreochromis niloticus*). The hearing specialist exhibited clear TTS after 24 h exposure to white noise (100-10000 Hz) at levels of 160-170 dB re 1 µPa. Auditory thresholds returned to control levels 14 days after 21-day noise exposures (Smith et al. 2004). The hearing generalist however, showed little or no TTS even after 28 days (Smith et al. 2004). Reduced hearing ability was also detected in fathead minnow (*Pimephales promelas*), another hearing specialist, after 2 h exposures of playback speed boat noise of 142 dB re 1 µPa. Significantly elevated auditory threshold was found in the most sensitive hearing range of the fish, i.e., at 1000 Hz, 1500 Hz and 2000 Hz. There was no recovery even 14 days after the exposure, indicating risks for long-term reduction in hearing ability in this and other hearing specialist fish species (Scholik and Yan 2002).

Effects on invertebrates

More recently, it has been more and more evident that anthropogenic noise also affects different invertebrates. The extent of these effects and which species are affected are still however poorly understood. With their great diversity in morphology and life history, responses among different invertebrates are unpredictable and generalisations are difficult if not impossible. Therefore, several species from outside Swedish waters have been included here to give a more comprehensive overview of possible effects. Sound-detection abilities of marine invertebrates are mostly unknown. The hearing range for the commercial decapod species European lobster

(*Homarus Gammarus*) has not been reported, but the closely related American lobster (*H. americanus*)) and Norway lobster (*Nephrops norvegicus*) hearing ranges have been described as 80-250 Hz and 20-180 Hz, respectively (Goodall et al 1990; Jezequel et al. 2021). Non-native bivalves have been shown to detect water-born vibrations in the range 30-1000 Hz (Zhadan 2005). The relevant research studies on invertebrates have been performed with either adult or larvae/juvenile individuals. The effects identified include impacts on larvae settling and numerous other behavioural parameters, masking, reproductive disturbances and effects on development and growth as well as morphological changes, elevated stress response and physical/acoustic trauma. The studies embody mainly laboratory experiments, almost exclusively using playback recordings. When identified, invertebrates seem to be affected by low frequency sounds (<600 Hz), but effect thresholds are generally unknown.

Many invertebrates use sound cues to locate appropriate habitats to settle and ship noise has been shown to induce **larvae settlement** in a wide range of animals native to Swedish waters, including the bivalves blue mussel (*M. edulis*) and Pacific oyster (*C. gigas*), sea squirt (*Ciona intestinalis*) and polychaetae (*Pomatoceros sp*.), and in non-native bryozoans (*Bugula neritina, Watersipora sps.*) (McDonald et al. 2014; Stanley et al. 2014; Jolivet et al. 2016). This indicates that noisier ships can lead to greater problems with biofouling on ship hulls. However, for other species the opposite reaction has been described; decreased settlement was shown in the barnacle (*Balanus amphitrite*) that were unable to metamorphose and settle in the presence of artificial low-frequency sounds (30 Hz), especially at younger age (<13 days) (Branscomb and Rittschof 1984).

Noise from ships can also affect other types of **behaviour,** as demonstrated in a range of crustaceans in tank- or aquaria-based playback experiments: While ship noise (80-3000 Hz at 65-155 dB re 1 µPa) did not impair the ability of shore crab (*Carcinus maenas*) to find food, crabs engaged in feeding were more likely to be disrupted and stop feeding (Wale et al. 2013a). Further, crabs exposed to a ship noise showed impaired antipredator behaviour, with longer time for shelter retreat at a simulated predator attack compared to those experiencing ambient noise (Wale et al. 2013a). In the Mediterranean spiny lobster (*Palinurus elephas*), increased locomotor activity was observed (Filiciotto et al. 2014) and the common prawn (*Palaemon serratus*) responded to ship noise (100-3000 at 70-140 dB re 1 µPa) by spending more time in unprotected environments, moving less and spending more time resting (Filiciotto et al. 2016). Reduced antipredator behaviour was also shown in juvenile lobster (*H. gammarus*) where a constant artificial low-frequency multi-tone noise of ca. 100-200 Hz (90-120 dB re 1 µPa) was found to affect substrate choice, sheltering and exploration behaviour during presence of a predator (Leiva et al. 2021). One day after a 30 min-exposure to simulated vessel noise (<1 kHz, 169-172 dB re 1 µPa), competitive impairment was demonstrated in juveniles and sub-adults of the non-native blue crab (*Callinectes sapidus)* in interactions with unexposed *C. maenas* (Hudson et al. 2022). *C. sapidus* showed a decrease in competitive behaviour such as fight initiation, food handling and food defence, while aggressive display and escape increased. In hermit crabs (*Pagurus bernhardus*), impaired shell-quality assessment was detected where crabs exposed to ship noise (<3000 Hz, 119-144 dB re 1 µPa) more often choose shells of lower quality compared to ambient sound environment (Tidau and Briffa 2019b). A related study found that when hermit crabs were exposed to similar ship noise, their own shell quality ceased to influence the preference for spending time in groups with conspecifics (Tidau and Briffa 2019a). Besides behavioural impairments in crustaceans, a graded antipredator behavioural response at sound exposure has been shown in the common cuttlefish (*Sepia officinalis*), where the intensity of the response depended on amplitude and frequency. Exposure to 3 s pure-tone bursts at lower frequencies (80-300 Hz) elicited jetting and inking. Inking was elicited at sound levels above 140 dB re 1 µPa. This is one of the few studies that reported levels of particle motion; jetting was observed at 0.01 m/s^2 and inking at 0.74 m/s^2. Body patterning changes and fin movements were observed at all frequencies and sound levels (Samson et al. 2014).

Above 500 Hz, a relatively high sound level was needed to induce any type of response. Habituation occurred to repeated 200 Hz tone bursts, although some response remained for most cuttlefish. Ship noise playback also has a negative impact on behaviours that are important for the whole **ecosystem**, such as reduced filtration in blue mussels (*M. edulis*) at 10-3000 Hz, at 150-155 dB re 1 µPa (Wale et al. 2019) and reduced bioturbation of sea sediment by Norway lobster (*N. norvegicus*) and a non-native venous mussel (*Ruditapes philippinarum*) at 100-2000 Hz, 135-140 dB re 1 µPa) (Solan et al. 2016).

The mechanistic causes of different kinds of behavioural impairments are often unknown but masking of natural noise signals is likely. **Masking** of acoustic intraspecific communication by shipping noise has been shown in a field experiment with the European lobster (*H. gammarus*) (Jezequel et al. 2021). Buzzing sounds are produced between male lobsters during agonistic encounters; sounds in 87-261 Hz have been documented for both sexes in the closely related *H. americanus* (Pye Henninger and Watson 2005). Masking by shipping noise (55-1000 Hz, 60-118 dB re 1 µPa) led to lobsters increasing their call rates, suggesting vocal compensation (Jezequel et al. 2021).

The **rate of development and growth** as well as **larvae survival** may be affected by vessel noise. Increased development speed and increased survival have been found for example in sea squirt (*C. intestinalis*) (McDonald et al. 2014). Looking to results from recreational boating, the growth of sea squirts on boat hulls was found to be highest where the noise level was highest, indicating greater problems with marine biofouling with noisier engines. In a sea hare from the Indo-pacific region (*Stylocheilus striatus*), playback of boat noise (100-3000 Hz, 50-110 dB re 1 µPa2 Hz^{-1}) in the field was instead found to reduce embryonic development by 21% and increase larvae mortality by 22% compared with those exposed to natural, background noise playbacks (Nedelec et al. 2014). Underwater sound can also influence the physiological development rate of crab larvae, although not yet shown for any Swedish species. Reduced time to metamorphosis has been reported for several larvae of temperate crabs (*Hemigrapsus sexdentatus, Cyclograpsus lavauxi, Macrophthalmus hirtipes*), following exposure to underwater reef noise in comparison with silent control conditions (Stanley et al. 2010).

Furthermore, underwater noise may also affect **animal morphology**. Body malformations have been found in non-native scallop larvae exposed to playbacks of seismic pulses (i.e., not yet shown for ship noise; de Soto et al. 2013). Reduced growth per moult but also reduced camouflage ability was found in shore crabs (*C. maenas*) exposed to ship noise (Carter et al. 2020). Crabs exposed to playback of ship noise (100-3000 Hz) were no longer able to blend into the surrounding environment by change of shell colour and this effect was not seen when crabs were exposed to natural noise of similar amplitude.

Physiological and cellular stress responses due to noise from ships have been observed in some species. A stress response in the form of an increased metabolic rate was found in shore crabs (*C. maenas*), with higher oxygen consumption in individuals exposed to playback of ship noise (<3000 Hz, 148–155 dB re 1 µPa) compared to those exposed to playback of ambient harbour noise (108–111 dB re 1 µPa) (Wale et al. 2013b). However, both increased and decreased oxygen consumption have been observed in other invertebrates, such as brown shrimp (*Crangon crangon*), Mediterranean spiny lobster (*P. elephas*) and blue mussel (*M. edulis*) (Regnault and Lagardere 1983; Filiciotto et al. 2014; Wale et al. 2019). There is a range of biochemical parameters that can be measured in invertebrates to detect sub-lethal stress response to noise pollution. In *P. elephas*, boat noise (1000-45000 Hz, 60-115 dB re 1 µPa) was found to increase haemolymphatic levels of glucose, total protein, heat-shock proteins and total haemocytes (Filiciotto et al. 2014), while tissue concentrations of glucose or lactate were unaffected by both continuous and impulsive anthropogenic noise (100-2000 Hz, 135-140 dB re 1 µPa) in Norway lobster (*N. norvegicus*) (Solan et al. 2016). Reduced filtration rate as well as induction of oxidative stress (increased TBARS in gill cells) and DNA damage have been shown after exposure to ship-noise playbacks (10-3000 Hz, 85-155 dB re 1 µPa2 Hz^{-1}) in the blue mussel (*M. edulis*) (Wale et al. 2019). These types of stress responses are all energy demanding and may eventually affect animal growth, immune response and survival, especially if exposures occur during the earlier, more sensitive life stages.

Finally, **physical/acoustic trauma** has been demonstrated in four cephalopod species (*Loligo vulgaris, Octopus vulgaris, Sepia officinalis* and *Illex coindetii*) exposed to artificial low-frequency noise (50-400 Hz, 152-175 dB re 1 µPa). This caused permanent and substantial alterations of the sensory hair cells of the statocysts (Solé et al. 2013) with effects appearing more rapidly in juvenile hatchlings (Sole et al. 2018).

Recommendations for future studies

It is clear that underwater noise from shipping can have major effects on marine organisms. However, although underwater noise is an environmental problem that recently has received more attention, we still know relatively little about how severe the effects may be for many species and taxonomic groups. A great deal of research is needed to be able to accurately assess environmental impacts from the underwater noise of shipping. The future goal is to set threshold limit and determine what noise levels are to be regarded as environmentally hazardous and what noise levels are to be considered sustainable in Swedish waters today. This will aid implementation of necessary policies and guidelines for mitigation measures.

To assess and understand impacts from shipping on marine life, realistic and carefully designed effect studies on key species are needed, using realistic noise sources and levels corresponding to those found in natural environments. To establish realistic noise levels, field noise measurements are needed, in and outside busy shipping lanes and harbours, particularly in shallower, more sensitive coastal areas with high biodiversity. We also need to investigate and compare noise levels emitted at different speeds and under certain operations. Ideally, future studies should include measurement of the particle motion component of the noise source, to provide a better understanding of the effects noise may have on marine fish and invertebrates, in particular those living at, in or near the seabed.

Future research should focus on relevant key species living in areas exposed to noise pollution from shipping. Those are indicator species identified as extra sensitive or vulnerable to noise exposure but may also include species of particular ecological or commercial importance, or species that are protected in specific areas. In Sweden, it has been discussed to base environmental quality assessments of ship underwater noise on cod, herring, a seal species and the harbour porpoise. For those key species we need to identify what effect parameters and life stages that are most sensitive. Establishing thresholds for sensitive effect parameters causing no or low negative impacts to a range of indicator species representing different taxa is crucial to enable comprehensive risk assessment of shipping noise. For a better understanding of which marine organisms are most sensitive to noise disturbances, we need to compare vulnerability between species and animal groups. Sensitivity may however not only differ between species, but effects within a species may vary depending on life stage, sex, or motivational stage, and may depend on the context or time of the year (Magnhagen et al., 2017). For example, larvae are generally considered more sensitive than adults and individuals may be more sensitive during their mating season, or during migration, or after the winter with longer starvation periods. Moreover, individual personality such as shyness and boldness may also affect the sensitivity to exposure to environmental pollutants (Chen et al. 2022). All these factors are known to be of importance from effect studies of other pollutants, e.g., affecting level of motivation for certain behaviours and thus sensitivity to disturbances of these behaviours. These considerations imply that investigations into the environmental effects of ship underwater noise need to be large-scale, including different species and a large number of individuals per species. These individuals need to be selected from different life stages and experiments need to be performed at different behavioural states and/or times of the year.

It is important to investigate what influences how harmful a certain noise sample is. Are high levels for shorter time periods more harmful than lower continuous levels? Which noise frequencies cause the most harm? Is a noise with several tones that are stronger than the broadband noise more harmful than a noise of the same power but without tonal components? Should the noise levels be distributed out over a large area, or is it better with some quiet areas and some very noisy areas? These are examples of questions that need answers. To establish critical threshold limits when noise pollution is to be considered detrimental, it is vital to establish dose-response relationships and determine the lowest effect levels for relevant physiological, behavioural or general stress responses. Such threshold limits are required by regulatory authorities to aid implementation of necessary policies, guidelines and legislation for mitigation measures to reduce levels and protect the environment (Popper et al. 2020). So far, this is something that is generally lacking in the current literature.

Strictly controlled laboratory-based experiments should ideally be complemented with field studies for more realistic settings and to validate laboratory results in situ. To enable more complete understanding of impacts and to disclose mechanistic causes for these, it is desirable to investigate effects on several levels of biological organisation. Short-term, acute effects as well as more long-term effects on growth, health and reproduction (i.e., with relevance for animals' fitness and health) should be determined, and whether habituation to particular noise occurs, diminishing stress responses over time, or increasing tolerance for those previously experiencing specific noises as shown e.g., for coral reef fish (Nedelec et al. 2016). Other important aspects that one needs to consider are effects on future generations, possible consequences for the populations and subsequent effects for the health and service function of marine ecosystems.

Since anthropogenic noise is one of many stressors for marine animals, it should be included in interaction with e.g., other pollutants, climate change related environmental changes and overfishing in assessments of cumulative pressures on marine ecosystems. A positive aspect is that compared to many other stressors, noise is typically a point-source pollutant where the effects will decline soon after the sources are removed, or noise levels are reduced below critical threshold limits.

All these kinds of investigations are required to thoroughly investigate and understand the impacts of noise pollution on marine life. However, the number of studies showing negative impacts of anthropogenic noise is steadily increasing, and already established test organisms and test variables can be used as a starting point for future studies to develop quantitative indicators for noise pollution and for initial assessments of environmental hazard. Yet, varying and non-standardised experimental methods have been used, making it difficult to compare results between studies. Moreover, the scarcity of studies designed to pinpoint lowest detectable effect thresholds make it difficult to draw conclusions on harmful noise exposure levels. Such threshold values are needed by regulatory authorities to be able to determine which noise levels are acceptable in Swedish waters, for assessment of good environmental status for underwater noise. Development of threshold limits of relevant noise sources for the most sensitive effect parameters in key species will be of great value when developing and evaluating the effectiveness of different mitigation measures through policy regulations or through deployment of technological solutions to reduce noise levels and protect the environment. This information can for example be used when assessing the effectiveness of a certain reduction in general noise levels, or in specific low frequency sound levels, as a result of mitigation measures. As an example, if we already know that mainly larval stages are sensitive in a certain key species and that negative effects are only seen at noise levels produced by particularly noisy vessels moving at high speeds, it may be sufficient to reduce speed for those particular vessels in certain areas during the reproductive season.

Current ship noise mitigation

To reduce the environmental impact of UWN, there of course needs to exist both effective methods to mitigate the noise, but also systems to drive the change towards ships with a smaller noise footprint. In the following sections, both of these components are described. The currently available mitigation methods and their readiness is described, followed by an overview of the relevant policies for UWN, and finally a summary of previously employed economic incentives for reducing UWN. Given the corpus of evidence of environmental impact from UWN described in the previous section, economic incentives are motivated both from purely environmental reasons as well as to reduce the loss of future profit in e.g., the fishing industry caused by a reduction of life in the seas.

Underwater noise mitigation methods

In this section we divide different methods to mitigate underwater noise pollution into technical methods and operational methods. This division is followed in many scientific reports. Technical methods are defined as methods concerning the vessel and its design, hence connected to the propeller, machinery, or hull. Operational methods are defined as methods concerning the movements of the vessel, hence where it operates and how. They could include how the vessel is navigated, the vessel speed, if ship owners have specific systems for regular propeller and hull cleaning, or if ships travel in convoy through certain sensitive sea areas.

Technical methods

Technical methods have the strong advantage that noise is reduced without affecting the operating schedules of the ships. However, there is insufficient literature on the efficacy of different methods, in particular on the potential to generalize methods between vessels of different construction. A report from Vard Marine Inc. (Vard 2019) describes various technical measures to reduce UWN, their advantages, challenges, readiness, applicability, and effectiveness. The report covers many types of technologies, including different propeller designs, wake flow modifications, engine modifications, and maintenance schemes. However, there is no information about how the judgements on noise reduction were done, or references to other material investigating the technologies (referenced materials mostly treat propulsion efficiency, not noise performance).

Gassmann et. al (2017) studied the noise reduction from retrofitting five G-class container ships with improved propellers, bulbous bows, and slow-steaming engines. This was done by measuring the UWN before and after the retrofit. The measurements were done at a relatively large range of 3-4 km, measuring only a single ship-length (approximately 350 m) of travel. The UWN from the ships were compensated for the acoustical conditions with a simple geometrical propagation model, compensating for distance and surface reflection only. Each vessel was measured between 4 and 8 times before the retrofit. One vessel was measured twice after the retrofit, other vessels were measured only once. Compared with the stringent criteria for dedicated measurements, these results are not as reliable, largely due to the uncertainties caused by the varying acoustical conditions over a period of five years. The retrofit resulted in between 6 dB and 8 dB reduction of source levels, as calculated by said authors. However, they also note that the deeper draft of the ships after the retrofit reduces the influence of the surface reflection, largely negating the reduction on source level when measured at the receiving hydrophone. The results are furthermore not controlled for maintenance and cleaning of the ship, likely done simultaneously with the retrofit. This highlights some of the difficulties in establishing the effects of technical measures; retrofits are rarely done in isolation and measurements are complicated and expensive.

It is far easier to achieve low underwater noise emissions during the design phase than through retrofits on active vessels. It is universally agreed that the dominant source of ship UWN is the ship's propeller(s) (Ross, 1976). Specifically, the main source of propeller noise is cavitation at or near the propeller blades. The formation of cavitation depends on propeller speed; at low enough speed, all propellers are non-cavitating. At a certain speed, known as the cavitation inception speed (CIS), cavitation forms, usually leading to a large increase in UWN. As the propeller speed is increased further, cavitation typically increases. However, modern ships are designed to operate at one or several speeds, where cavitation and fuel consumption may be reduced compared to speeds just above or just below the design speed(s). It is important to note that when a propeller-driven ship is propelled in a fuel-efficient manner, cavitation will occur. Historically, design measures have been taken to avoid extreme cavitation. This was due to the erosion that it causes on the propeller rather than the high levels of UWN that it causes.

While propeller noise is the dominant source of ship UWN on average, this is not necessarily true for any particular ship. Machinery noise is generally considered the second strongest source of underwater noise and is dominant on some ships. It is caused by the engines and generators onboard, that cause the ship's hull to vibrate. These vibrations may radiate into the water as sound. Airborne sound inside the ship can also excite hull vibrations and cause underwater noise.

