Assessing auditory injury from anthropogenic underwater noise on marine mammals

Guidance note

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What is this document about?

This document explains the criteria to be used and how to assess significance and adverse effects on site integrity from hearing injuries to marine mammals, sustained from underwater noise generated by marine development.

Who is this document for?

This guidance is aimed at:

- Those within NRW who may be advising on Environmental Impact Assessment (EIA) and Habitats Regulations Assessment (HRA) of Special Areas of Conservation (SACs) with marine mammal features
- NRW Marine Licensing Team, who may wish to understand how this advice should be applied
- Other Competent Authorities (CA) / regulators / UK Statutory Nature Conservation Bodies who may wish to understand our approach and consider its use in conducting EIA and HRA on sites with marine mammal features
- Developers and their consultants who wish to understand this approach and submit an EIA and applications with enough information to allow the CA to assess sites with marine mammal features in the same way

Version History

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1. Purpose of the Guidance Note

The purpose of this guidance note is to provide information on which criteria to use when assessing auditory injury from underwater noise, and to advise on the approach to take when assessing the level of effect from this impact pathway. It brings our advice up to date with the latest published set of injury criteria.

This guidance note also outlines our specific positions on which metrics to evaluate, how to consider when mitigation is required, and the assumptions that should be made when calculating the impact range. Finally, to help contribute to reductions in conservatism, we have provided some details on approaches that could be used to provide further context to an assessment.

2. Diben y Nodyn Cyfarwyddyd

Diben y nodyn cyfarwyddyd hwn yw darparu gwybodaeth am ba feini prawf i'w defnyddio wrth asesu niwed i'r clyw o ganlyniad i sŵn tanddwr, a chynghori ar ba ddull i'w fabwysiadu wrth asesu lefel yr effaith o'r llwybr effaith hwn. Mae'n diweddaru ein cyngor gyda'r set ddiweddaraf o feini prawf anafiadau a gyhoeddwyd.

Mae'r nodyn cyfarwyddyd hwn hefyd yn amlinellu ein safbwyntiau penodol ar ba fetrigau i'w gwerthuso, sut i ystyried pryd mae angen lliniaru, a'r rhagdybiaethau y dylid eu gwneud wrth gyfrifo ystod yr effaith. Yn olaf, er mwyn helpu i gyfrannu at ostyngiadau mewn ceidwadaeth, rydym wedi darparu rhai manylion am ddulliau y gellid eu defnyddio i roi cyd-destun pellach i asesiad.

3. Position statement

Exposure of marine mammals to loud noise from either continuous or impulsive anthropogenic sources can lead to auditory injury. The most recent set of criteria for noise levels which result in auditory injury can be found in NMFS (2024) which NRW has endorsed. In line with these criteria and the latest evidence, NRW has also adopted the use of the term auditory injury while noting that it includes permanent threshold shift (PTS).

When assessing the impacts of impulsive noise, both noise metrics (peak sound pressure level (SPL_{pk}) and sound exposure level (SEL)) need to be evaluated and in line with the precautionary principle the one predicting the largest range of impact is used to inform the assessment conclusions. Mitigation must be considered for both metrics and whether it is required is determined by the assessment. When carrying out the assessment we assume that: (1) the magnitude of the injury depends only on the total sound exposure regardless of how the sound is distributed in terms of duration or duty cycles (i.e. how much time a noise source is “on” or “off”), and (2) impulsive noise will retain its impulsive characteristics as it propagates.

NRW are aware that ranges of auditory injury onset from impulsive noise are overestimates because current criteria do not account for hearing recovery between impulses or the loss of impulsive characteristics as sound propagates away from the source. Methods are being developed to allow us to consider these aspects (see section 6.3), but more evidence and data are needed before we can definitively use them to inform conclusions in environmental assessments. These methods can currently be used only to provide additional context for informative purposes as they still require further validation.