Some sources also quote the hull as a separate source of underwater noise (Hildebrand, 2009). The flow of water past the hull generates flow noise, but for merchant vessels this is typically weaker than propeller and machinery noise.

Since propeller noise is generally the dominant source of ship UWN, it is natural to first attempt to reduce it. The propeller is carefully designed together with the hull. If noise is given more importance during this process, propeller UWN can typically be reduced. This may lead to increased fuel consumption; all involved parties must agree on the best trade-off. Financial incentives for reduced UWN can have an influence here. The following discourse on noise reduction measures follows "Practical considerations for underwater noise control" by the American Bureau of Shipping, Feb 2021. The list of technical measures given there is provided in Table 4.

Table 4. Technical methods for ship underwater noise mitigation, as listed by the American Bureau of Shipping (2021).

Propeller design	High skewed propeller	Forward-skew propellers	Contracted and loaded tip propellers	Contra-rotating propellers	Kappel propellers	Podded and azimuthing tractor propulsors
	Waterjet	Composite propellers	CPP combinator optimization	Reduction of turn per knot (tpk)	Voith schneider propulsion	
Wake improvement devices	Schneekluth duct	Mewis duct	Grothues spoilers	Pre-swirl stator	Propeller boss cap fins and propeller cap turbine	Stern flap
	Twisted rudder					
Other propulsion enhancement measures	Regular propeller maintenance	Air bubble curtain				
Machinery treatment	Selection of quiet equipment	Resilient mount	Two-stage isolation	Acoustic enclosure	Active vibration cancellation	
Hull treatment	Hull form optimization	Regular cleaning of the hull	Decoupling coating	Damping		
Emerging technologies	Air lubrication	Kite sails	Flettner rotors	Shore power		

There are several strategies that can be employed to reduce the load on the propeller blades, thus reducing cavitation and UWN. These include high skewed and forward skewed propeller blades, contracted and loaded tip (CLT) propellers, contra-rotating and Kappel propellers. Podded propulsors and waterjets are common on non-merchant vessels and may offer UWN benefits if they can be adapted to the needs of merchant vessels. One can also consider composite propellers, optimising the operation of controllable pitch propellers together with engine speed, and reducing the propeller speed by using a larger propeller. Existing vessels can be retrofitted with a new propeller for UWN reductions, but since the hull design cannot be changed this may be less efficient than designing the hull and propeller together.

Another class of measures aiming at reducing propeller noise addresses the wake, i.e., the flow past the hull and the propeller. A controlled and stable wake makes it easier to design for low UWN and may reduce cavitation. Wake conditioning devices that have been connected to reduced UWN include different types of ducts, fins and spoilers. The shape of the rudder can also be optimised for reduced propeller-related UWN.

Both new and existing vessels benefit from regular hull and propeller cleaning. This is an important measure to reduce UWN, because it strives to keep the flow and the wake as well as the propeller operation close to what it was designed for. Like recreational boats, merchant vessels are susceptible to biological growth under the water line.

There are several different ways of reducing machinery noise. Switching to diesel-electric propulsion may be highly efficient. The engine can be placed anywhere on the ship and is no longer rigidly connected to the propeller through a shaft. Isolation and reduction of engine noise is then facilitated. Conventional engines can be placed on resilient mounts, reducing the transmission of vibrations to the hull. Active cancellation of vibrations can be effective at reducing vibrations at single frequencies, but at a high cost. High-speed diesel engines are typically quieter than low- and medium speed engines but are not as fuel efficient. Gears can also generate vibrations and UWN and need to be properly designed.

Air bubble injection has been tried as a way to reduce the drag of the hull, thus potentially reducing flow noise. This is also known as air lubrication. Bubbles have also been released from the propeller blades themselves, aiming to reduce noise transmission to a distant receiver. This can reduce UWN but may cause reduced efficiency.

Finally, we would like to mention sails, which are currently being evaluated as a way to generate propulsion power primarily at low and medium speeds. These sails have little in common with those that brought our ancestors across the oceans; they are rigid, very tall, have optimized shapes and can be rotated to achieve maximum propulsion according to wind speed and direction. In December 2022, Wallenius Marine and Alfa Laval founded the company AlfaWall Oceanbird, aiming to develop and provide technology for fully wind-powered vessel propulsion.

Operational methods

UWN mitigation may also be achieved through operational methods, which entail changing how a ship or a fleet is operated. Speed reduction and re-routing are two commonly discussed operational UWN mitigation measures.

Re-routing means that vessels are directed to travel in a different route. This may have small or no effects on the levels of radiated UWN, but if the ships are re-routed to areas where the environment is less sensitive to noise, the environmental impact of the noise may be reduced. If a shipping lane that is moved to a less sensitive area becomes longer, the lower environmental impact from a certain UWN radiation must be balanced against the greater duration of UWN emissions. Since ships experience greater resistance when travelling through shallow waters than through deep waters, another possible re-routing alternative may be to place shipping lanes in deeper waters.

Across a large fleet, speed reductions can be expected to lead to reduced average emissions of UWN and also of greenhouse gases. But that doesn’t necessarily hold for any particular ship; ships are designed to operate at a certain speed and operating below that speed may in fact lead to greater UWN emissions for some vessels. A relevant case study of speed reduction is presented by MacGillivray et al (2019), where a zone of voluntary slow-down was used outside the port of Vancouver. The noise levels generated by individual ships were tracked both during the trials but also outside the trial period. During the trial, the ships reported whether they participated and reduced their speed to around 11 knots, or if they maintained their usual speed. In total the noise from 1317 ship passages were successfully measured, out of which 577 were from participation during the trial. The ships were classified as one of five categories: bulker, containership, cruise ship, tanker, or vehicle carrier. Their results showed that the slowdown will on average decrease the noise radiated from ships, in varying degrees for the different ship classes, see Table 5. The authors note that the difference between ships with fixed-pitch propellers and those with variable-pitch propellers is not covered by their analysis. This is important since slowing down will influence the properties of cavitation differently for the two propeller types. Another aspect which is not considered is the biological effects, e.g., if a weaker noise event of longer duration is advantageous compared to a shorter but louder noise event.

Table 5 Noise reduction and speed reduction during slowdown test. Data from MacGillivray et. al (2019).

Vessel Category	Mean speed reduction (kn)	Mean noise reduction (dB)	dB per knot of speed reduction
Bulker	2.09	5.56	2.66
Containership	7.67	11.17	1.46
Cruise ship	6.15	10.74	1.75
Tanker	2.30	5.78	2.25
Vehicle Carrier	5.89	9.24	1.57

The port of Vancouver ran a voluntary ship slowdown trial in Swiftsure Bank from the 1st of June 2020 until the 30th of November 2021 (Port of Vancouver Swiftsure, 2022). Large commercial ships were asked to lower their speed and the participation rate was 81 % in 2021. During 2020 the broadband noise was reduced by approximately 2 dB. During 2021, however, acoustic results show that the noise levels, particularly in the lowest frequency bands, increased steadily from April to November. This was contrary to expectations and will be further investigated by the Canadian Department of Fisheries and Oceans (Port of Vancouver Swiftsure Summary report 2021, 2022).

The Protecting Blue Whales and Blue Skies program along the coast of California asked shipping companies to reduce speeds to 10 knots or less in the Southern California Region and the San Francisco Bay area to lower emissions of carbon dioxide and noise. Vessel source levels of ships that participated in the slowdown trial were on average 5 dB lower than source levels in 2018, when the program was inactive (slowdown: 195 dB re 1µPa @ 1m, baseline: 190 dB re 1µP^{a} @ 1m) (ZoBell et al., 2022).

Fairway design for reduced ship noise transmission

Fairway or channel design is a mature field that is covered by several books and guideline documents, e.g., PIANC, 2014 and ASCE, 2007. However, designing fairways to reduce noise transmission appears not to have been discussed before; a literature search to find previous efforts found no hits. Moreover, no reports on the effect of fairway design on the spread of underwater noise were found. The main findings about the effect of fairway design on ships relate to the so-called squat effect.

Ships moving through shallow water encounter a larger drag than in deep water. The draft of the ship increases, and it is “sucked” towards the bottom. This is designated the squat effect and results in increased fuel consumption. The altered flow around the hull and propeller and the increased drag when operating in shallow water may affect the radiated underwater noise. Both hull and propeller are carefully designed to optimise the flow and the efficiency of the propeller. If the flow differs from what the ship was designed for, the cavitation pattern at the propeller will change, which will cause the noise radiation to change. Propellers for civilian vessels are typically designed to be efficient rather than quiet, so the efficiency is likely to drop, but the effect on the radiated noise is more difficult to predict.

To put the squat effect into perspective, Serban and Panatiescu, 2012, compare different equations for estimating the squat effect. They illustrate with a cargo ship of length 188 m, width 17.1 m, depth 7.76 m and displacement of 7800 tonnes moving through a canal of width 123 m and depth 10 m. The different formulas predict a squat at 8 knots of between 0.29 m and 0.52 m. At 12 knots, the predicted squat increased to between 0.75 and 1.4 m.

Increasing the **channel depth** will lead to drag reduction and a reduced squat effect. It may potentially also reduce the spread of noise. The rationale behind this is that more noise may get "trapped" in a deeper channel compared to a shallower one.

Norrbin, 1986, describes the results of towing tank tests at SSPA Sweden AB and gives relations between ship power and speed loss as a function of water depth and channel blockage. Ship propeller rpm and delivered power to drive the ship are reduced in shallow water and when travelling in a channel. The results show that for a ship in shallow water at depth-to-ship draft ratio of about 1.1, only 70 percent of the design sea speed could be sustained. For a depth-to-draft ratio of 1.2, 75 percent of the design speed could be sustained; an increase of 5 percentage points. Conversely, less power is required to sustain a certain speed in a deeper channel as compared to a shallower one. The potential fuel and cost savings occur at the ship owner, not the operator of the waterway who dredged the channel. Profit can potentially be redistributed to the waterway operator through fairway dues. The value of the reduction of environmental impact must also be considered but may be difficult to estimate.

It is well known that in shallow water, low frequency sound attenuates rapidly below the so-called cut-off frequency. The shallower the water, the higher the cut-off frequency, so there is less propagation of low frequencies and therefore lower levels of low frequency noise are spread from ships operating in shallow waters. These considerations apply to flat seabed areas. A depth change in the fairway will affect the local cut-off frequency, but whether that will have a significant effect on the transmission of noise to a receiver well outside the fairway is not clear.

Increasing the **channel width** will also lead to drag reduction, which will influence the flow around the hull and my potentially have a mitigating effect on noise generation. According to Norrbin (1986), when the ratio of channel cross section and midship area is less than 5, the speed reduction is large. Widening the channel reduces the effect.

Changing channel slopes may also have an effect on the squat effect and noise transmission. **Channel slopes** are typically 1:3 if the seabed material is easily disturbed and 1:2 to 1:1,5 for sand and light moraine. These slopes can be made shallower but not steeper as the material would then move. If the seabed is rock, channel sides can be vertical.

Placing **walls or mounds** around fairways is another alternative, but the idea has several challenges. Soft material that is placed along the edge of a fairway will be subjected to erosion. A wall or mound will require an additional permit, which may be difficult to obtain, particularly if the structure changes the currents in the area.

It is also possible to **put soft materials on top of rock** in an effort to reduce the spread of noise, but to maintain the fairway depth, additional blasting will be required, followed by dredging and moving the soft materials. This will make this approach expensive.

Fairway turns cannot be avoided, but it may be possible to make them longer and smoother. Ship turns and speed changes create increased noise on board (Bertil Skoog, Sjöfartsverket, pers. comm., 2022). Whether this is also true for noise radiated into air or into water was investigated in this study and is described below. Measurement standards require travel in a straight course at constant speed. But in many of Sweden's coastal areas, islands and depth variations make it impossible or inappropriate to make a straight channel. There are guidelines on allowed curvatures, but these do not take noise into account. A merchant ship is typically designed for its most common mode of operation, i.e., travelling at a straight course at the design speed, and what happens during turns is regarded as less important. The flow around the hull and propeller during a turn is different than during straight travel. Placing the rudder at an angle from the longitudinal causes the flow near the propeller to be longitudinally unsymmetrical.

Lots of expertise and balancing of different considerations goes into **placing a waterway**. However underwater noise is not currently one of those considerations. A first step to introducing underwater noise into this process is understanding more about how different fairway designs influence the radiated underwater noise of ships that ply the channel.

Senior fairway expert Bertil Skoog at the Swedish Maritime Administration provided detailed information on fairway design and construction in Sweden. Here follows a summary. Fairway design is fundamentally a tradeoff between the need for dredging and blasting, length, turns and depth. The fairway is designed according to the traffic it will support and the environment in which it will be placed. An important design parameter is the under-keel clearance, which is the distance between the deepest point of a ship and the seabed. The absolute minimum under keel clearance used in designing Swedish fairways is 70 cm. The width of the fairway depends both on ship dimensions and on the types of ships that will use the fairway. The fairway must be wide enough to permit wind drift, which is stronger for some ship types.

When considering an altered fairway design, it is important to determine the financial impact. According to Bertil Skoog, dredging in Sweden typically costs between 30 and 80 SEK per cubic meter of material (2022). Costs for blasting are much higher, typically from 400 to several thousand SEK per cubic meter of material (2022). To illustrate fairway redesign costs, consider the southern channel into Gothenburg port, the busiest port in Scandinavia. From where it merges with the northern channel East of Böttö to where the two channels merge south of Torshamnen, its length is approximately 3.7 nmi and width 300 m. Assuming vertical edges, the bottom area of the channel is approximately 2 million square meters. According to the estimated cost of dredging soft materials, dredging this channel to increase its depth by 1 m would cost between 60 and 160 MSEK. If any sections need blasting, the costs will rise significantly. Additional dredging or blasting beyond what is required will thus incur significant costs. It must be clear who will pay these costs. If additional dredging or blasting contributes to reduced spread of underwater noise, it is marine life that benefits. It may be difficult to value this benefit in the commonly used monetary value model. Humans may benefit in turn, and it may be important to calculate the monetary value of these gains.

When the capacity of a fairway is increased, one usually needs to increase its depth and width. A current example is the Luleå Malmporten project, which extends the capacity of the fairway into the port of Luleå. The cost of this project is on the order of 2 billion SEK and 22 million cubic meters of material will be removed. The material is dumped in a nearby deep-sea area following a rigorous environmental impact assessment process, which is the common practice when trenching in Sweden.

Policies applicable to underwater noise mitigation

International policy framework

There are currently no international legally binding instruments to mitigate and control underwater noise from commercial vessels (Chang & Zhang, 2022 and Vakili et al, 2020). The International Maritime Organization (IMO), the UN governing organisation with responsibility for prevention of pollution from ships, developed non-mandatory technical guidelines in 2008 and in 2014 the guidelines were approved (MSC.1/Circ.833). These guidelines are currently under review. However, there is an IMO project called GloNoise that aims to engage and assist developing countries to build capacity, raise awareness and promote international policy dialogue on mitigation of underwater noise from shipping. The project started in June 2022 and ends in December 2024 (IMO 2022). The IMO MARPOL Convention (the International Convention for the Prevention of Pollution from Ships) aims at lowering the effects that shipping have on the environment. However, the Convention has a narrow definition of pollution including only harmful substances or "effluents", thus excluding noise. Possibly, the Particularly Sensitive Sea Areas (PSSA) could be used to address noise (Chang & Zhang, 2022).

There are other international agreements that could be expanded to include anthropogenic underwater noise, if States decide to do it. For instance, States ratifying the United Nations Convention on the Law of the Sea (UNCLOS) have the obligation to protect and preserve the marine environment and the Convention is flexible enough to also include noise, if State parties would want to. The Convention on Biological Diversity (CBD) points out that ratifying States have a responsibility to ensure that the environment is not damaged in their own territory or in areas beyond the limits of national jurisdiction. It states that States should cooperate and share information, research and technical knowledge with each other. The Fish Stock Agreement emphasises the need to ensure conservation of fish stocks and biodiversity, and the definition of pollution stated in the agreement could include noise. Additionally, the Bonn Convention (the Convention on the Conservation of Migratory Species of Wild Animals) had focus on marine noise during its 12th meeting in 2017. The meeting also focused on getting the attention of the IMO to further its work on minimizing the effects of shipping noise on marine species (Chang & Zhang, 2022).

Policy framework from a Swedish perspective

The framework set by the European Union in the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC) influences national policies on limiting adverse effects of underwater noise. This is implemented in the "Havsmiljöförordningen" (2010:1341) in Swedish law. The Directive points at the importance of considering regional specificities and the necessity of regional cooperation. Accordingly, the regional sea conventions produce inventories and action plans of noise mitigating measures that aid contracting parties to reduce sound levels and negative impacts (e.g., OSPAR, 2020; HELCOM, 2021b). The action plans and work within the conventions are in line with the MSFD, and the MSFD recognizes and encourages regional cooperation.

Europe has further addressed anthropogenic underwater noise through the Agreement on the Conservation of Small Cetaceans of the Baltic, Northeast Atlantic, Irish and North Seas (ASCOBANS). The ASCOBANS states that in order to conserve and manage the habitat of these animals, there should be a prevention of "other significant disturbance, especially of an acoustic nature". The precautionary principle should be applied; several methods are suggested to lower noise exposure to the animals, such as use of technical measures to lower impact and restricting human activities in time and place to minimise disturbance to the animals. Parties and non-parties should also collaborate to lower the impact of noise on the cetaceans (ASCOBANS, 2022).

The Swedish Agency for Marine and Water Management is responsible for national monitoring of underwater noise in Sweden. Sweden is represented in expert groups in the EU, and in the regional sea conventions HELCOM and OSPAR. These groups have central roles in the development of monitoring practices and assessment methods. Swedish monitoring efforts are coordinated with the countries in HELCOM.

The urgency to address the issue of underwater noise has resulted in several research projects. An overview of European-funded projects and other relevant initiatives was published by the EU Technical Group of Underwater Noise in March 2022 (TG Noise, 2022). EU-funded projects contribute to strengthening regional cooperation to reduce underwater noise and increase knowledge, thus contributing to the implementation of the MSFD.

Levels of continuous underwater noise are monitored in two Swedish locations since 2014, one in Norra Midsjöbanken east of Öland in the Baltic Sea and one close to Hönö in northern Kattegat. Since 2018 there is also a monitoring station in the Bothnian Sea east of Sundsvall. The EU regulates the monitoring practices in order to assure consistent approaches in different member states. The monitoring data are used to describe the environmental status of our marine environments. These monitoring stations measure long-term levels of underwater noise rather than ship underwater noise signatures. In addition to the Marine Strategy Framework Directive, noise data are valuable for the follow-up of obligations in the Habitats Directive, Swedish national environmental quality objectives, and UN sustainable development goal number 14 "Life below water". The data can also serve as input to marine spatial planning (Havs- och Vattenmyndigheten, 2022).

Marine Strategy Framework directive

The Marine Strategy Framework Directive (MSFD), adopted in 2008, presents a policy framework for the safeguarding of the marine environment across Europe (EU, 2008). The Directive includes eleven so-called "descriptors". Descriptors are parameters that describe what the environment will look like when good environmental status is achieved. Descriptor number 11 covers underwater noise and states that a good environmental status is reached when "Introduction of energy (including underwater noise) does not adversely affect the ecosystem". Descriptor 11 (D11) contains criteria for both impulsive sound and anthropogenic continuous low-frequency sound. Sound emitted from operating ships are in the latter sound category (European Commission, 2022a).

A decision by the European Commission from 2017 further specifies how the different descriptors can be assessed (EU, 2017). Specifications on low frequent continuous noise include:

1. Noise level, spatial distribution and temporal duration should not exceed levels that negatively affect populations of marine animals.
2. Member states shall determine threshold values for the "not-to-exceed" levels through cooperation on a European Union level, considering regional and subregional specifics
3. Assessment of whether the environmental status is good or not can be done for regions, subregions, or subdivisions, which are smaller areas than subregions.
4. For the assessed areas, good environmental status should be evaluated based on annual average sound levels. Other relevant time metrics can be used if agreed within a region or

sub region. The average values should be presented on a spatial grid. The evaluation shall also consider the extent to which the threshold values have not been achieved. This should be communicated as a percentage of the assessment area.

5. How the criteria are to be implemented should be agreed at Union level.
6. For monitoring, the squared sound pressure in each of two '1/3-octave bands' should be measured. One of the bands should be centered at 63 Hz and the other at 125 Hz, and sound levels expressed as total levels within the bands in units of dB re 1 μPa. Member States may also decide at regional or subregional level to monitor additional frequency bands.

A group of nationally nominated experts from different member states form the TG Noise. The experts have experience from different regions and relevant scientific expertise. The aim of the technical group is a coordinated implementation of D11. TG Noise presented recommendations for an assessment framework for EU threshold values on continuous anthropogenic underwater noise in November 2021 (TG Noise, 2021). The recommendations describe in detail how an assessment can be based on habitats of indicator species and the condition of each habitat. TG Noise recommends that habitats of indicator species are geographically split into smaller areas, grid cells. An assessment, considering exposure and sensitivity of animals, will answer whether the grid cell of a habitat is affected significantly or non-significantly. Additional research is needed to establish exposure-response mechanisms for different species and groups of marine animals. Effects on whole populations can be made by applying the grid cell methodology for all grid cells constituting a habitat. The tolerable exposure of anthropogenic continuous noise in time and space for grid cells, and populations, should consider the sensitivities of different species. The selection of habitat and indicator species, grid cell size, and temporal resolution in the assessment is recommended to be made at regional or subregional level taking any regional specificities into account (TG Noise, 2021). However, the tolerable impacted area is fixed at 20 % of each evaluation region. A key term is Good environmental status (GES), which for ship underwater noise is, said to hold for a region in which the impacted area is less than 20 % of the total area.

The recommendation opens up for the use of different methods. Differences in availability of data and choice of method will influence both the result and the precision in the assessment of impact and risk of impact on population dynamics. In October 2022, TG Noise submitted their final proposal for environmental quality standards (Swedish: *miljökvalitetsnormer*) for underwater noise in EU waters. The proposal was approved by the EU maritime directors and is currently (Jan 2023) being adapted for national implementation. This includes selection of indicator species and setting threshold values. According to the Swedish Agency for Marine and Water Management (Swedish: *Havs- och Vattenmyndigheten*), by 2024, the first assessment of environmental status of descriptor 11 should be complete. The status will be presented as a map with red and green marine areas, where red areas do not fulfil GES, and green fulfil GES. Based on the map, targets will be set in order to reach GES in the red areas in 2025.

The framework of the proposed quantitative load indicators for underwater noise revolves around modelling. Using weather data, a model predicts the natural underwater background noise that is generated by wind, waves and rain as well as tectonic processes. Another model uses ship position data and design particulars to predict the underwater noise that is generated by ships. Both the natural and ship noise models generate noise maps, the show how noise levels and spectra vary with location. Now, a key parameter in the framework is the so-called excess. This is equal to how far the ship noise is above the natural noise; the "difference" between ship noise and natural noise levels. The excess is used to evaluate whether a certain grid square is considered to achieve GES or not. Now biology comes into the equation. The sensitivity to underwater noise is highly species dependent. Therefore, a new term is introduced. This is the Level of Significant Effect (LOSE). This is a species-dependent parameter that describes how high an excess a particular species can tolerate before significant negative effects occur. In Sweden, cod, herring, a seal species and harbour porpoise have been discussed as indicator species. Swedish authorities will determine what the LOSE threshold values should be, and then it is possible to calculate the percentage of area in any region that is considered to comply with the environmental quality standards. The EU dictates that no more than 20 % of any given region should fail to fulfil the GES thresholds. This constitutes the outline of the coming quantitative load indicator framework for underwater noise.

Regional Sea Conventions

Regional Sea Conventions (RSC) are cooperation structures that aim to protect the marine environment and bring together neighboring countries that share marine waters (European Commission, 2022b).

There are four such RSCs in Europe:

1. The Convention for the Protection of the Marine Environment in the North-East Atlantic of 1992 (OSPAR)
2. The Convention on the Protection of the Marine Environment in the Baltic Sea Area of 1992 (HELCOM)
3. The Convention for the Protection of Marine Environment and the Coastal Region of the Mediterranean of 1995 (UNEP-MAP)
4. The Convention for the Protection of the Black Sea of 1992 (the Bucharest Convention).

Amongst other functions, the RSCs provide frameworks for cooperation between Contracting Parties that are European Union (EU) Member States in their efforts in defining and achieving good environmental status under the EU Marine Strategy Framework Directive. The RSCs are instrumental in order to harmonize the methods and implementation of standards on underwater noise and their monitoring set out in the MSFD.

Sweden participates in OSPAR and HELCOM. Likewise, the EU is a contracting party to both conventions.

HELCOM

Although an issue on the agenda for several years, HELCOM’s work on underwater noise was given increased formalized attention in 2013 when a HELCOM Ministerial Declaration agreed that the level of ambient and impulsive sounds in the Baltic Sea should not have negative impact on marine life. It further agreed 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 (HELCOM, 2022a).

In order to prepare and facilitate the implementation of measures for underwater noise mitigation in HELCOM, an Expert Network on Underwater noise (EN-Noise) has been established and is active since the mid 2010’s. Initially the network’s main purpose was to build a knowledge base (HELCOM, 2022a). The EN-Noise presented a roadmap for that purpose that was adopted in 2016. The next task included producing an action plan, and from 2021 when the plan was adopted, the network aims at the implementation of the plan (HELCOM, 2021a).

The HELCOM regional action plan on underwater noise was developed primarily in line with the commitments made in a HELCOM Ministerial Declaration from 2018. The regional action plan fed into the updated Baltic Sea Action Plan adopted on 20 October 2021. The Baltic Sea Action Plan is an overarching document that provides a vision to achieve good environmental status of the Baltic Sea by 2030. The plan includes underwater noise for the first time in the version from 2021 (HELCOM, 2021b, HELCOM 2021c).

The BSAP gives a time plan for actions on the theme underwater noise. The actions address both impulsive and ambient noise and comprise monitoring, scientific studies, threshold values and assessment methods. Figure 4 presents an overview of the actions, interpreted from the BSAP. Text in bold focus significant factors relating to continuous noise.

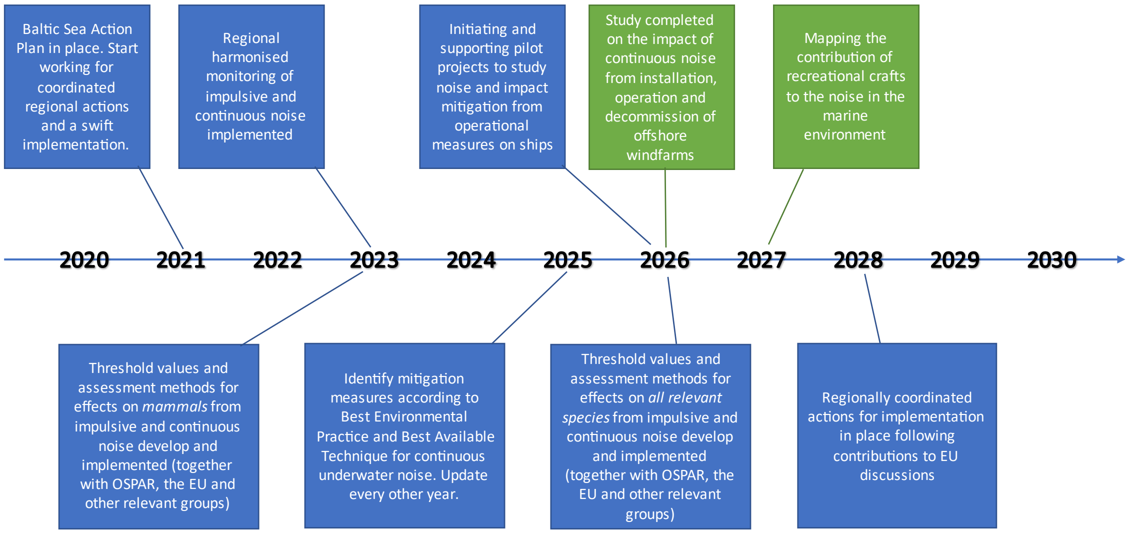


Figure 4. Time plan for actions on mitigations of underwater noise from the Baltic Sea Action Plan (HELCOM, 2021b).

Further, the HELCOM Science agenda from 2021 specifically points out research needs in the field of underwater noise. The identified needs on continuous ambient noise include long-term acoustic monitoring methods, modelling in shallow waters, refinement of methods to quantify impact from continuous noise sources on animal populations, and more. The purpose of the Science agenda is to support the implementation of the BSAP and other HELCOM agreements. It aims at communicating HELCOM science needs with funding agencies and scientists, and to increase the interaction between science and policy (HELCOM 2021d).

OSPAR

A Quality Status Report from 2010 (QSR 2010) included recommendations to OSPAR to increase efforts in mitigating underwater noise. Guidelines on best available technology (BAT) and best environmental practice (BEP) should, according to the report, be developed to help contracting parties abate underwater noise pollution (OSPAR, 2010). A lot of the OSPAR efforts on underwater noise mitigation are made in the Intersessional Correspondence Group on underwater noise (ICG-Noise) under the thematic area Environmental Impact of Human Activities Committee (EIHA).

Since 2010, the OSPAR work on underwater noise includes, but is not limited to:

1. **Monitoring strategy**; In 2015 the EIHA agreed to a principle of a joint monitoring strategy for ambient noise. The approach for monitoring of underwater sound uses sound maps, generated from a combination of models and measurements. Modelling is the main method, validated by measurements.
2. **Monitoring and assessment of impulsive noise**; the International Council for the Exploration of the Sea (ICES) developed a database of impulsive noise activities for OSPAR in 2016. Several countries upload data to the register. A first assessment of distribution of impulsive sound sources in OSPAR Region II (greater North Sea) was presented in 2017. The assessment builds on specific types of sound generating activities reported to the ICES database and, when available, information on the intensity of the impulsive sources. The likelihood and consequences of the effects of impulsive sounds were not assessed (OSPAR, 2022a).
3. **Indicator specifications**; Indicators are the basis for OSPAR's assessments of the changing status of the marine environment and the intensity of pressures from human activities. Work is ongoing to develop an indicator specification for ambient sound sources through ICG-Noise (Royal Haskoning DHV, 2020). A common indicator for impulsive underwater noise was agreed upon in 2017, but yet there is no indicator for continuous anthropogenic noise (OSPAR, 2022b).

Importantly, underwater noise objectives have also been prepared for the North East Atlantic Environmental Strategy (NEAES) 2030, which is OSPAR's approach to contribute to the United Nations Sustainable Development Goals (UN SDGs) under Agenda 2030 (OSPAR, 2021). It includes twelve strategic objectives to protect the marine environment of which reducing anthropogenic underwater noise is one. Two actions to reach the objective on underwater noise are specified:

1. By 2025 OSPAR will agree a regional action plan setting out a series of national and collective actions and, as appropriate, OSPAR measures to reduce noise pollution.
2. By 2022 OSPAR will develop and implement a coordinated monitoring and modelling programme for continuous sound to support an assessment of anthropogenic underwater noise in the OSPAR maritime area.

The OSPAR Science Agenda from 2018 identified knowledge gaps on underwater noise, relating to impulsive as well as low frequency continuous noise. The identified gaps in the field of underwater noise aim mainly at indicator development. The issues identified and described are communicated with researchers and research funding institutions (OSPAR, 2019).

Incentives for underwater noise reduction

Initiatives that address ship owners and their efforts to reduce underwater noise include both voluntary actions without economic incentives, such as voluntary speed reduction in certain areas or ports, and economic incentives through port fee reductions. In a scan of incentive systems, we also found a scheme evaluating ship environmental performance that includes underwater noise as one of the performance parameters. We also describe notations for silent vessels in use by classification societies. These may serve as incentives to ship owners who wish to demonstrate environmental considerations.

Port initiatives

Visiting ships in ports pay fees for the port services. It has become increasingly common to use this fee for environmental differentiation by reducing port fees for ships that have a good environmental performance. The differentiation can be based on very specific emission categories or make use of existing incentive schemes. Examples of such schemes are Clean Shipping Index (CSI), Environmental Ship Index (ESI) and Green Marine. Though many ports show interest in environmental differentiation of fees, the Port of Vancouver stands out as the first port to target underwater noise.

Port of Vancouver has three levels of rates per gross registered tonne depending on environmental performance (base rate, bronze rate, silver rate and gold rate), see Table 6. To reach the best rate (the gold rate), vessels need to provide a record of silent notation of a classification society, currently either by ABS, Bureau Veritas, DNV, Korean Register, Lloyd's Register or RINA. These notations are described below. To reach the second-best rate (the silver rate), vessels need to have technologies to reduce underwater noise, such as a combination of complementary technologies (e.g., Nakashima GPX propeller and Nakashima Neighbour Duct or Nakashima GPX Propeller and Nakashima Composite Stator). A supplier certificate or owner/engineer attestation or similar document must be provided to reach this rate level. To reach the third-best rate (the bronze rate), propeller modifications are needed to reduce cavitation and improve wake flow. A supplier certificate or similar must be shown for the propeller modifications. Accepted modifications are Becker Mewis duct, Hyundai Pre Swirl Duct, Mitsui OSK Lines Propeller Boss Cap Fins (PBCF), MMG Energy saving cap, Nakashima Composite Stator, Nakashima ECOCap, Nakashima GPX Propeller, Nakashima Neighbor Duct, Nakashima Ultimate Rudder, Schneekluth duct and Wärtsilä EnergoProFin (Port of Vancouver port fees, 2022).

Table 6 Harbour due rates per gross registered tonne depending on UWN efforts (Port of Vancouver Port Fee Document, 2021-12-30 version).

Base rate	$0.099
Bronze rate	$0.076
Silver rate	$0.064
Gold rate	$0.052

The *Strait of Juan de Fuca voluntary inshore lateral displacement* was a voluntary program to evaluate operational methods for reducing underwater noise in a sensitive area near Vancouver. Tug operators were asked to not approach areas where southern resident killer whales feed, either by passing in a displacement zone or an outbound shipping lane. In the summary report for 2021 (Port of Vancouver, 2021), it was concluded that many tug operators moved away from the shipping lane, which is beneficial for the whales but also makes it more challenging to assess changes during the voluntary assessment time. The lateral displacement was successfully managed during 2021 with no dangerous occurrences or incidents recorded. There were no safety or operational concerns recorded with the vessels navigating in the inshore zone during the study period and the participation rate was 88 % in 2021.

The port of Vancouver also had a voluntary ship slowdown in Swiftsure Bank from the 1st of June until the 30th of November 2021. Large commercial ships were asked to lower their speed in the same way as in the Haro Strait and the participation rate was 81 % in 2021.

This study has also found other voluntary initiatives, where the participating shipping companies get publicity for entering in the programs, as for instance the Protecting Blue Whales and Blue

Skies program along the coast of California. From the 15th of May to the 15th of November 2021, companies were asked to reduce speeds to 10 knots or less in the Southern California Region and the San Francisco Bay area to lower emissions of carbon dioxide and noise. 483 ships from 16 global shipping companies participated in the vessel speed reduction program in 2020. Participating companies receive financial rewards, awards and recognition based on the percentage of total nautical miles travelled at 10 knots or less by each company's fleet of vessels. In 2020 five companies had travelled 75-100 % of the total nautical miles in the designated slowdown area at the speed of 10 knots or less, nine companies reached 50-74 % and one company travelled 25 – 50 % of the total nautical miles at the speed of 10 knots or less (APCD, 2022).

Green Marine is an environmental program, started in 2011 for the North American maritime industry, where ship owners (and others) can show and benchmark their environmental performance in 14 performance indicators. The indicator on underwater noise has five levels, where level 1 is to monitor regulations and level 5 is the highest level. Today the initial objective for the noise indicator covers marine mammals, but the scope may be expanded over time. Level 2 criteria include regular hull cleaning, propeller blade maintenance, and that the ship owner or operator should review a list of sensitive areas in Canadian and US waters to determine whether the ship owners' vessels transit through these areas. Another criterion on this level is to participate in voluntary traffic measures like a slow down or lateral displacement in specific zones. Level 3 includes criteria to collect whale sighting data in a logbook or other application and develop a Marine Mammal Management Plan (MMMP) to lower negative effects in sensitive marine areas. Level 4 includes using vessel quieting techniques on retrofits and new vessels. Besides this, ship owners need to either work with ports to estimate ship noise levels on at least one vessel or estimate ship noise levels of at least one vessel using a hydrophone or contribute to scientific research on underwater noise and estimate ship noise levels for at least one vessel. On level 5, the highest level, it is required to perform a detailed analysis of the vessel noise footprint of at least one ship using the standard ANSI/ASA S12.64-2009 or ISO 17208-1:2016. (These standards require measurement in water of more than 150 m depth, so are of limited interest in Swedish waters.) Besides this, the ship owner needs to either work with ports, or use a hydrophone, or contribute to scientific research on underwater noise to estimate ship noise levels for 15% of the vessels in their fleet (at least 3 vessels need to be mapped). To receive the Green Marine label, the ship owners annually measure their environmental performance through self-assessment and then become certified externally by an independent verifier accredited by Green Marine. The label can be used as marketing or benchmarking (Green Marine, 2022) and carriers and ships that score highly can be rewarded a discount on harbour fees (Port of Prince Rupert, 2022, Port of Vancouver, 2022, Port of Milwaukee, 2023 and Quebec Port Authority, 2023).

The Green Marine Europe program was launched in 2020 and currently includes ship owners. The program on noise is like the one described for Green Marine North America, but applicable to EU waters, and is revised during 2022 (Green Marine Europe, 2022).

Silent notations

A recent overview by Ainslie et al (2022) listed five classification societies that have implemented classification rules for underwater radiated noise (URN) and associated standards that describe how URN should be measured. Recently, Korean Register of Shipping published its rule for underwater noise, bringing the total number of classification societies with underwater noise rules to six:

- American Bureau of Shipping (ABS),

- Bureau Veritas (BV),
- Det Norske Veritas (DNV),
- Korean Register of Shipping (KR),
- Lloyd's Register (LR) and
- Registro Italiano Navale (RINA)

The project met with one of the classification societies that have developed a silent notation. From the meeting we received valuable information on measurement methodology, the costs for measurements and the number of vessels with a "silent notation" from the class society. The costs for performing measurements according to their guidelines are a few hundred thousand SEK and depend to some extent on location and setup. Besides this, the shipping company need to take their ship out of service for the length of the measurements, which adds further costs.

Figure 5 depicts the URN limits prescribed by the classification societies mentioned above. The KR limits are not shown; they are identical to the DNV ones. Each society has two different limits; one "transit" or "controlled", and one "quiet" or "advanced" which is lower than the transit/controlled one. The limit curves all have similar shapes and slopes but are not identical. There are also differences in how the societies express the limit curves; some use the so-called monopole source level, employing a detailed compensation for sound propagation, and some use the so-called radiated noise level.