4. Introduction

Exposure of marine mammals to loud noise can lead to reductions in hearing sensitivity known as "threshold shifts", the magnitude of which can increase depending on the amount and time of noise exposure. These reductions in sensitivity can be temporary threshold shifts (TTS) or result in auditory injury damage to the inner ear that can result in permanent destruction of tissue. Auditory injury includes, but is not limited to, permanent threshold shifts (PTS) which are an irreversible loss in hearing sensitivity at a specific frequency or portion of an animals hearing range. While existing interagency guidance in the UK currently lists PTS but not TTS as an injury (JNCC et al, 2010), the most recent evidence has shown that auditory injury can occur which may or may not result in PTS (NMFS 2024). We therefore advise the use of the term auditory injury while noting that it includes PTS.

Noise sources are defined as impulsive or non-impulsive based on their characteristics at the source (NMFS 2024; Southall et al, 2007, 2019). Impulsive noise is short-duration, is often very loud and has a sudden onset, whereas non-impulsive noise does not have a sudden onset and can be continuous or intermittent. Impact pile driving and seismic airguns are considered impulsive sources, while vessels and vibratory pile driving are considered non-impulsive sources. To avoid complexity, impulsive noise sources are defined by the nature of the sound at the source even though impulsive noise loses its impulsive characteristics at greater ranges (NMFS 2024; Southall et al, 2019). Threshold shifts and auditory injury can be caused by both impulsive and non-impulsive noise. The levels of impulsive or non-impulsive noise that are thought to result in TTS or auditory injury in marine mammals are described by a set of criteria (currently NMFS 2024). These criteria are calculated from TTS data measured in the ear of captive marine mammals but extrapolated for auditory injury since it is unethical to intentionally cause injury in test animals.

To account for the different aspects of noise such as noise exposure and duration, two types of metrics are used to assess for auditory injury - peak sound pressure level (SPL_{pk}) and frequency-weighted sound exposure level, (SEL). SPL_{pk} is a measure of absolute maximum exposure at any one time and is unweighted, whereas SEL is a measure of the sound energy of exposure accumulated over time and is frequency weighted (see Glossary for further explanation). Exceeding either metric is sufficient to result in auditory injury.

The NMFS (2024) criteria have been endorsed by NRW and at the time of publication of this guidance also by other Statutory Nature Conservation Bodies (SNCBs). They supersede the older NMFS (2018) guidelines and the Southall et al (2019) guidelines, which NRW no longer advise use of.

The auditory injury pathway requires assessment under the Marine Works (EIA) Regulations (2007) and/or the Conservation of Species and Habitats Regulations (2017) where they apply to plans or projects or similar. Although the process for assessing auditory injury is the same for both an Environmental Impact Assessment (EIA) and Habitats Regulation Assessment (HRA), significance and assessment methods can differ, e.g. for HRA it is dependent on site conservation objectives. European Protected Species (EPS) are also protected against deliberate injury under the Habitats and Species Regulation (2017), Conservation of Offshore Marine Habitats and Species Regulations (2017) and due attention should be given to avoid the risk of committing a deliberate offence.

This document sets out our advice on how to assess significance (in EIA and EPS terms) and adverse effect on site integrity (AEOSI in HRA terms) from auditory injury to marine mammals as a result of anthropogenically induced underwater noise. It includes which NMFS 2024 criteria to use, which metrics to consider for mitigation, a description of the assumptions to make regarding the characteristics of impulsive noise, and our views on available tools that can help provide additional context and justification to an assessment approach. We are producing a parallel technical appendix to further inform this guidance which will be published in due course.

5. Assessing significance and AEOSI from auditory injury

5.1 Noise modelling

To assess the potential impact of auditory injury, we recommend the use of appropriate bespoke modelling to predict the spread of underwater noise from its source over an increasing area (referred to as sound or noise propagation). The sound level decreases with range, and the distance from the source at which the sound decreases to below the level of auditory injury onset (i.e. the auditory injury threshold) can be determined. The number of animals affected by auditory injury can be estimated by multiplying the maximum area where this will occur by the species density. This can then be used to assess the level of significance or AEOSI from auditory injury (see section 5.3).