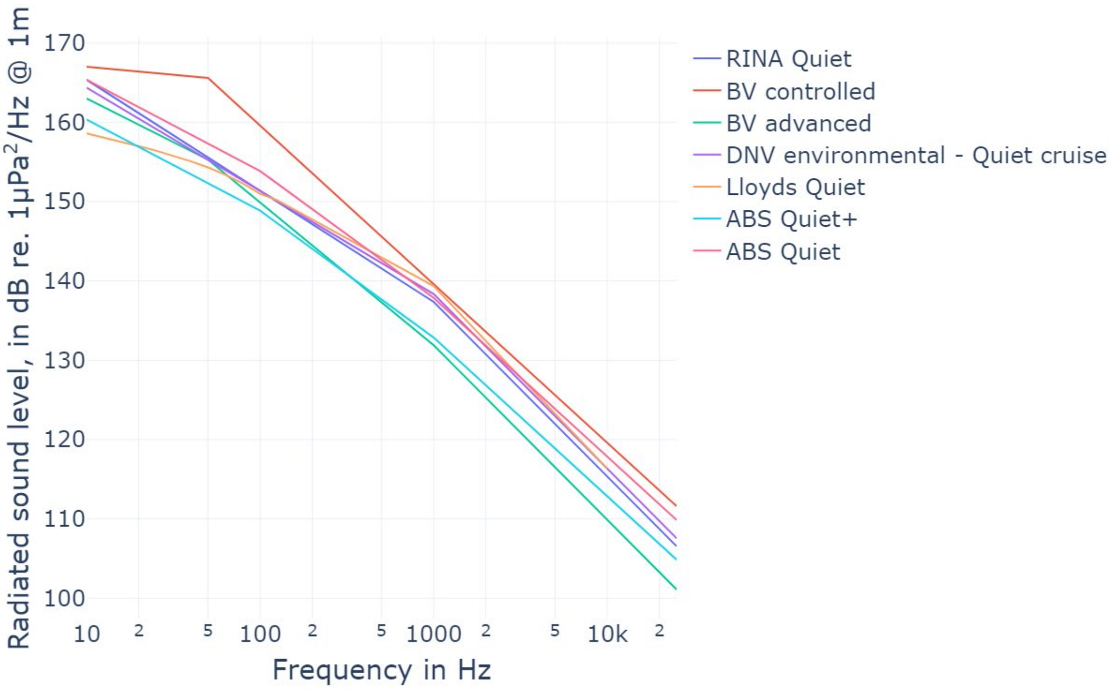


Figure 5. URN limit spectra for silent class notations.

The classification societies do not describe how they have arrived at their respective URN limits. However, the shapes of the limit curves are similar to typical ship URN spectra. This suggests that the curves may have been defined from such typical spectra rather than from the noise sensitivity of marine life. This may make them easier to relate to for people in the shipping sector and also may make them easier to attain. However, funding of underwater noise research projects is driven by a desire to reduce its environmental impact. The impact on a single animal of any one species depends on the sensitivity of the species to sounds of different frequencies, characteristics and durations. It also depends on behavioural state and individual characteristics. The audiogram, i.e., the lowest level of a tone at a given frequency that can be perceived, has often been used as an indicator of noise sensitivity. This is a coarse measure that neither considers the character of ship noise nor the behavioural relevance of sounds of different frequencies. However, considering the audiograms of different species as a first step to setting URN limits may result in limits that are more relevant to the environmental impact of ship noise. Typical fish and marine mammal audiograms show a mid-frequency region of high sensitivity and decreasing sensitivity towards the lower and higher edges of the animal's hearing range. The URN limits of the classification societies do not appear to display this shape.

Stakeholder analysis and network activities

Stakeholders from industry, research, and authorities all have different functions to fill in order to abate the environmental impacts of underwater noise. Progress is fast in many of the related research areas, and the policy framework for European waters has intensified in the last years.

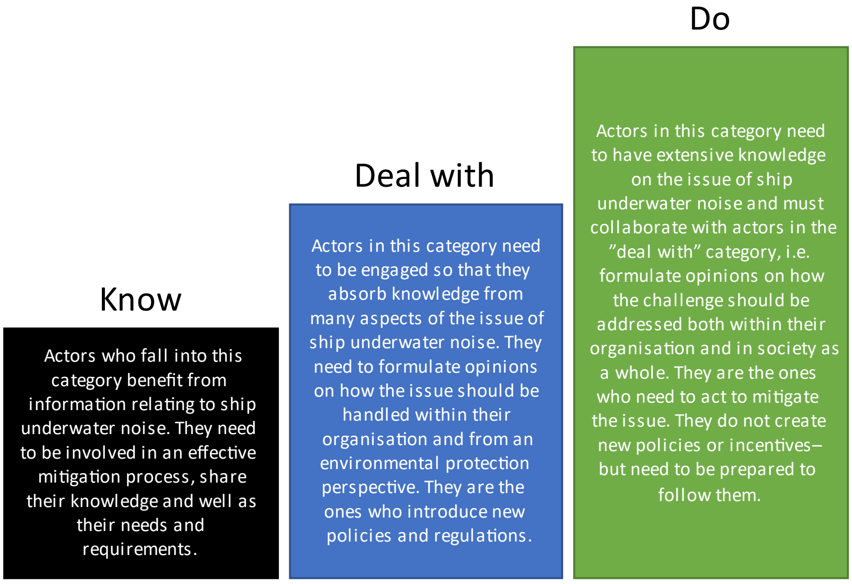
This study has initiated a network of relevant stakeholders that are important to efficiently mitigate underwater noise from a Swedish perspective. Discussions in a diverse and functioning network make it possible to focus future work on the most appropriate and relevant topics. It also increases the chances of successful implementations of abatement measures of different character.

The project has mapped current activities, general knowledge levels and relations to the issue of underwater noise among the identified stakeholders. A number of contacts have also been made internationally. Outreach activities have included two workshops, interviews with stakeholders, and bilateral meetings with key organisations and persons.

Analysis framework

Stakeholder analysis is growing in popularity and is currently used within different sciences as a tool to scan current and future organisational development. The general aim of this stakeholder analysis is to understand different actors' intentions, agendas, resources and interests. Our analysis identified key stakeholders to learn more about their activities and roles for the reduction of underwater noise. Specifically, our aim was to understand their roles in relation to expected future policy developments. The model we used was adopted from a method presented by the Gothenburg Region (The Gothenburg Region, 2021).

Initially, a brain storming activity gave a list of all stakeholders that potentially have interest in the analysed issue. Thereafter, the stakeholders were categorized into three different groups depending on the level of involvement of each respective stakeholder. The groups were called "*Know*", "*Deal with*" or "*Do*", see Figure 6.



Know

Actors who fall into this category benefit from information relating to ship underwater noise. They need to be involved in an effective mitigation process, share their knowledge and well as their needs and requirements.

Deal with

Actors in this category need to be engaged so that they absorb knowledge from many aspects of the issue of ship underwater noise. They need to formulate opinions on how the issue should be handled within their organisation and from an environmental protection perspective. They are the ones who introduce new policies and regulations.

Do

Actors in this category need to have extensive knowledge on the issue of ship underwater noise and must collaborate with actors in the ”deal with” category, i.e. formulate opinions on how the challenge should be addressed both within their organisation and in society as a whole. They are the ones who need to act to mitigate the issue. They do not create new policies or incentives– but need to be prepared to follow them.

Figure 6. Method of stakeholder categorisation.

The categorisation had two primary reasons:

- to identify important stakeholders to interview and target in other outreach activities
- to initiate a network that covers stakeholders from all categories.

The actors in the category ”*Know*” need to be well informed of one or several aspects of ship underwater noise, its environmental impact and related possible future incentives and policies. Their main task in a future project would be to have good and updated knowledge on the issue, and tasks related to communication on an overall level. This actor category includes for example research institutes and technology developers. Since there are still many knowledge gaps in relation to the issue of ship underwater noise it is important to include stakeholders in the category “*Know*” in the network.

The actors in the category “*Deal with*” need to gather knowledge from several aspects of the issue of ship underwater noise. They also need to understand the roles of other stakeholders. From a broad knowledge base, they formulate opinions on how to address the issue within their organisation in order to protect the environment. This actor category includes for example policy makers.

The actors in category ”*Do*” need both good knowledge and the ability to formulate opinions (compare with categories ”*Know*” and ”*Deal with*”) and, in addition, they need to act in order to mitigate the emissions of underwater noise. This category includes stakeholders that need to be prepared to change according to coming policies and incentives.

A number of stakeholders from the categories “*Deal with*” and “*Do*” were interviewed in order to map their interests, knowledge focus, and intentions relating to the question of underwater noise. The interviews were semi-structured, allowing the interviewees to speak freely to a large extent, and aimed at gathering valuable information for future work.

Following the interviews, a workshop was organised. The primary purpose of the first workshop was to present recent information on ship underwater noise and upcoming policies and to establish a network for collaboration around the issue of ship underwater noise. Knowledge gaps and needs for further work were identified. The network established during the workshop also met in January 2023 to discuss fairway design for reduced noise transmission and incentive schemes for underwater noise reduction. The workshops gave important input to continued research and innovation projects.

Categorization of stakeholders

In Figure 7, the assignment of stakeholders into the categories "*Know*", "*Deal with*", and "*Do*" is presented. Some of these stakeholders were selected for interviews. The purpose of the interviews was to map the interviewees' current knowledge about the environmental impact of underwater noise, the technical needs, needs to participate in a network with UWN focus and if the upcoming changes in EU legislation have an implication on the interviewee or the organisation that they represent.

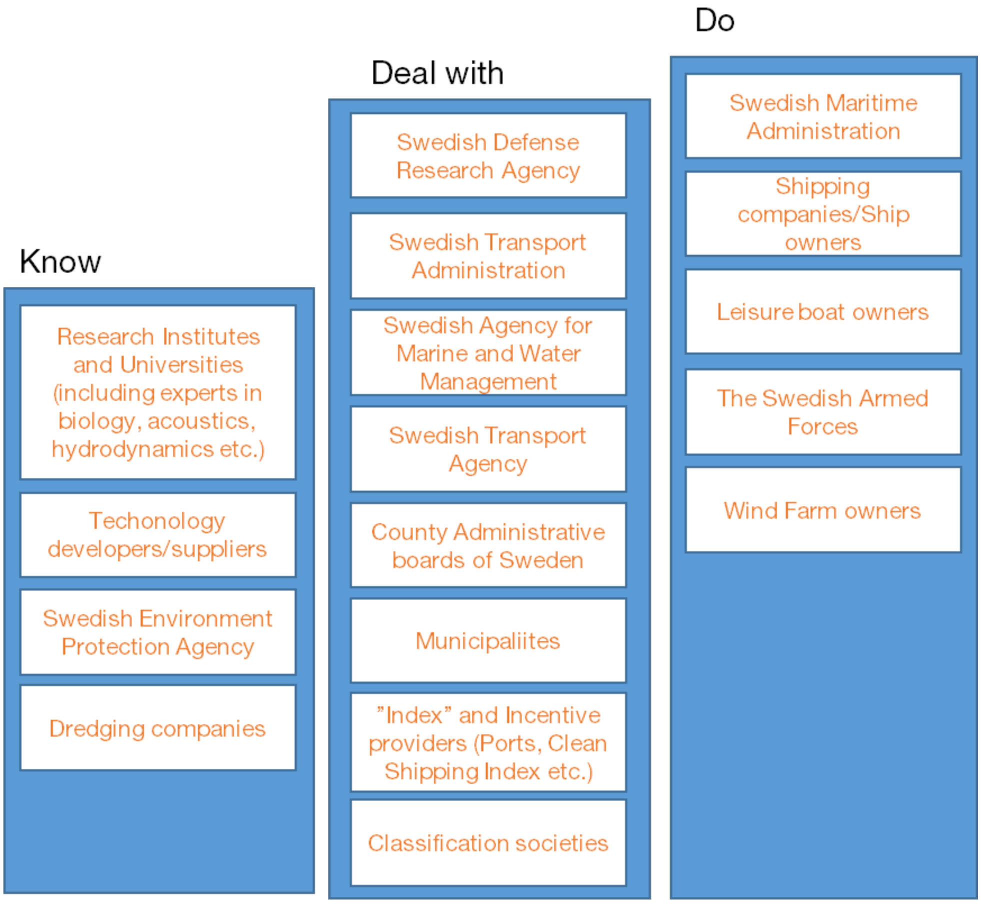


Figure 7. Stakeholder categorisation.

Category “*Do*” stakeholders

In the category “*Do*” we find organisations that own ships and the Swedish Maritime Administration, in its role as a fairway keeper. The outreach activities have not addressed stakeholders outside the shipping sector due to the clear focus on underwater noise from ships in coming environmental quality standards.

Many Swedish shipping companies are organised in the Swedish Shipowners’ Association (*Svensk Sjöfart)*. In the autumn of 2022, the organisation has 54 members. The purpose of the organisation is to protect the interests of the Swedish shipping industry and to ensure that there is a level playing field internationally. The organisation participates in meetings in the IMO committees on Ship Design and Construction (SDC) and the Marine Environment Protection Committee (MEPC) as part of the Swedish delegation. Both committees are important in relation to the underwater noise issue.

Separate interviews were held with a representative for the Swedish Shipowners’ Association and a representative from the ship owner company within the Swedish Transport Administration. In addition to the interviews, a number of shipowners participated in the two workshops organised by the project. The members of the Swedish Shipowners’ Association have many different types of ships like tankers, Ro-Ro ships, Ro-Pax ships, car carriers and general cargo vessels in their fleets. The ship owner company within the Swedish Transport Administration operates car ferries, mainly in coastal areas.

Based on our outreach activities we can formulate a few conclusions relating to the interests of shipowners and their thoughts on reduced emissions of underwater noise:

- Shipping companies are not a homogenous group, and they have different drivers and challenges. Some companies conclude based on anecdotes of marine life observed from ships that the problem has gained unproportional attention as an environmental problem, while others have spent money on their newly built ships to assure they have the latest sound reducing technologies on board.
- There is a consensus that too little is known about the issue of underwater noise, and in general the companies prioritise environmental issues that are more mature from the perspectives of existing regulations, measurement methods, and environmental effects. The industry is presently very involved in decarbonization matters and finding fuel alternatives for the future.
- There is a rather general consensus among shipowners that knowledge gaps should be filled before implementation of noise reduction measures and incentives is initiated. Important knowledge gaps suggested by the industry representatives relate to noise measurement methods, biological effects, and technological improvements. The representative from the Swedish Shipowners’ Association further suggests awaiting the adoption of the updated IMO guidelines and to align the different types of silent notations.
- The coming EU regulations giving geographically dependent threshold levels were, in general, not well known within the industry.
- Many shipowners were positive to participate in studies on underwater noise, although there are economic limits that makes it difficult to change normal operational routines for the purpose of a research study.

The Swedish Maritime Administration (SMA; *Sjöfartsverket*) is important in the category “*Do*” due to its role as fairway keeper. SMA‘s work in determining the establishment of new, and maintenance of existing, fairways is presented in more detail in the previous section, see page 36.

The responsibilities of SMA when European regulations on threshold values have come into effect is not clear.

Category "*Deal with*" stakeholders

Many stakeholders in the "*Deal with*" category are public actors such as governmental agencies. Representatives from the Swedish Agency for Marine and Water Management (SwAM; *Havs- och Vattenmyndigheten*), the Swedish Transport Agency (STA; *Transportstyrelsen*), and the Swedish Defense Research Agency (FOI; *Totalförsvarets forskningsinstitut*) were interviewed with focus on the upcoming changes in EU legislation as well coming updates to IMO guidelines on ship underwater noise. The Swedish Transport Administration (*Trafikverket*) was contacted for an interview, but referred us to their ship owner branch, since they are not focussing on underwater noise in any other parts of their organisation. Classification Societies are another important stakeholder group within this category. A ship classification society or organisation establishes and maintains technical standards for the construction and operation of ships. Currently twelve class societies are members of the International Association of Classification Societies (IACS). As mentioned earlier in the section "Silent notations" there are six classification societies that have implemented classification rules for underwater radiated noise. Each society has different limits and there is ongoing work in both IACS and ISO to find a common standard for silent notations. One Classification Society was contacted within this project. Interviews with Ports, County Administrative Boards and Municipalities were not prioritised in this project.

The SwAM represents Sweden in the European efforts in line with the Marine Strategy Framework Directive and the establishment of environmental quality standards stemming from the Directive. SwAM has assigned the FOI to assist in development of models and maps to evaluate where good environmental status is achieved in Swedish waters. At the time of publication, it was not clear how EU legislation will be implemented regionally. SwAM holds meetings together with other agencies to collaborate on the UWN issue.

STA represents Sweden in the IMO meetings regarding both fairways and environmental protection. STA formulates the standpoints of the Swedish state in the IMO in collaborations with other organisations, mainly government authorities. At the time of publication, the IMO is conducting a review of the non-mandatory technical IMO guidelines for underwater noise that were approved in 2014 (MSC.1/Circ.833). The new guidelines are, like previous versions, non-mandatory and will probably be approved in 2023. It is likely that slow steaming will be one of the suggested measures to lower emissions of underwater noise together with different types of ship specific measures.

FOI is a research institute dealing with defence and security issues. It also performs research connected to underwater noise. FOI is a government agency under the Ministry of Defence and performs assignments from the Swedish Armed Forces as well as other government authorities, municipalities and companies. As some of the assignments are defence-focused even though they are connected to an environmental problem such as underwater noise, the agency is not able to share results from these studies. FOI has a broad knowledge in underwater noise and its implications and is a key stakeholder within the area of underwater noise.

In addition to the interviews and meetings, there was representation from both STA and FOI at the workshops. Based on the outreach activities we conclude that that the responsibilities of SwAM and STA are rather well-defined regarding regulations from the EU and the IMO, respectively. The role of FOI role appears to be based on their knowledge of underwater noise, which in turn is probably motivates their cooperation with SwAM. The representatives from different agencies and authorities that were interviewed had different levels of maturity when it comes to knowledge on the impacts of UWN on the environment and upcoming regulations and guidelines, indicating an importance to connect the right representatives in a potential future network. In general though, the organisations are well informed on the issue of ship underwater noise and could possibly have a more pronounced role in communicating with the actors in the category "*Do*" and "*Know*".

Category "*Know*" stakeholders

In the "*Know*" category we find research institutes and universities with experts in marine biology, underwater acoustics, hydrodynamics etc. In addition, there are several Swedish companies and organisations with technical or maritime knowledge relevant for mitigation of underwater noise. Some are specialised in ship and propeller design or operational efficiency and others more focused on technology aimed at lowering emissions of underwater noise. If mitigating policies or incentives for underwater noise from shipping were put in place, it can be assumed that these organisations would benefit as their services would be more sought after.

Technology providers and representatives from several academic fields were present at the workshops and a few were approached for individual meetings.

The technical companies or consultants that participated in the outreach activities point out that

- almost every ship is unique in its' design and therefore has an underwater noise signature unique to that specific ship
- it is important to know what threshold level of emitted noise results in negative effects on the marine environment and what dose gives a certain response in the animals

The researchers are aware of the complexity of the issue.

The Swedish EPA (*Naturvårdsverket*) and dredging companies were not prioritised for interviews or contacted for outreach activities in this project.

International contacts

As mentioned earlier, IMO has developed non-mandatory guidelines for underwater noise. These were approved in 2014 and are currently under review. An IMO project called GloNoise aims to engage and assist developing countries to build capacity, raise awareness and promote international policy dialogue on mitigation of underwater noise from shipping. The project started in June 2022 and ends in December 2024 (IMO 2022). During an interview with GloNoise staff it was explained that the aim of the project is also to organise a number of awareness-raising workshops to reach out with the current scientific knowledge on the issue and discuss measures possible to developing countries. This may assist in creating mandatory legislation on underwater noise from ships on an international level in the maritime industry.

The World Maritime University (WMU) mission is to be the world centre in postgraduate maritime and oceans education, professional training and research, and is located in Malmö in the south of Sweden. The project interviewed an associate researcher who has worked on maritime research regarding underwater noise for several years. The interviewee sees three possible ways forward in order to be able to lower the underwater noise from shipping. One suggested way is to go through the IMO and create legally binding levels on UWN emission that the shipping companies must follow – and do this together with the industry. The second suggested way forward is to further connect UWN to decarbonization, thus promoting engagement in the underwater noise issue. The third suggested way is to use the polluter pays principle by measuring ships' UWN signatures – like in the Vancouver region – and connect to noise levies. Increased UWN data sharing is another area where more work is needed. If UWN data could be shared to a greater extent, the research community would benefit and be able to reach better conclusions jointly. This would be a benefit for the whole shipping industry. Keeping a holistic perspective on the environmental impact of shipping could help raise awareness for UWN as an environmental problem in the oceans. The interviewee agreed that a way forward here could be to include underwater noise in an environmental index for shipping.

Fairway design for reduced noise transmission

This chapter describes measurements of the effect of fairway design on underwater noise transmission. The goal of these investigations is to attempt to verify the predicted effects of fairway design on noise transmission.

Due to a the availably of different fairway characteristics within a small area and a relative ease of obtaining a permit for underwater noise measurement, it was decided to measure in Lake Mälaren, close to the port of Västerås. Positions for noise measurements in Lake Mälaren were set following detailed discussions with the pilots operating in the lake, see Table 7. The pilots suggested a shallow area and a turn, where noise on board often increases dramatically during passage. Acoustic autonomous sensors were placed near these two fairway features, with one sensor at the feature, and one at a similar position nearby as a reference. The idea is to compare the noise radiated from a ship at the feature with the noise radiated at the nearby reference site. The noise radiated from ships varies strongly not only between different ships but also when the same ship is operated under different loading conditions. Therefore, we will use the difference in radiated noise from single ships passing by both the feature-sensor and the reference-sensor as our quantitative metric for the effects of the fairway design.

Table 7. Positions for Lake Mälaren noise measurements.

Name	Description	WGS 84 Lat	WGS 84 Long	Depth (m)
SoundTrap 1	Shallow area reference	59.5479	16.5764	10
SoundTrap 2	Shallow area feature	59.5366	16.5771	7.5
SoundTrap 3	Sharp turn spare	59.5309	16.6244	7.5
Sylence 1	Sharp turn reference	59.5287	16.6071	10
Sylence 2	Sharp turn feature	59.5288	16.5893	10

Equipment and rigs

Two different types of autonomous recorders were available: three units of SoundTrap 300 by Ocean Instruments and two units of Sylence-LP by RTSYS. SoundTraps are set to record at 96 kHz at 16 bits resolution. Gain is set to high, meaning that they can record sound up to 172 dB re 1 μPa. We should not reach those levels and will need the high gain to resolve small details in the noise recordings. The Sylence-LP units are set to record at 128 kHz at 24 bits resolution, using HTI-92-WB hydrophones. All units are programmed to record continuously during the entire deployment time.

Each recorder was mounded in a rig with a rope, a bottom weight, and some floats. The hydrophones were 2 m above the 20 kg weight, and 2 m below a float with 4 kg of buoyancy.

Additionally, each rig had a larger surface buoy to avoid collisions. This means that the hydrophones have the same distance from the bottom at each site, but different distances from the surface. Figure 8 shows the rigs after retrieval.

Figure 8. The rigs deployed in lake Mälaren after retrieval.

The two Sylence-LP units were used to monitor the sharp turn feature, while two SoundTraps were used for the shallow area. The third SoundTrap was deployed as a backup reference for the sharp turn due to uncertainties in where the main traffic flow was. This unit was not utilized for the final comparisons.

Ship traffic and passage selection

The recorders were deployed on Tuesday the 20th of September and retrieved on Tuesday the 25th of October, for a total duration of five weeks. During this time, a total of 189 unique ships (with an AIS-transponder) visited the area, 56 of which were commercial ships registered with the IMO. The movement of these commercial ships is shown in Figure 9, along with the positions of the sensors.

The ships passed the sensors at different distances and speeds. A summary of the statistics of the closest passage distance and the passage speed is shown in Table 8. The typical speeds are quite low, around 11 knots, which was confirmed to be the typical operating speed for many of the ships. The distances are overall reasonably close, with a total spread of a few hundred meters.

Table 8: Summary of passage distances and speeds.

	Median distance	Distance 5th percentile	Distance 95th percentile	Median speed	Speed 5th percentile	Speed 95th percentile
SoundTrap 1	201 m	132 m	265 m	11.3 kts	8.4 kts	13.1 kts
SoundTrap 2	137 m	98 m	214 m	10.6 kts	8.5 kts	12.3 kts
SoundTrap 3	183 m	80 m	352 m	10.9 kts	8.2 kts	12.7 kts
Sylence 1	136 m	44 m	193 m	10.8 kts	8.0 kts	12.7 kts
Sylence 2	112 m	70 m	168 m	10.5 kts	8.2 kts	12.2 kts

Figure 9: Overview of the measurement area. Sensor positions are marked with triangles. Other black marks are positions of commercial ships.

Passages were extracted from the AIS-data by selecting the segments when the ship was within a 400 m range of a manually positioned position in the middle of the fairway. A passage was considered for analysis only if there were no other ships reported within 2 km of the sensor. For the passages in the shallow area, we also removed passages which had more than 1 knot speed difference between the two sensors. This criterion was not used at the sharp turn, since any necessary reductions in speed in the turn is in a way part of the fairway design and should be represented in the data. Considering these selection criteria, a total of 83 passages were recorded at the shallow feature, and a total of 78 passages at the sharp turn.

Acoustic data processing

All five autonomous hydrophones record continuous time-streams of sound pressure data, which need to be processed to calculate quantities from which meaningful conclusions can be made. A segment of acoustic data is selected for each ship passage. This pressure signal is reduced to time-varying third-octave band levels with a 1 second time-resolution (computed from a spectrogram with 2 second Hann windows and 50% overlap).

Over the course of the five weeks the clocks of a few sensors had a significant drift. This resulted in that the timestamps in the recorded data were not accurate, and the time-segment of acoustic data could not be perfectly centered at the ship passage. Therefore, we aligned time for the maximum received sound pressure level with the actual time when the ship was closest to the sensor. This was followed by a manual inspection of all passage data to confirm that the alignment succeeds reasonably well.

Since the ships pass by the sensors at very different distances, the noise received by the sensors must be compensated for the different propagation distances. Otherwise, the main difference between the noise from the same ship at the feature-sensor and at the reference-sensor will be caused by differences in the passage distance. This was done with a simple $20 \log r$ rule, compensating the received levels to so called radiated levels.

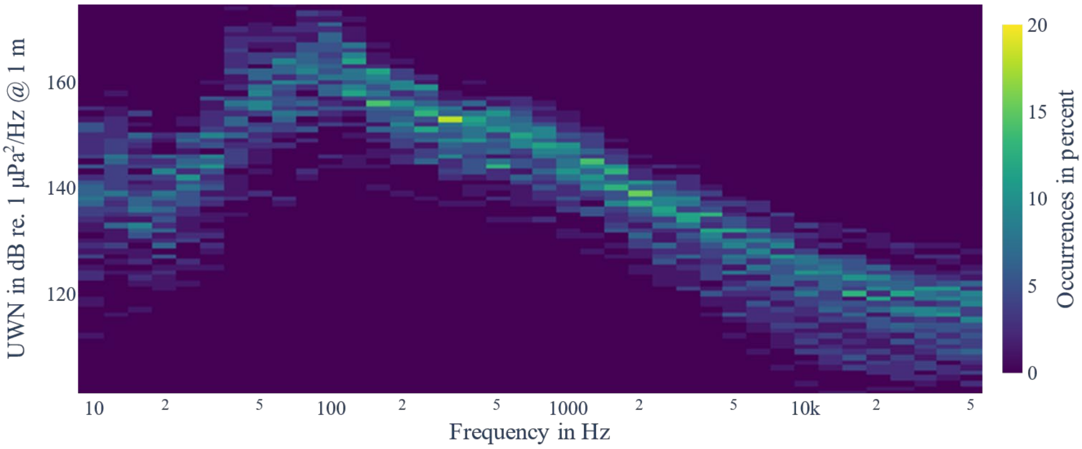


Figure 10 Underwater radiated noise levels measured at the sharp turn. The colours show the distribution of the passages.

The final analysis is done on a smaller segment of the time-varying third-octave band levels, corresponding to when the ship was within 400 m of the point in the fairway closest to the sensor. The noise levels for each passage were averaged over this selected time segment, to produce a representative third-octave band spectrum for each time a ship passed by a sensor. The distribution of these levels for all passages by the sharp turn (sensor "Sylence 2") is shown in Figure 10. Each time a ship passes by the fairway feature, two third-octave band spectrums are generated, one from the feature-sensor and one from the reference-sensor. The difference between these two spectra is used as a single sample in the investigation of that fairway feature.

Results from fairway shallow area

The differences between the measured noise levels at the shallow area and the nearby reference sensor are presented in Figure 11 through Figure 14. The data is presented as a histogram of the level differences in each third-octave band. This gives information about what level differences occur often in the data, offering a quick way to judge both the trends and the spread in the values. The convention used here is that a positive difference indicates a higher noise at the fairway feature, and vice versa.

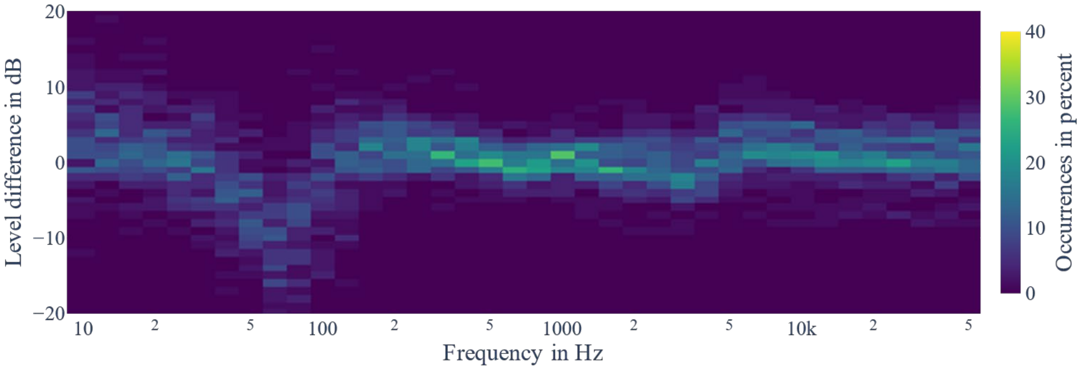


Figure 11: Distribution of noise level differences at the shallow feature, for all included ships.

As seen in Figure 11, in a large frequency range there is no notable difference in noise level – the most passages have a small or no difference between the sites. The spread of the differences in the middle frequency range (200 Hz to 2 kHz) is around 8 dB, while at high frequencies (>5 kHz) and low frequencies (<50 Hz) the spread of the differences is larger, around 15 dB. In the frequency bands around 40 Hz to 100 Hz, the noise level is smaller in the shallow area than in the nearby reference position. This is a clear trend shared amongst most ship passages. One likely explanation for this dip is that the normal mode cutoff frequency is higher for the shallow area than for the deep area (Forrest et al, 1993).

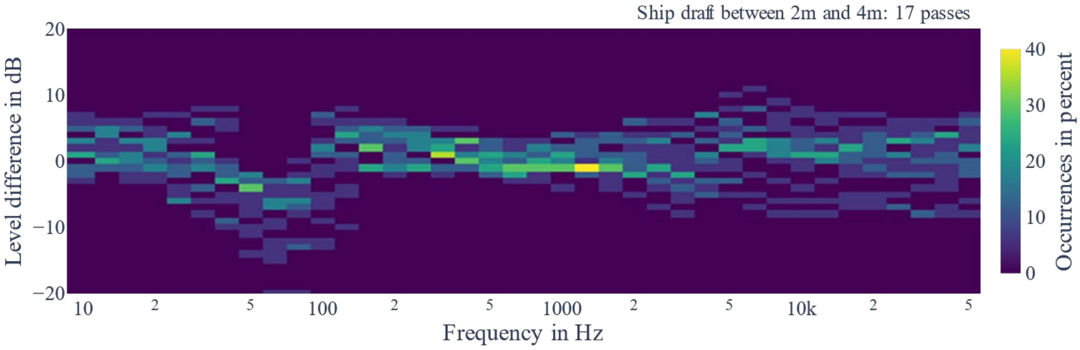


Figure 12: Distribution of noise level differences at the shallow feature, for ships with a small draft.

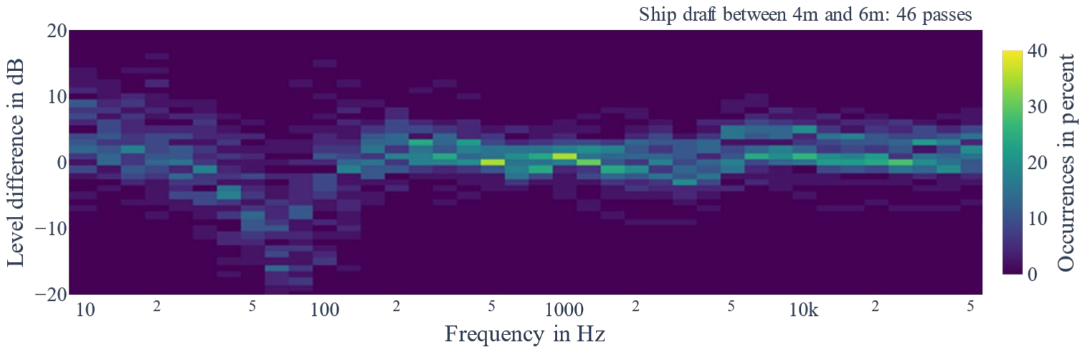


Figure 13: Distribution of noise level differences at the shallow feature, for ships with a medium draft.

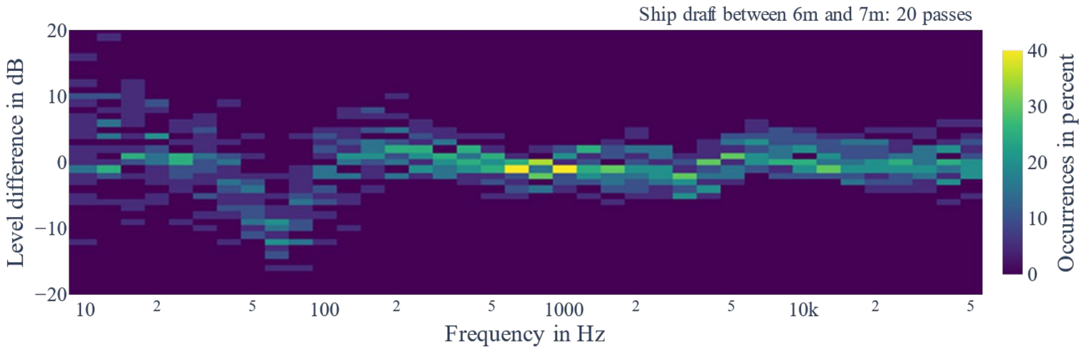


Figure 14: Distribution of noise level differences at the shallow feature, for ships with a large draft.

Since the hypothesis is that the shallow water depth has an influence on the ships themselves, the data was divided in three groups based on the reported draft of the ship during passage, with roughly 25% of the ships in the “small draft” category, see Figure 12, 25% in the “large draft” category, see Figure 14, and the remaining ships with reported draft in Figure 13. Unfortunately, there seems to be no significant effect that can be observed by grouping the data based on reported draft. Similar investigations were done grouping the data on ship type, length, speed over ground, engine power, total displacement, design draft, draft relative to design draft, passage direction, and passage distance. None of these additional groupings indicate systematic relations in the data.

Results from fairway turn

In Figure 15, the level differences from all the analyzed passages at the fairway turn are presented the same way as the data from the shallow area. Similar to the results from the shallow area, the spread of the data is larger at high and low frequencies when compared to the middle frequency range. There is a small tendency of increased levels around 1 kHz and decreased levels around 200 Hz.

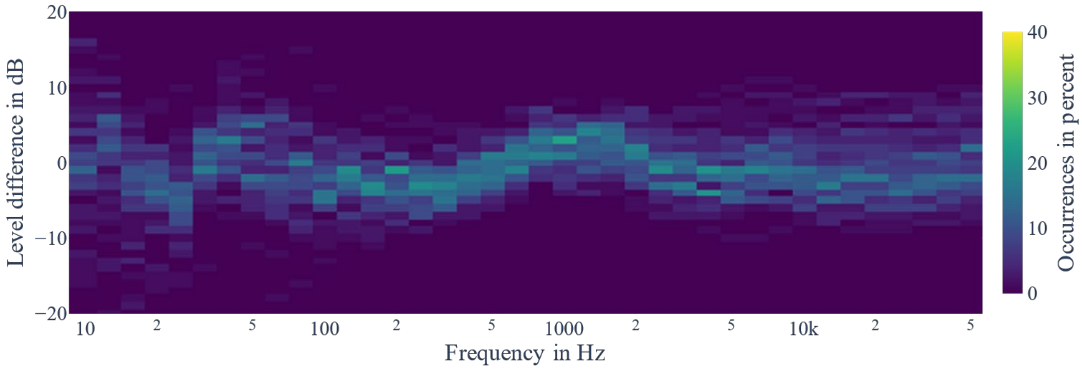


Figure 15: Distribution of noise level differences at the turn feature, for all included ships.

If these tendencies are related to the turning of the ship, e.g. rudder angle, it should appear differently depending on the turning radius of the ship track in the fairway turn. However, grouping the data in three groups for small radius (Figure 16), medium radius (Figure 17), and large radius (Figure 18) do not show any strong indications that this is the case.

This data was also grouped on the same parameters as for the shallow area, with none of them indicating a systematic relation to the noise level differences.

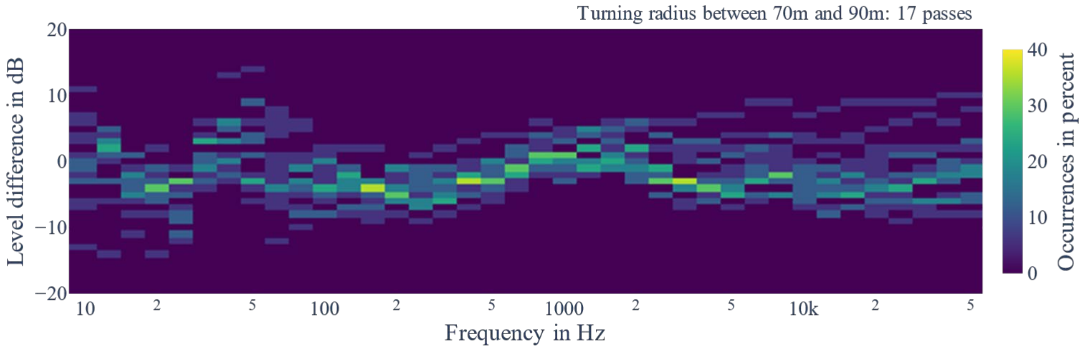


Figure 16: Distribution of noise level differences at the turn feature, small turning radius.

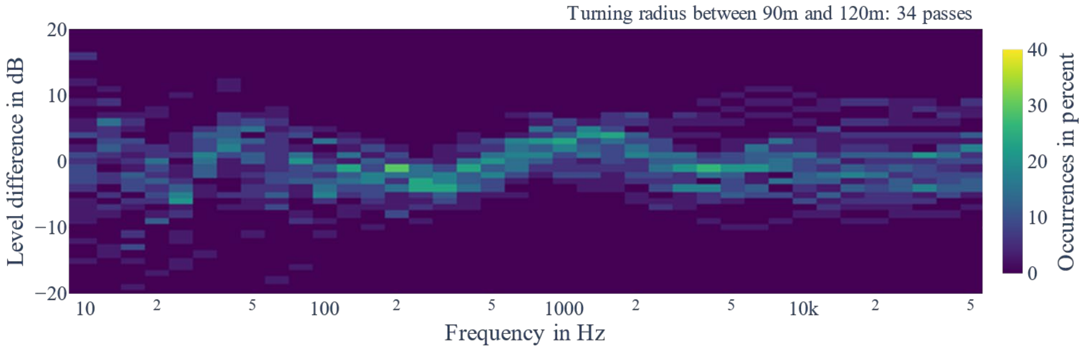


Figure 17: Distribution of noise level differences at the turn feature, medium turning radius.