5.2 Auditory injury criteria

The most recent set of auditory injury criteria (NMFS 2024), can be found in Table 1 below. Onset of auditory injury (including PTS) is considered to have occurred if either of the two metrics is exceeded.

Table 1. Summary of marine mammal auditory injury criteria (NMFS 2024): (a) underwater; (b) in-air. Decibel values in water have a reference value of 1μPa, decibel values in air have a reference value of 20μPa. For peak sound pressure level, the subscript *"pk"* indicates a zero-to-peak level and the subscript *"flat"* denotes an unweighted threshold. Subscripts for sound exposure level indicate the relevant marine mammal auditory weighting function, and the recommended accumulation period of 24 hours. Refer to the glossary for further information on these terms.

Table 1a: Auditory injury criteria underwater

Hearing Group	Impulsive	Non Impulsive
Low-frequency cetaceans (LF)	$SPL_{pk,flat}$ 222 dB	$SEL_{LF,24h}$ 197 dB

(e.g. Minke whale)	$SEL_{LF,24h}$ 183 dB	
High-frequency cetaceans (HF) (e.g. Bottlenose dolphin, Risso's dolphin)	$SPL_{pk,flat}$ 230 dB $SEL_{HF,24h}$ 193 dB	$SEL_{HF,24h}$ 201 dB
Very high-frequency cetaceans (VHF) (e.g. Harbour porpoise)	$SPL_{pk,flat}$ 202 dB $SEL_{VHF,24h}$ 159 dB	$SEL_{VHF,24h}$181 dB
Phocid pinnipeds in water (PW) (e.g. Grey seal, harbour seal)	$SPL_{pk,flat}$ 223 dB $SEL_{PW,24h}$ 183 dB	$SEL_{PW,24h}$195 dB
Otariid pinnipeds in water (OW)	$SPL_{pk,flat}$ 230 dB $SEL_{OW,24h}$ 185 dB	$SEL_{OW,24h}$ 199 dB

Table 1b: Auditory injury criteria in air

Hearing Group	Impulsive	Non Impulsive
Phocid pinnipeds in air (PA) (e.g. Grey seal, harbour seal)	$SPL_{pk,flat}$ 162 dB $SEL_{PA,24h}$ 140 dB	$SEL_{PA,24h}$ 154 dB
Otariid pinnipeds in air (OA)	$SPL_{pk,flat}$ 177 dB $SEL_{OA,24h}$ 163 dB	$SEL_{OA,24h}$ 177 dB

5.3 Assessment

Many approaches can be used to assess the level of effect from auditory injury and whether that is significant (in EIA terms) or an AEOSI (in HRA terms). Some of these are described below.

A widely used method of assessment is to compare the number of animals injured against the underlying reference population. For EIA purposes, the reference population used is typically the relevant Management Unit (MU) for the species being assessed. For HRA, the site conservation objectives tend to relate auditory injury to population viability either at the site level or the MU level, where typically the species should be maintaining itself in the long term as a viable component of the site. To determine whether this will result in a significant effect or an AEOSI also requires qualitative consideration of other factors such as the degree of injury, impacts of repeated exposures (including cumulative and in-combination), the range of frequencies affected and how this may affect the species in question, stage of life (e.g. presence of an associated calf), sex ratio, and the age of acquisition of the injury (Booth and Heinis 2018; NMFS 2024). This will be based on case by case information and expert judgement in consultation with NRW.

The Interim Population Consequences of Disturbance (iPCoD) model (Harwood et al 2013) can be used to help quantify the impact from auditory injury. However, we note that it should not be the sole approach, given that it is currently based on expert elicitation rather than empirical data to quantify the relationship between the amount of disturbance and injury experienced and its vital rates (i.e. survival and the probability of giving birth) in the model. IPCoD is also intended as a comparative rather than an absolute tool. We would expect that if, as a result of auditory injury, a population shows a continued decline of >1% per year (versus a modelled unimpacted reference population) over a set period of time (e.g. the first 6 years, based on the former Favourable Conservation Status (FCS) reporting period), then there is a high likelihood that a significant effect and AEOSI cannot be ruled out. This is dependent on the case specifics and subject to expert judgement. For further information on the 1% threshold, refer to the technical appendix (to be published in due course) and NRW's position on determining AEOSI in relation to potential anthropogenic removals (NRW, 2022). NRW may consider alternative approaches to iPCoD where adequately justified (e.g. Population Viability Analysis, PVA) in consultation with NRW at the scoping stage.