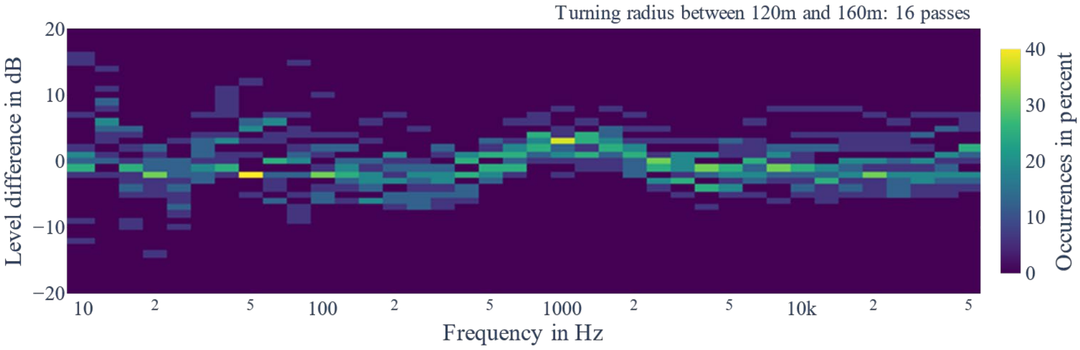


Figure 18: Distribution of noise level differences at the turn feature, large turning radius.

Conclusions from measurements in Lake Mälaren

The measurements in Mälaren were performed with constraints set by the project scope and budget. Considering these factors, the experiment was designed with the hypothesis that the effect that the surrounding environment has on a ship as a source of underwater noise are rather large. The data show that the effects are much smaller than anticipated, such that they are difficult to separate from other effects that influence the measurements. As a result, it is not possible to conclude that the observed effects are caused by any one particular source.

The end goal of an improved fairway design for underwater noise is to reduce noise levels in the environment. The noise at a certain point in the environment is a combination of how much noise is generated by a ship, how efficiently that noise propagates to the receiving position, and how much traffic occurs in the fairway. Designing a fairway to reduce environmental levels without reducing the overall traffic means that there are two avenues to investigate: reducing the noise generated by ships or reducing the transmission of that noise to the environment. Both these options are very complicated topics due to the interaction between the environment and each individual ship. All ships are not affected the same way by the environment, and the propagation of the noise from a ship to the environment is not identical for every ship. This means that any investigation must include many ships, otherwise there is a risk that the results are only valid for the few ships studied and mitigations designed based on such results might not have the intended effect. At the same time, dedicated test ships can travel in a controlled manner and share onboard operation data such as power and propeller speed, contributing to a greater control of the experimental conditions.

For future studies, we identify three types of investigations that target different aspects of how noise from fairways can be reduced.

To quantify the effect of the fairway design on the ship as a noise source, an investigation should focus on reducing the influence of the noise propagation in the measured data. This is typically done by measuring or modelling the propagation loss and compensating for this loss in the measured data. In the ideal case this would reduce the uncertainty of where an observed effect comes from. However, propagation loss estimation is a difficult topic, which reintroduces some uncertainty in the results.

A second type of investigation focuses on the propagation of the noise from ships to the environment. This could entail measurements and modelling of propagation loss on a larger scale, by investigating how the local topography of the fairway influences the noise levels. It is important to study the effects of fairway topography both locally around the fairway and further away, to ensure that the noise problem is actually reduced, not just moved to a different location.

Since the interactions between noise propagation, noise generation, and the surrounding environment are difficult to predict, it is also important to study the combined effect directly. This approach was followed in our study. Such an experiment should measure the noise levels in the broader surrounding of a fairway feature instead of at a single point. This would enable the quantification of the overall noise levels in an area, which reduces the impact of propagation loss uncertainties. Ideally, one would implement one or several test treatments along a fairway and measure the noise received from one or several passing ships. Alternatively, measuring before and after a fairway redesign may offer insight into how the design affects the spread of noise. However, this would need to be timed to the construction. No suitable projects that met the timing requirements of this short project were found.

With more knowledge on the environmental impact of ship underwater noise, changing the traffic flow may be found to be a viable way to reduce the impact. This would require a comprehensive knowledge of what effects are important to avoid and what traits should be enhanced. As an example, it could be the case that it is important to have certain quiet regions, or that it is more important to have quiet times, or that the noise should avoid too high levels in either time or space. Without knowledge of what the harmful effects are, it is not possible to use mitigation metrics that are based on changing the distribution of noise.

A financial incentive for underwater noise reduction in Swedish waters

When a ship arrives at a port, the ship owner is typically charged a port fee. In Sweden and Finland, ship owners are also levied with fairway dues. In Sweden, these dues are payable to the Swedish Maritime Administration (*Sjöfartsverket*). The dues are differentiated based on the ship's environmental performance, which provides a financial incentive for ship owners to improve their environmental performance. Ports are free to structure their fees as they see fit and may choose to implement financial incentives for improved environmental performance (see page 45).

Ship owners who have registered and verified their ships' environmental performance within the Clean Shipping Index (CSI) system are eligible for a rebate on the Swedish national fairway dues. In the beginning of 2023, Clean Shipping Index evaluates a ship's environmental performance in categories (Clean Shipping Index, 2022). These are

- Carbon dioxide emissions
- Nitrous oxides emissions
- Sulphur oxides and particulate matter emissions
- Use of chemicals
- Water and waste management

CSI scores the environmental performance on a scale from 0 to 150. Each category is assigned a maximum of 30 points (Figure 19). A ship owner wishing to certify a ship answers a questionnaire to determine the environmental performance. The CSI is structured in such a way that emission measurements are not required, placing emphasis on the low financial effort required of the ship owner to obtain the certification. However, a validation by a third party is sometimes required to obtain specific economic incentives, e.g., by the Swedish Maritime Administration.

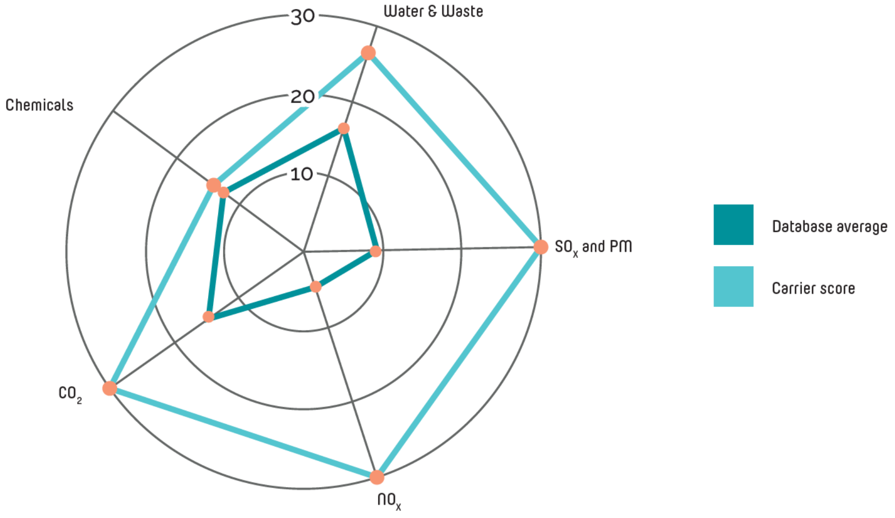


Figure 19. Category scoring by Clean Shipping Index.

Introducing an underwater noise category in the Clean Shipping Index would be a way of implementing a financial incentive for the reduction of ship underwater noise. It is therefore of interest to investigate how this could be done. Note that there are several other systems for evaluating a ship's environmental performance, e.g. the Environmental Ship Index (ESI) and Green Marine. Each index has its own way of operating and scoring. While the focus in this report is on Clean Shipping Index, we will also attempt to draw general conclusions on introducing ship underwater noise into an environmental scoring system for ships.

Basing an incentive on dedicated measurement[1] of the underwater radiated noise of a ship is not appropriate. First, Clean Shipping Index does not require measurement of any other environmental category. Second, performing an accurate measurement of ship underwater radiated noise requires specialised equipment and skills and is costly. There are few actors who offer this service to ship owners. However, if the revised IMO guidelines on underwater noise recommend dedicated ship noise measurements, this may change, and the costs may also decrease.

This study has evaluated six different ways of developing an environmental score for the underwater noise radiated by a ship. These are

- Predicting the radiated noise of a ship based on its characteristics
- Rewarding speed reductions
- Rewarding technical measures for noise mitigation
- Basing the score on silent notations from classification societies
- Performing a noise investigation (without direct measurement)
- Establishing bespoke measurement stations that measure the ship underwater noise with sufficient accuracy to establish a score

We will now discuss each of these alternatives in turn.

Predicting the radiated noise of a ship

The section "ship noise prediction" discusses different models that can be employed to predict the radiated underwater noise from a ship, see page 15. The conclusion is that these models are currently not accurate enough to use for incentives. They can produce reasonably correct averages across a large fleet of ships of different types and characteristics and are useful for noise mapping. They can also inform operative measures such as speed reduction by predicting the effect of a potential speed reduction, as long as the intended speed reduction is not outside the range of the data that was used to develop the model(s). However, the predictions for individual vessels may be quite inaccurate. Moreover, the models do not consider the propeller or hull design or any technical measures that may affect the underwater radiated noise performance. As such, they will not stimulate mitigation of underwater radiated noise.

Rewarding speed reductions

An incentive may reward vessel speed reductions. Large scale trials in Vancouver and off the coast of California (see page 35) found that on average, speed reductions led to underwater noise reductions. A vessel's average or peak speed when travelling through an area may be determined from AIS data without the need for external verification. An incentive could then be based on giving rebates to those ships that have performed a speed reduction. Speed reductions are generally also beneficial for fuel efficiency and carbon footprint, thus may yield multiple benefits.

---

[1] See the section on dedicated measurements on page 14 and the section on silent notations on page 47.

It would not be sufficient to apply the same speed limit for all ship types, as some ships are designed to travel at slower speeds and may otherwise be granted the rebate despite not having changed their operations.

It is not certain that a speed reduction will lead to a noise reduction; for some ships, there may be no noise reduction or even an increase in radiated noise levels. This depends on the ship's design and propeller. Ships are typically designed to operate at one or a few speeds, e.g., the "cruise" speed. Lowering the speed slightly from this cruise speed puts the ship outside its designed mode of operation which may result in noise and efficiency drawbacks.

A large enough speed reduction that the speed drops below the cavitation inception speed (CIS) will make the propeller significantly quieter than what it is above the CIS, which will probably have a large positive effect on the overall levels of underwater radiated noise. However, such large speed reductions may not be feasible; transit times will increase significantly which will affect the financial situation of ship owners. During interviews and workshops, several ship owners have expressed that significant speed reductions are only feasible in small areas, so that the average transit times are not greatly affected.

In Swedish and European waters, controllable pitch propellers (CPP) are common. This is not the case in North American waters. It is more difficult to describe the noise radiation of a CPP propeller across its different operation modes because not only the speed but also the pitch of the propeller blades is variable. The combination of speed and pitch is known as the combinator curve. This curve is typically optimized for fuel efficiency, and it is not clear how levels of radiated noise are affected by speed reductions for ships equipped with CPP propellers.

Rewarding technical measures for noise mitigation

Technical measures for noise mitigation are described on page 32. The list of technical noise mitigation measures is long, but there are doubts about their efficiency in operation. The port of Vancouver rewards a number of such measures with port fee rebates as described on page 45. It would be straightforward to apply a similar rebate system in Sweden. To secure the quality of such a system, it would be vital to obtain independent scientific results on typical noise reductions that result when using a specific technology. Such results are missing at the time of this report's publication. It appears likely that noise reductions that can be obtained with a certain technology depend on ship characteristics, and it may be that certain technologies are only applicable to ships that fulfil certain requirements. According to interviews with technical ship design experts, there is also room for improvements on propeller design. It would be difficult to reward such efforts since it is difficult to define quantitative propeller requirements for low noise radiation. Nevertheless, the efforts of the port of Vancouver stimulate the adoption of technical measures that can be expected to reduce the radiated noise and should be commended. Basing an incentive on technical measures for noise mitigation rewards effort on the part of the ship owner, which in turn may drive a positive development in terms of ship underwater noise.

Using silent notations

Currently, six ship classification societies have issued guidelines on underwater radiated noise, including measurement principles. These guidelines all prescribe one or two spectral limit curves. If the noise radiation of a ship under test is below the limit curve in all frequency bands, some form of silent notation is awarded. An incentive for underwater noise reduction could reward ships that have such silent notations. This would be a straightforward way to introduce an incentive and it would also be cost effective for the incentive organization. Classification societies perform independent investigations so there would be no need for external third-party verification. However, silent notations are not commonly issued. A representative of one of the classification societies stated that less than 100 ships had obtained their silent notation. The scarcity of silent notations is probably due to the lack of incentives or regulations that could motivate obtaining such a notation. Contracting a classification society to perform the detailed measurements that are required will cost at least a few hundred thousand SEK, equivalent to at least 20-30 k€. If the ship cannot be measured in route, it will need to be taken out of operation for the noise measurements, which may incur an even larger loss of income to the ship owner.

For a level playing field, all silent notations should be given the same score within an incentive. It is however worth noting that classification societies have different limit curves for ship underwater noise.

When a silent notation is issued, the classification society may report the noise levels of the vessels. If societies are willing to share these results with the incentive, a ship’s score may be refined based on the actual radiated noise levels. If not, a simple pass/pass/failure is what is available, and only two different scores can be awarded.

Performing a noise inquiry

A noise inquiry may be performed to determine likely noise sources onboard a ship and identify relevant mitigations for reduced underwater radiated noise. This inquiry should be performed by an external party and may list recommended mitigations considering mitigation and cost efficiency as well as operational constraints. A lower level of incentive may be awarded at completion of such an inquiry. Upon fulfilment of one or several recommended mitigations, a higher level of incentive may be awarded. An advantage of this approach is that measurements are not needed. A drawback is that it may not be clear from the inquiry what the dominant noise sources are.

Establishing bespoke measurement stations

There is really no alternative to direct measurement if one wants to know how much noise a certain vessel radiates. Thus, if one desires to base an incentive on the actual levels of radiated noise, these must be measured. Classification societies measure underwater noise for their silent notations, and we have seen that using silent notations issued by classification societies is an alternative. However, these notations are not commonly awarded, are costly to obtain, and societies may not disclose full information on a ship’s noise radiation.

Given that ships typically travel in specific fairways, underwater noise fingerprints may potentially be obtained by deploying autonomous measurement stations at certain points where many ships pass. Such measurements have been performed e.g., near the port of Vancouver. The data has been used to investigate average effects of speed reduction and to develop prediction models, but not to set incentives. Opportunistic measurements typically suffer from poor accuracy due to e.g., a lack of control of the studied ships and uncertain noise propagation conditions. The type of studies performed in Vancouver can still achieve their goals, but to set incentives on individual vessels the accuracy may need to be better. If the accuracy can indeed be improved, measurement stations could be placed at or near inlets to major ports and collect noise fingerprints on which an incentive could be based.

Given a radiated noise source level spectrum for a ship, one needs to define a process by which to determine an incentive level. A simple method would be to use the total broadband noise power. A better method would be to weight the frequency spectrum given information on the noise sensitivity of different animals. There is probably not enough information to set up such a weighting for fish or invertebrates, but weighting schemes have been proposed for marine mammals (Southall et al, 2019).

Figure 20 shows a photo of the island Böttö, which sits adjacent to the main fairway into the port of Gothenburg, Sweden – Scandinavia's busiest port. In 2020, a measurement station was deployed at Böttö to collect ship noise signatures. The arrows indicate the placements of microphones and hydrophones. A single cabled hydrophone was placed at a depth of 13 m in close vicinity to the fairway. AIS data showed that ships passed at ranges of 100 to 250 meters at constant speed, which for a sample of ships agreed with the listed cruise speeds. The island of Böttö is not only scenic, but it also appears to be a suitable location for a novel ship noise measurement station that can provide ship noise signatures for use in a financial incentive scheme. A national incentive should offer measurement of all or, if not feasible, nearly all the ships that ply Swedish waters, which would necessitate placing measurement stations in different locations. Selection of locations can be done using ship traffic patterns, which can be extracted from AIS data.

Figure 20. A ship noise measurement station deployed at the island of Böttö, Sweden, adjacent to the main fairway into the port of Gothenburg. The upper arrow indicates the position of a microphone, while the lower arrow indicates the position of a hydrophone at 13 m depth.

Conclusions

This report has summarised the state of the art in ship underwater noise, including its characteristics, sources, measurement, prediction, mapping, mitigation and environmental impact. Two innovations that address ship noise mitigation were investigated: fairway design for reduced noise transmission and including ship underwater noise in a financial incentive for ship owners. Fairway design could not be shown to be a viable way to reduce underwater noise transmission to the environment, but several feasible ways to include ship underwater noise in a financial incentive were found. An exciting development would be to develop an opportunistic ship noise measurement station with better accuracy than current stations. Then, opportunistic measurements could be used for incentives and to investigate the efficiency of different types of mitigations.

There is much to do in mitigating ship underwater noise, and several challenges and knowledge gaps remain. However, unlike other pollutions, when emissions are reduced, the levels in the environment and the environmental impact are immediately reduced. So once mitigations are implemented, we will immediately see improvements in the environmental status of our seas.

Bibliography

Introduction

Chahouri, A., N. Elouahmani, and H. Ouchene (2022). Recent progress in marine noise pollution: A thorough review, *Chemosphere*, 291.

de Soto, N. A. (2016). Peer-reviewed studies on the effects of anthropogenic noise on marine invertebrates: from scallop larvae to giant squid. In Popper AN, Hawkins A (Eds), The effects of noise on aquatic life II, Advances in Exerimental Medicine and Biology, Springer, New York, pp. 17-26.

Duarte, C. M., L. Chapuis, S. P. Collin, D. P. Costa, R. P. Devassy, V. M. Eguiluz, C. Erbe, T. A. C. Gordon, B. S. Halpern, H. R. Harding, M. N. Havlik, M. Meekan, N. D. Merchant, J. L. Miksis-Olds, M. Parsons, M. Predragovic, A. N. Radford, C. A. Radford, S. D. Simpson, H. Slabbekoorn, E. Staaterman, I. C. Van Opzeeland, J. Winderen, X. L. Zhang, and F. Juanes. 2021.''The soundscape of the Anthropocene ocea'', *Science*, 371: 583-+.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R. Dooling. 2016.''Communication masking in marine mammals: A review and research strateg'', *Marine Pollution Bulletin*, 103: 15-38.

Haviland-Howell, G., A. S. Frankel, C. M. Powell, A. Bocconcelli, R. L. Herman, and L. S. Sayigh. 2007.''Recreational boating traffic: A chronic source of anthropogenic noise in the Wilmington, North Carolina Intracoastal Waterwa'', *Journal of the Acoustical Society of America*, 122: 151-60.

Hermannsen, L., L. Mikkelsen, J. Tougaard, K. Beedholm, M. Johnson, and P. T. Madsen. 2019.''Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscap'', *Scientific Reports*, 9.

Hildebrand, J. A. 2009.''Anthropogenic and natural sources of ambient noise in the ocea'', *Marine Ecology Progress Series*, 395: 5-20.

Kasumyan A.O. (2009). Acoustic signaling in fish. Journal of Ichthyology. 49: 963-1020.

Moksnes P-O, Eriander L, Hansen J, Albertsson J, Andersson M, Bergström U, Carlström J, Egardt J, Fredriksson R, Granhag L, Lindgren F, Nordberg K, Wendt I, Wikström S, Ytreberg E. (2019). Fritids-båtars påverkan på grunda kustekosystem i Sverige. Havsmiljöinstitutets Rapport nr 2019:3.

Mustonen, M., A. Klauson, M. Andersson, D. Clorennec, T. Folegot, R. Koza, J. Pajala, L. Persson, J. Tegowski, J. Tougaard, M. Wahlberg, and P. Sigray. 2019.''Spatial and Temporal Variability of Ambient Underwater Sound in the Baltic Se'', *Scientific Reports*, 9.

Nedelec, S. L., J. Campbell, A. N. Radford, S. D. Simpson, and N. D. Merchant. 2016.''Particle motion: the missing link in underwater acoustic ecolog'', *Methods in Ecology and Evolution*, 7: 836-42.

Popper, A. N., and A. D. Hawkins. 2019.''An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishe'', *Journal of Fish Biology*, 94: 692-713.

Popper, A. N., Salmon, M. & Horch, K.W. (2001). Acoustic detection and communication in decapod crustaceans. *J. Comp. Physiol. A.* **187**: 83-89.

Shannon, G., M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, and G. Wittemyer. 2016.''A synthesis of two decades of research documenting the effects of noise on wildlif'', *Biological Reviews*, 91: 982-1005.

Slabbekoorn, H., N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, and A. N. Popper. 2010.''A noisy spring: the impact of globally rising underwater sound levels on fis'', *Trends in Ecology & Evolution*, 25: 419-27.

Southall, B. L., in: Final Report of the NOAA International Symposium: "Shipping Noise and Marine Mammals: A forum for science, management, and technology", 18-19 May 2004, Arlington VA, USA, 2005.

Spence, J. and Fischer, R. Underwater noise from ships–- causes and general approaches to noise control, in 2^{3r}d International Congress on Sound and Vibration, 2016.

Urick, R.J. (1983) Principles of Underwater Sound. 3rd Edition, McGraw-Hill, New York.

Wale, M. A., R. A. Briers, and K. Diele. 2021.''Marine invertebrate anthropogenic noise research-Trends in methods and future direction'', *Marine Pollution Bulletin*, 173.

Underwater noise from ships

Abrahamsen, K. A. (2012). The Ship as an Underwater Noise Source. Proceedings of Meetings on Acoustics. 17: 070058 doi:10.1121/1.4772953

Ainslie, M. A., Martin, S. B., Trounce, K. B., Hannay, D. E., Eickmeier, J. M., Deveau, T. J., Lucke, K., MacGillivray, A. O., Nolet, V., Borys, P. (2022). International harmonization of procedures for measuring and analyzing of vessel underwater radiated noise. Marine Pollution Bulletin. 174: 113124.

Arveson, P. T., and Vendittis D. J. (2000). Radiated noise characteristics of a modern cargo ship. The Journal of the Acoustical Society of America. 107: 118-129.

Audoly, C., Rousset, C., & Leissing, T.M. (2014). AQUO Project - Modelling of ships as noise source for use in an underwater noise footprint assessment tool.

BIAS, 2016, Baltic sea information on the acoustic soundscape LIFE11 env/se/841–- Layperson's report

Breeding, J. E., Pflug Jr., Bradley Lisa A., Walrod Marshall, and Melanie H. (1996) Research Ambient Noise dIrectionality (RANDI) 3.1 Physics Description. *Fort Belvoir, VA: Defense Technical Information Center.* doi:10.21236/ADA316034.

Bureau Veritas, 2014. Underwater Radiated Noise (URN). Rule Note NR 614 DT R00 E. Bureau Veritas, Marine & Offshore Division, Cedex, France.

Erbe, C., MacGillivray, A., & Williams, R. (2012). Mapping cumulative noise from shipping to inform marine spatial planning. The Journal of the Acoustical Society of America. 132(5): 423-428. doi:10.1121/1.4758779

Frantzis, A. Does acoustic testing strand whales?. Nature 392, 29 (1998). https://doi.org/10.1038/32068

Freitas, L. (2004). Evans, Peter G.H.; Miller, Lee A. (eds.). The Stranding of Three Cuvie''s Beaked Whales Ziphius Cavirostris in Madeira Archipelago – May 2000. European Cetacean Society. pp. 28–32.

Hermannsen, L., Beedholm, K., Tougaard, J., & 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(4): 1640-1653. doi:10.1121/1.4893908

Hildebrand J. A. Anthropogenic and natural sources of ambient noise in the ocean, Mar. Ecol. Prog. Ser. 395 (2009) 5-20.

Johansson A. T., J. Hallander, R. Karlsson, A. Långström and M. Turesson (2015),“"Full scale measurement of underwater radiated noise from a coastal tanker”" OCEANS 2015–- Genova, Genova, Italy, pp. 1-10, doi: 10.1109/OCEANS-Genova.2015.7271771.

JOMOPANS (2021), 10 Years of North Sea Soundscape Monitoring, End Report from the Interreg NSR JOMOPANS project, https://northsearegion.eu/media/17501/interreg_jomopans_10-years-of-north-sea-soundscape-monitoring_final.pdf

Karasalo, I., Östberg, M., Sigray, P., Jalkanen, J.-P., Johansson, L., Liefvendahl, M., & Bensow, R. (2017). Estimates of Source Spectra of Ships from Long Term Recordings in the Baltic Sea. Frontiers in Marine Science, 4. doi:10.3389/fmars.2017.00164

Leaper, R. C., & Renilson, M. R. (2012). A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering, 154(A2). doi:10.5750/ijme.v154iA2.877

MacGillivray, A., & de Jong, C. (2021). A Reference Spectrum Model for Estimating Source Levels of Marine Shipping Based on Automated Identification System Data. Journal of Marine Science and Engineering, 9(4). doi:10.3390/jmse9040369

MacGillivray, A. O., Ainsworth, L. M., Zhao, J., Dolman, J. N., Hannay, D. E., Frouin-Mouy, H., Trounce, K. B., & White, D. A. (2022). A functional regression analysis of vessel source level measurements from the Enhancing Cetacean Habitat and Observation (ECHO) database. The Journal of the Acoustical Society of America, 152(3), 1547–1563. doi:10.1121/10.0013747

McKenna, M. F., Ross, D., Wiggins, S. M., & Hildebrand, J. A. (2012). Underwater radiated noise from modern commercial ships. The Journal of the Acoustical Society of America, 131(1), 92-103. doi:10.1121/1.3664100

Merchant, N. D., Brookes, K. L., Faulkner, R. C., Bicknell, A. W., Godley, B. J., & Witt, M. J. (2016). Underwater noise levels in UK waters. Scientific Reports, 6, 36942. doi:10.1038/srep36942

Mustonen, M., Klauson, A., Andersson, M., Clorennec, D., Folegot, T., Koza, R., Pajala, J., Persson, L., Tegowski, J., Wahlberg, M., Sigray, P. (2019). Spatial and Temporal Variability of Ambient Underwater Sound in the Baltic Sea. Scientific Reports, 9(1), 13237. doi:10.1038/s41598-019-48891-x

Putland, R. L., de Jong, C., Binnerts, B., Farcas, A., and Merchant, N. D. (2022). Multi-Site Validation of Shipping Noise Maps Using Field Measurements. Marine Pollution Bulletin 179:113733. doi:10.1016/j.marpolbul.2022.113733.

Simard, Y., Roy, N., Gervaise, C., & Giard, S. (2016). Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway. The Journal of the Acoustical Society of America, 140(3), 2002-2018. doi:10.1121/1.4962557

Wales, S. C., & Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated noise. The Journal of the Acoustical Society of America, 111(3), 1211-1231. doi:10.1121/1.1427355

Wijngaarden, W. (2011). Prediction of Propeller-Induced Hull-Pressure Fluctuations. PhD Thesis, Delft Technical University, Netherlands.

Wittekind, D. K. (2014). A Simple Model for the Underwater Noise Source Level of Ships. Journal of Ship Production and Design, 30(1), 7-14. doi:10.5957/jspd.30.1.120052

Environmental impacts

Akamatsu, T., Okumura, T., Novarini, N. & Yan, H. Y. (2002). Empirical refinements applicable to the recording of fish sounds in small tanks. J. Acoust. Soc. Am. 112: 3073- 3082.

Andersson, M.H., Lagenfelt, I., Ahlsén, J., Cremle, M., Molander, L., Persson, L.K.G., Lennartsson, M., Blom, E-L., Sigray, P. (2015). Displacement effects of ship noise on fish population. AQUO Achieve qUieter Oceans by shipping noise footprint reduction FP7–- Collaborative Project n° 314227. WP 4: Sensitivity of marine life to shipping noise.

Andre, M., K. Kaifu, M. Sole, M. van der Schaar, T. Akamatsu, A. Balastegui, A. M. Sanchez, and J. V. Castell. 2016.''Contribution to the Understanding of Particle Motion Perception in Marine Invertebrates'' in A. N. Popper and A. Hawkins (eds.), Effects of Noise on Aquatic Life II.

Au, W. W. L. (2000). "Hearing in whales and dolphins: An overview," in Hearing by Whales and Dolphins, edited by W. W. L. Au, A. N. Popper, and R. R. Fay (Springer-Verlag, New York), pp. 1–42.

Bagočius, D. (2014). Potential masking of the Baltic grey seal vocalisations by underwater shipping noise in the Lithuanian area of the Baltic Sea. Environ. Res. Eng. Manag. 70, 66–72. doi: 10.5755/j01.erem.70.4.6913

Blom, E. L., C. Kvarnemo, I. Dekhla, S. Schold, M. H. Andersson, O. Svensson, and M. C. P. Amorim. 2019.''Continuous but not intermittent noise has a negative impact on mating success in a marine fish with paternal care'', Scientific Reports, 9.

Blundell, G. M., and G. W. Pendleton. 2015.''Factors Affecting Haul-Out Behavior of Harbor Seals (Phoca vitulina) in Tidewater Glacier Inlets in Alaska: Can Tourism Vessels and Seals Coexist'', Plos One, 10.

Bpanscomb ES & Rittschof D (1984). An investigation of low frequency sound waves as a means of inhibiting barnacle settlement. J. Exp. Mar. Biol. Ecol., 1984, Vol. 19, pp.149-154.

Breithaupt, T. (2002). Sound perception in aquatic crustaceans. In: The crustacean nervous system (ed. K. Wiese), pp. 548-559. Basel: Birkhaüser.

Bruintjes, R., and A. N. Radford. 2013.''Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fis'', Animal Behaviour, 85: 1343-49.

Carter, E. E., T. Tregenza, and M. Stevens. 2020. Ship noise inhibits colour change, camouflage, and anti-predator behaviour in shore crabs, Current Biology, 30: R211-R12.

Celi, M., F. Filiciotto, G. Maricchiolo, L. Genovese, E. M. Quinci, V. Maccarrone, S. Mazzola, M. Vazzana, and G. Buscaino. 2016.''Vessel noise pollution as a human threat to fish: assessment of the stress response in gilthead sea bream (Sparus aurata, Linnaeus 1758'', Fish Physiology and Biochemistry, 42: 631-41.

Chahouri, A., N. Elouahmani, and H. Ouchene. 2022.''Recent progress in marine noise pollution: A thorough revie'', Chemosphere, 291.

Charifi, M., M. Sow, P. Ciret, S. Benomar, and J. C. Massabuau. 2017.''The sense of hearing in the Pacific oyster, Magallana giga'', Plos One, 12.

Chen Y, Li W, Xiang L, Mi X, Duan M, Wu C (2022). Fish personality affects their exposure to microplastics. Ecotoxicology and Environmental Safety 233 (2022) 113301

de Soto NA (2016). Peer-reviewed studies on the effects of anthropogenic noise on marine invertebrates: from scallop larvae to giant squid. In Popper AN, Hawkins A (Eds), The effects of noise on aquatic life II, Advances in Exerimental Medicine and Biology, Springer, New York, pp. 17-26.

de Soto, N. A., N. Delorme, J. Atkins, S. Howard, J. Williams, and M. Johnson. 2013.''Anthropogenic noise causes body malformations and delays development in marine larva'', Scientific Reports, 3.

Drastik, V., and J. Kubecka. 2005.''Fish avoidance of acoustic survey boat in shallow water'', Fisheries Research, 72: 219-28.

Duarte, C. M., L. Chapuis, S. P. Collin, D. P. Costa, R. P. Devassy, V. M. Eguiluz, C. Erbe, T. A. C. Gordon, B. S. Halpern, H. R. Harding, M. N. Havlik, M. Meekan, N. D. Merchant, J. L. Miksis-Olds, M. Parsons, M. Predragovic, A. N. Radford, C. A. Radford, S. D. Simpson, H. Slabbekoorn, E. Staaterman, I. C. Van Opzeeland, J. Winderen, X. L. Zhang, and F. Juanes. 2021.''The soundscape of the Anthropocene ocea'', Science, 371: 583-+.

Duncan, A. J., Lucke, K., Erbe, C. & McCauley, R. D. (2016). Issues associated with sound exposure experiments in tanks. Proc. Mtgs. Acoust. 27: 070008.

Dyndo, M., D. M. Wisniewska, L. Rojano-Donate, and P. T. Madsen. 2015.''Harbour porpoises react to low levels of high frequency vessel nois'', Scientific Reports, 5.

Edmonds, N. J., C. J. Firmin, D. Goldsmith, R. C. Faulkner, and D. T. Wood. 2016.''A review of crustacean sensitivity to high amplitude underwater noise: Data needs for effective risk assessment in relation to UK commercial specie'', Marine Pollution Bulletin, 108: 5-11.

Enger, P. S. (1967). Hearing in herring. Comparative Biochemistry and Physiology 22: 527–538.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R. Dooling. 2016.''Communication masking in marine mammals: A review and research strateg'', Marine Pollution Bulletin, 103: 15-38.

Erbe, C., S. A. Marley, R. P. Schoeman, J. N. Smith, L. E. Trigg, and C. B. Embling. 2019.''The Effects of Ship Noise on Marine Mammals–- A Revie'', Frontiers in Marine Science, 6.

Fakan, E. P., and M. I. McCormick. 2019.''Boat noise affects the early life history of two damselfishe'', Marine Pollution Bulletin, 141: 493-500.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. Arizza, G. de Vincenzi, R. Grammauta, S. Mazzola, and G. Buscaino. 2016.''Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (Palaemon serratus, Pennant 1777'', Journal of Experimental Marine Biology and Ecology, 478: 24-33.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. Di Stefano, S. Mazzola, and G. Buscaino. 2014.''Behavioural and biochemical stress responses of Palinurus elephas after exposure to boat noise pollution in tan'', Marine Pollution Bulletin, 84: 104-114.

Finstad, J. L. & Nordeide, J. T. (2004). Acoustic repertoire of spawning cod. Gadus morhua. Environ. Biol. Fishes 70, 427–433.

Goodall, C., Chapman, C., Neil, D., (1990). The acoustic response threshold of the Norway lobster, Nephrops norvegicus (L.) in a free sound field (1976) In: Wiese, K., Krenz, W.D., Tautz, J., Reichert, H., Mulloney, B. (Eds.), Frontiers in Crustacean Neurobiology. Birkhäuser Verlag, Basel, pp. 106–113.

Haviland-Howell, G., A. S. Frankel, C. M. Powell, A. Bocconcelli, R. L. Herman, and L. S. Sayigh. 2007.''Recreational boating traffic: A chronic source of anthropogenic noise in the Wilmington, North Carolina Intracoastal Waterwa'', Journal of the Acoustical Society of America, 122: 151-60.

Hawkins, A. D. & Amorim, M. C. P. (2000). Spawning sounds of the male haddock. Melanogrammus aeglefinus. Environ. Biol. Fishes 59, 29–41.

Hawkins, A. D., A. E. Pembroke, and A. N. Popper. 2015.''Information gaps in understanding the effects of noise on fishes and invertebrate'', Reviews in Fish Biology and Fisheries, 25: 39-64.

HELCOM Copenhagen Ministerial Declaration (2013)

Hermannsen, L., L. Mikkelsen, J. Tougaard, K. Beedholm, M. Johnson, and P. T. Madsen. 2019.''Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscap'', Scientific Reports, 9.

Hildebrand, J. A. 2009.''Anthropogenic and natural sources of ambient noise in the ocea'', Marine Ecology Progress Series, 395: 5-20.

Hudson, D. M., J. S. Krumholz, D. L. Pochtar, N. C. Dickenson, G. Dossot, G. Phillips, E. P. Baker, and T. E. Moll. 2022.''Potential impacts from simulated vessel noise and sonar on commercially important invertebrate'', Peerj, 10.

Hughes, A. R., Mann, D. A. and Kimbro, D. L. (2014). Predatory fish sounds can alter crab foraging behaviour and influence bivalve abundance. Proc. R. Soc. B 281, 20140715. doi:10.1098/rspb.2014.0715

Insley, S.J., Phillips, A.V., Charier, I. (2003) A review of social recognition in pinnipeds. Aquatic Mammals 29(2): 181–201.

Jezequel, Y., I. T. Jones, J. Bonnel, L. Chauvaud, J. Atema, and T. A. Mooney. 2021.‘'Sound detection by the American lobster (Homarus americanus'', Journal of Experimental Biology, 224.

Jezequel, Y., J. Bonnel, and L. Chauvaud. 2021.‘'Potential for acoustic masking due to shipping noise in the European lobster (Homarus gammarus'', Marine Pollution Bulletin, 173.

Jolivet, A., R. Tremblay, F. Olivier, C. Gervaise, R. Sonier, B. Genard, and L. Chauvaud. 2016.‘'Validation of trophic and anthropic underwater noise as settlement trigger in blue mussel'', Scientific Reports, 6.

Kaifu, K., T. Akamatsu, and S. Segawa. 2008.‘'Underwater sound detection by cephalopod statocys'', Fisheries Science, 74: 781-86.

Kasumyan A.O. (2005). Structure and function of auditory system in fish. Journal of Ichthyology. 45: S223-S270.

Kasumyan A.O. (2009). Acoustic signaling in fish. Journal of Ichthyology. 49: 963-1020.

Ladich, F., and R. R. Fay. 2013.‘'Auditory evoked potential audiometry in fis'', Reviews in Fish Biology and Fisheries, 23: 317-64.

Lara, R. A., and R. O. Vasconcelos. 2021.‘'Impact of noise on development, physiological stress and behavioural patterns in larval zebrafis'', Scientific Reports, 11.

Leiva, L., S. Scholz, L. Gimenez, M. Boersma, G. Torres, R. Krone, and N. Tremblay. 2021.‘'Noisy waters can influence young-of-year lobster'' substrate choice and their antipredatory response'', Environmental Pollution, 291.

London JM, Hoef JMV, Jeffries SJ, Lance MM, Boveng PL. (2012). Haul-Out Behavior of Harbor Seals (Phoca vitulina) in Hood Canal, Washington. Plos One 7(6). doi: 10.1371/journal.pone.0038180 PMID:

Lovell, J. M., Findlay, M. M., Moate, R. M. and Yan, H. Y. (2005). The hearing abilities of the prawn Palaemon serratus. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 140, 89-100. doi:10.1016/j.cbpb.2004.11.003

Lovell, J. M., M. M. Findlay, R. M. Moate, and H. Y. Yan. 2005.‘'The hearing abilities of the prawn Palaemon serratu'', Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology, 140: 89-100.

Magnhagen, C., K. Johansson, and P. Sigray. 2017.‘'Effects of motorboat noise on foraging behaviour in Eurasian perch and roach: a field experimen'', Marine Ecology Progress Series, 564: 115-25.

McCauley RD, Fewtrell J and Popper AN (2003). High intensity anthropogenic sound damages fish ears. The Journal of the Acoustical Society of America. 113: 1-5.

McDonald, J. I., S. L. Wilkens, J. A. Stanley, and A. G. Jeffs. 2014.‘'Vessel generator noise as a settlement cue for marine biofouling specie'', Biofouling, 30: 741-49.

McDonald, M. A., J. A. Hildebrand, and S. M. Wiggins. 2006.‘'Increases in deep ocean anibient noise in the northeast pacific west of San Nicolas Island, Californi'', Journal of the Acoustical Society of America, 120: 711-18.

Moksnes P-O, Eriander L, Hansen J, Albertsson J, Andersson M, Bergström U, Carlström J, Egardt J, Fredriksson R, Granhag L, Lindgren F, Nordberg K, Wendt I, Wikström S, Ytreberg E. (2019). Fritids-båtars påverkan på grunda kustekosystem i Sverige. Havsmiljöinstitutets Rapport nr 2019:3.

Mooney, T. A., Hanlon, R. T., Christensen-Dalsgaard, J., Madsen, P. T., Ketten, D. R. and Nachtigall, P. E. (2010). Sound detection by the longfin squid (Loligo pealeii) studied with auditory evoked potentials: sensitivity to low-frequency particle motion and not pressure. J. Exp. Biol. 213, 3748-3759. doi:10.1242/jeb.048348

Mustonen, M., A. Klauson, M. Andersson, D. Clorennec, T. Folegot, R. Koza, J. Pajala, L. Persson, J. Tegowski, J. Tougaard, M. Wahlberg, and P. Sigray. 2019.‘'Spatial and Temporal Variability of Ambient Underwater Sound in the Baltic Se'', Scientific Reports, 9.

Nedelec, S. L., A. N. Radford, S. D. Simpson, B. Nedelec, D. Lecchini, and S. C. Mills. 2014.‘'Anthropogenic noise playback impairs embryonic development and increases mortality in a marine invertebrat'', Scientific Reports, 4.

Nedelec, S. L., J. Campbell, A. N. Radford, S. D. Simpson, and N. D. Merchant. 2016.‘'Particle motion: the missing link in underwater acoustic ecolog'', Methods in Ecology and Evolution, 7: 836-42.

Nedelec, S. L., S. C. Mills, D. Lecchini, B. Nedelec, S. D. Simpson, and A. N. Radford. 2016.‘'Repeated exposure to noise increases tolerance in a coral reef fis'', Environmental Pollution, 216: 428-36.

Nedelec, S. L., S. D. Simpson, E. L. Morley, B. Nedelec, and A. N. Radford. 2015.‘'Impacts of regular and random noise on the behaviour, growth and development of larval Atlantic cod (Gadus morhua'', Proceedings of the Royal Society B-Biological Sciences, 282.

Popper, A. N., and M. C. Hastings. 2009a.‘'The effects of anthropogenic sources of sound on fishe'', Journal of Fish Biology, 75: 455-89.

Popper, A. N., and M. C. Hastings. 2009b.''The effects of human-generated sound on fish'', Integrative Zoology, 4: 43-52.

Popper AN and Hawkins AD (2018). The importance of particle motion to fishes and invertebrates. Citation: The Journal of the Acoustical Society of America 143, 470 (2018); doi: 10.1121/1.5021594

Popper, A. N., and A. D. Hawkins. 2019.''An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishe'', Journal of Fish Biology, 94: 692-713.

Popper, A. N., A. D. Hawkins, O. Sand, and J. A. Sisneros. 2019.''Examining the hearing abilities of fishe'', Journal of the Acoustical Society of America, 146: 948-55.

Popper, A. N., A. D. Hawkins, and F. Thomsen. 2020.''Taking the Animal'' Perspective Regarding Anthropogenic Underwater Soun'', Trends in Ecology & Evolution, 35: 787-94.

Popper, A. N., Salmon, M. & Horch, K.W. (2001). Acoustic detection and communication in decapod crustaceans. J. Comp. Physiol. A. 187: 83-89.

Purser J, Radford AN (2011). Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks (Gasterosteus aculeatus). pLoS ONE 6(2): e17478. doi:10.1371/journal.pone.0017478

Pye Henninger H and Watson WH (2005). Mechanisms underlying the production of carapace vibrations and associated waterborne sounds in the American lobster, Homarus americanus. J Exp Biol. Sep;208(Pt 17):3421-9. doi: 10.1242/jeb.01771.

Radford, C. A., Tay, K., Goeritz, M. L. (2016). Hearing in the paddle crab, Ovalipes catharus. Proc. Meetings Acoustics 27, 010013. doi:10.1121/2.0000259

Regnault, M., and J. P. Lagardere. 1983.''EFFECTS OF AMBIENT NOISE ON THE METABOLIC LEVEL OF CRANGON-CRANGON (DECAPODA, NATANTIA'', Marine Ecology Progress Series, 11: 71-78.

Roberts, L., S. Cheesman, M. Elliott, and T. Breithaupt. 2016.''Sensitivity of Pagurus bernhardus (L.) to substrate-borne vibration and anthropogenic nois'', Journal of Experimental Marine Biology and Ecology, 474: 185-94.

Samson, J. E., T. A. Mooney, S. W. S. Gussekloo, and R. T. Hanlon. 2014.''Graded behavioral responses and habituation to sound in the common cuttlefish Sepia officinali'', Journal of Experimental Biology, 217: 4347-55.

Sara, G., J. M. Dean, D. ''Amato, G. Buscaino, A. Oliveri, S. Genovese, S. Ferro, G. Buffa, M. Lo Martire, and S. Mazzola. 2007.''Effect of boat noise on the behaviour of bluefin tuna Thunnus thynnus in the Mediterranean Se'', Marine Ecology Progress Series, 331: 243-53.

Scholik, A. R., and H. Y. Yan. 2002.''Effects of boat engine noise on the auditory sensitivity of the fathead minnow, Pimephales promela'', Environmental Biology of Fishes, 63: 203-09.

Schwarz, A. L. and Greer, G.L. (1984). Responses of Pacific herring, Clupea harengus pallasi, to some underwater sounds. Can. J. Fish. Aquat. Sci. 41 : 1183-1192. doi: https://doi-org.ezp.sub.su.se/10.1139/f84-140 41

Shannon, G., M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, and G. Wittemyer. 2016.''A synthesis of two decades of research documenting the effects of noise on wildlif'', Biological Reviews, 91: 982-1005.

Sierra-Flores R, Atack T, Migaud H & Davie A (2015) Stress response to anthropogenic noise in Atlantic cod Gadus morhua L.. Aquacultural Engineering, 67: 67-76. https://doi.org/10.1016/j.aquaeng.2015.06.003

Simpson, S. D., J. Purser, and A. N. Radford. 2015.''Anthropogenic noise compromises antipredator behaviour in European eel'', Global Change Biology, 21: 586-93.

Slabbekoorn, H., N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, and A. N. Popper. 2010.''A noisy spring: the impact of globally rising underwater sound levels on fis'', Trends in Ecology & Evolution, 25: 419-27.

Smith, M.E., Kane, A.S., Popper, A.N., (2004). Noise-induced stress response and hearing loss in goldfish (Carassius auratus). The Journal of Experimental Biology 207, 427–435.

Solan, M., C. Hauton, J. A. Godbold, C. L. Wood, T. G. Leighton, and P. White. 2016.''Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem propertie'', Scientific Reports, 6.

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., André, M. (2013). Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep Sea Research Part II: Topical Studies in Oceanography, Volume 95: 160-181. https://doi.org/10.1016/j.dsr2.2012.10.006

Sole, M., M. Lenoir, J. M. Fontuno, M. Durfort, M. van der Schaar, and M. Andre. 2016.''Evidence of Cnidarians sensitivity to sound after exposure to low frequency noise underwater source'', Scientific Reports, 6.

Sole, M., M. Lenoir, J. M. Fortuno, M. van der Schaar, and M. Andre. 2018.''A critical period of susceptibility to sound in the sensory cells of cephalopod hatchling'', Biology Open, 7.

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., Tyack, P.L. (2007). Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals 33(4): 273-275

Southall, B. L., R. J. Schusterman, D. Kastak, and C. R. Kastak. 2005.''Reliability of underwater hearing thresholds in pinniped'', Acoustics Research Letters Online-Arlo, 6: 243-49.

Staaterman, E. R., Clark, C.W., Gallagher, A. J., de Vries, 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, 97-10. doi:10.3354/ab00361

Stanley, J. A., C. A. Radford, and A. G. Jeffs. 2010.''Induction of settlement in crab megalopae by ambient underwater reef soun'', Behavioral Ecology, 21: 113-20.

Stanley, J. A., S. M. Van Parijs, and L. T. Hatch. 2017.''Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddoc'', Scientific Reports, 7.

Stanley, J. A., S. L. Wilkens, and A. G. Jeffs. 2014.''Fouling in your own nest: vessel noise increases biofoulin'', Biofouling, 30: 837-44.

Tidau, S., and M. Briffa. 2019a.''Anthropogenic noise pollution reverses grouping behaviour in hermit crab'', Animal Behaviour, 151: 113-20.

Tidau, S., and M. Briffa. 2019b.''Distracted decision makers: ship noise and predation risk change shell choice in hermit crab'', Behavioral Ecology, 30: 1157-67.

Tougaard, J., A. J. Wright, and P. T. Madsen. 2015.''Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoise'', Marine Pollution Bulletin, 90: 196-208.

Wale, M. A., R. A. Briers, and K. Diele. 2021.''Marine invertebrate anthropogenic noise research-Trends in methods and future direction'', Marine Pollution Bulletin, 173.

Wale, M. A., R. A. Briers, M. G. J. Hard, D. Bryson, and K. Diele. 2019.''From DNA to ecological performance: Effects of anthropogenic noise on a reef-building musse'', Science of the Total Environment, 689: 126-32.

Wale, M. A., S. D. Simpson, and A. N. Radford. 2013a.''Noise negatively affects foraging and antipredator behaviour in shore crab'', Animal Behaviour, 86: 111-18.

Wale, M. A., S. D. Simpson, and A. N. Radford. 2013b.''Size-dependent physiological responses of shore crabs to single and repeated playback of ship nois'', Biology Letters, 9.

Voellmy, I. K., J. Purser, D. Flynn, P. Kennedy, S. D. Simpson, and A. N. Radford. 2014.''Acoustic noise reduces foraging success in two sympatric fish species via different mechanism'', Animal Behaviour, 89: 191-98.

Wisniewska, D. M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R., et al. (2018). High rates of vessel noise disrupt foraging in wild harbour porpoises (Phocoena phocoena). Proc. R. Soc. B Biol. Sci. 285:20172314. doi: 10.1098/rspb.2017.2314.

Zhadan, P. M. Directional Sensitivity of the Japanese Scallop Mizuhopecten yessoensis and Swift Scallop Chlamys Swifti to Water-Borne Vibrations. Russ. J. Mar. Biol. 31(1): 28-35 (2005)

Current ship noise mitigation

Norrbin, N. H. 1986. “Fairway Design with Respect to Ship Dynamics and Operational Requirements,” SSPA Research Report No. 102, SSPA Maritime Consulting, Gothenburg, Sweden.

American Society of Civil Engineers, Ship Channel Design and Operation, Edited by Bruce L. McCartney; Laurie L. Ebner; Lyndell Z. Hales; and Eric E. Nelson, Revised Edition, 2005. ISBN 978-0-7844-0770-7. https://doi.org/10.1061/9780784407707

Harbour Approach Channels - Design Guidelines, PIANC - The World Association for Waterborne Transport Infrastructure - MarCom Working Group 121 (2014)

Vard Marine Inc., Kendrick, A., Terwei, R. (2019). Ship Underwater Radiated Noise. Report 368-000-01, Rev 4.

Gassmann, M., Kindberg, L. B., Wiggins, S. M., and Hildebrand J. A. (2017). Underwater noise of pre- and post-retrofitted MAERSK G-class container vessels. Technical report MPL TM-616, Marine Physical Laboratory, University of California San Diego.

Chang, Y.-C.; Zhang, X., Legal Issues Concerning the Impact of Anthropogenic Underwater Noise in the Marine Environment. Sustainability 2021, 13, 4612. https://doi.org/10.3390/su13094612

Vakili, S.V.; Ölcer, A.I.; Ballini, F. The development of a policy framework to mitigate underwater noise pollution from commercial vessels. Mar. Policy 2020, 118, 104004.

International Maritime Organization, “GloNoise Partnership – Global Partnership for Mitigation of Underwater Noise from Shipping”, OceanAction 48193. https://sdgs.un.org/partnerships/glonoise-partnership-global-partnership-mitigation-underwater-noise-shipping (accessed 2022-10-19)

Ascobans, “Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas”, 1992 with 2003 amendments. https://www.ascobans.org/en/documents/agreement-text (accessed 2022-04-14)

E. Lalander, M. Svedendahl, R. Nordström-Larsson, T. Johansson and M. H. Andersson, ”The underwater soundscape in the port of Gothenburg and estimations of the underwater radiated noise from ships”, Technical Report FOI-R--5156—SE, Nov 2021.

A. T. Johansson and M. H. Andersson, “Ambient Underwater Noise Levels at Norra Midsjöbanken during Construction of the Nord Stream Pipeline”, Technical report FOI-R—3469—SE, Sept 2012.

Port of Vancouver, “Fee Document”, 2022. https://www.portvancouver.com/wp-content/uploads/2020/11/2022-01-01-FINAL-Fee-Document-for-2022-2021-12-30-version-no-GIF-2022-fees.pdf, accessed 2022-04-14.

Port of Vancouver, 2020. ”2020 voluntary vessel slowdown in Haro Strait and Boundary Pass”. https://www.portvancouver.com/wp-content/uploads/2021/06/2021-06-11-Summary-Report-2020-Haro-Boundary-slowdown.pdf accessed 2022-04-14.

ZoBell VM, Frasier KE, Hildebrand JA. Sound Levels of Participating Vessels during the 2021 Vessel Speed Reduction Program in the Santa Barbara Channel. Final Report. Marine Physical Laboratory Technical Memorandum 659. April 2022.

APCD, Air pollution Control District Santa Barbara County, “Protecting Blue Whales and Blue Skies”. https://www.ourair.org/wp-content/uploads/052521-Digitial-VSR-Version-Compressed.pdf, accessed 2022-04-14.

Port of Vancouver, 2021. “Summary report: 2021 voluntary inshore lateral displacement in the Strait of Juan de Fuca”. SUMMARY-REPORT-2021-SJDF-lateral-displacement.pdf (portvancouver.com), accessed 2023-01-17

Port of Vancouver, 2022a. “2022 Strait of Juan de Fuca voluntary inshore lateral displacement”. https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/maintaining-healthy-ecosystems-throughout-our-jurisdiction/echo-program/projects/lateraldisplacement/, accessed 2022-04-14.

Port of Vancouver, 2022b. “2022 Swiftsure Bank voluntary ship slowdown trial”. https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/maintaining-healthy-ecosystems-throughout-our-jurisdiction/echo-program/projects/swiftsure-bank-slowdown/, accessed 2022-04-14.

Green Marine, “Underwater noise performance indicators”. https://green-marine.org/certification/scope-and-criteria/underwater-noise-ship-owners/, accessed 2022-04-14.

Port of Prince Rupert, “Green Wave Program for Shippers”, https://www.rupertport.com/environmental-stewardship/green-wave-program-for-shippers/, accessed 2022-12-28

MacGillivray, Alexander O., Zizheng Li, David E. Hannay, Krista B. Trounce, and Orla M. Robinson. 2019. 'Slowing Deep-Sea Commercial Vessels Reduces Underwater Radiated Noise'. The Journal of the Acoustical Society of America 146(1):340–51. doi: 10.1121/1.5116140.

Port of Milwaukee, "Port Milwaukee's StewardSHIP Initiative". https://portmilwaukee.com/stewardSHIP#:~:text=As%20such%2C%20Port%20Milwaukee%20announced,environmental%20stewardship%20in%20their%20operations accessed 2023-01-19

Quebec Port Authority, 2023, "EcoCargo program". https://www.portquebec.ca/en/were-committed/we-have-a-sustainable-vision/ecocargo-program, accessed 2023-01-19

European Commission, 2008, Directive 2008/56/ec of the European parliament and of the council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0056&from=EN

European Commission, 2017, Commission Decision (EU) 2017/848, available at https://eur-lex.europa.eu/legal-content/SV/TXT/PDF/?uri=CELEX:32017D0848&from=EN

Havs- och Vattenmyndigheten, 2022, personal communication, 11 Feb 2022

HELCOM, 2021a, Terms of Reference for the HELCOM Expert Group on Underwater Noise (EG Noise) 2022-2024, Adopted by HOD 61-2021

HELCOM, 2021b, Baltic Sea Action Plan 2021 Update

HELCOM, 2021c, HELCOM Recommendation on the Regional Action Plan on Underwater Noise

HELCOM, 2021d, HELCOM Science Agenda

HELCOM 2021e, HELCOM Guidelines for monitoring continuous noise (Updated HELCOM Guidelines as noted by State & Conservation 14-2021), https://www.helcom.fi/wp-content/uploads/2019/08/Guidelines-for-monitoring-continuous-noise.pdf

OSPAR, 2010, Quality Status Report 2010, OSPAR Commission, London

OSPAR, 2019, OSPAR Science Agenda 2018 Update, OSPAR Commission, London

OSPAR, 2021, Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2030, Agreement 2021-01: North-East Atlantic Environment Strategy (replacing Agreement 2010-03)

Royal Haskoning DHV, 2020, Proposal Assessment Framework – OSPAR candidate indicator ambient underwater sound, Ref: BH2849WATRP2011251151

TG Noise, 2021, Sigray, P., Borsani, J.F., Le Courtois, F., Andersson M., Azzellino A., Castellote M., Ceyrac L., Dekeling R., Haubner N., Hegarty M., Hedgeland D., Juretzek C., Kinneging N., Klauson A., Leaper R., Liebschner A., Maglio A., Mihanovic H., Mueller A. , Novellino A., Outinen O., Tougaard J., Prospathopoulos A., Weilgart L., Assessment Framework for EU Threshold Values for continuous underwater sound, TG Noise Recommendations, Editorial coordination : Maud Casier, DG Environment, European Commission

TG Noise, 2022, Management and monitoring of underwater noise in European Seas – Overview of main European-funded projects and other relevant initiatives, 3rd Communication Report, MSFD Common Implementation Strategy Technical Group on Underwater Noise

European Commission, 2022a, Our Oceans, Seas and Coasts MSFD Descriptor 11: Energy incl. Underwater Noise, https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-11/index_en.htm, accessed 2022-04-14

European Commission, 2022b, Our Oceans, Seas and Coasts Regional Sea Conventions, https://ec.europa.eu/environment/marine/international-cooperation/regional-sea-conventions/index_en.htm, accessed 2022-04-14

Havs- och Vattenmyndigheten, 2022, Kontinuerligt undervattensbuller, https://www.havochvatten.se/overvakning-och-uppfoljning/miljoovervakning/marin-miljoovervakning/kontinuerligt-undervattensbuller.html, accessed 2022-04-14

HELCOM, 2022a, Underwater noise, https://helcom.fi/action-areas/marine-litter-and-noise/underwater-noise/, accessed 2022-04-14

OSPAR, 2022a, Distribution of Reported Impulsive Sounds, https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/distribution-reported-impulsive-sounds-sea/, accessed 2022-04-14

OSPAR, 2022b, OSPAR Common Indicators, https://www.ospar.org/work-areas/cross-cutting-issues/ospar-common-indicators, accessed 2022-04-14

Ross D. (1976) Mechanics of underwater noise. Pergamon Press, New York.

American Bureau of Shipping (2021). Practical considerations for underwater noise control. https://ww2.eagle.org/content/dam/eagle/publications/whitepapers/underwater-noise-control-whitepaper-21011.pdf

Stakeholder analysis

The Gothenburg region (2021), Aktörsanalys - Metodguide till samhällsplanerare i Göteborgsregionen. https://goteborgsregionen.se/download/18.61ae4c9917ce9a92048268d8/1638808187847/Bilaga%203,%20Metodguide%20Akt%C3%B6rsanalys_tillg%C3%A4nglig.pdf

Fairway design for reduced noise transmission

Forrest, T. G., Miller, G. L., & Zagar, J. R. (1993). Sound Propagation in Shallow Water: Implications for Acoustic Communication by Aquatic Animals. *Bioacoustics,* *4*(4), 259-270. doi:10.1080/09524622.1993.10510437

A financial incentive for underwater noise reduction in Swedish waters

Clean Shipping Index (2022). Methodology and Reporting Guidelines 2022. Clean Shipping Index, Gothenburg, Sweden.

Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P., & Tyack, P.L. (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals 45(2). https://doi.org/10.1578/AM.45.2.2019.125

Recovery of ship underwater noise measurement equipment

IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // www.ivl.se