Given that auditory injury is predicted to have little effect on the vital rates of animals (Booth and Heinis, 2018), we expect that the number of animals impacted would need to be very high to lead to a measurable modelled effect on the impacted population. With regard to this impact pathway we therefore note that minimising the risk of committing an injury offence on an EPS is of greater concern. JNCC has developed a suite of mitigation guidelines in collaboration with other SNCBs to help reduce potential impacts from impulsive noise sources to marine mammals. Mitigation guidelines have been developed for geophysical surveys, impact piling and explosive use in the marine environment and these are also usually industry best practice:

- JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys (seismic survey guidelines) | JNCC Resource Hub
- Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise | JNCC Resource Hub
- JNCC guidelines for minimising the risk of injury to marine mammals from explosive use in the marine environment | JNCC Resource Hub

6. Metrics to use, assumptions, and tools that can provide additional context

6.1 Metrics

We advise the use of dual metrics for impulsive noise: peak sound pressure level (SPL_{pk}) and sound exposure level (SEL) in line with NMFS (2024) and Southall et al (2019) previously. These two metrics are applied under the condition that exceeding either threshold is sufficient to result in auditory injury onset. In accordance with the precautionary principle the metric predicting the largest range of impact should be used for the impact assessment, and whether mitigation of this pathway is required will be determined by the assessment.

Sound exposure can be cumulative over multiple repeated impulsive noise exposures that occur in rapid succession (e.g. a pile driving sequence). This is referred to as cumulative sound exposure (SEL_{cum}) and the same thresholds as SEL are used since the exposure builds over many events instead of just one.

6.2 Assumptions on TTS onset and impulsive noise

At present, criteria for TTS onset (used in auditory injury estimation due to the unethical nature of intentionally causing auditory injury in test animals) are based on cumulative exposure over all impulsive noise events, without taking into account the recovery of hearing that takes place between successive impulses. As a result this leads to overestimates of the range of auditory injury onset.

When calculating the cumulative sound exposure we assume that equal sound exposures have the same TTS growth – in other words threshold shifts are dependent only on the total sound exposure regardless of how the sound is distributed in time. This is known as the equal energy hypothesis. Some studies have shown that exposures to noise with equal SEL but with different levels, durations and duty cycles do not result in the same amount of TTS and that quiet periods between noise exposures will allow some recovery of hearing (e.g. Kastelein et al 2014, 2016; von Benda Beckman et al 2020, 2022). However, the current consensus is that more data is needed before we can apply these findings to the conclusions of noise impact assessments (Finneran 2015; von Benda Beckman et al 2020, 2022; Southall 2021; NMFS 2024). This means that, at present, there is insufficient evidence to depart from the use of the cumulative sound exposure metric based on the equal energy hypothesis.

At ranges over several kilometres impulsive noise gradually also loses its impulsive characteristics and becomes more non-impulsive in nature due to refraction, absorption and scattering attenuating high frequencies more than low frequencies. Sound also reflects off the surface and bottom of the sea taking different paths, thus it takes a different amount of time to arrive at a given point, lengthening the pulse (Hastie et al 2019; Martin et al 2020). In this way noise that is impulsive at the source becomes less likely to cause injury at longer range. However, we do not yet have enough data about these changes in impulsive character to be able to apply them to impact assessments or to advise distances at which noise can be considered non-impulsive (Southall 2021; NMFS 2024; Matei et al 2024).

6.3 Approaches and tools that can provide additional context in an assessment

Approaches and tools to allow the findings discussed above to be applied to TTS growth calculations have been proposed and are being developed further by academic research. These include the modified power law model (von Benda Beckman et al 2020) and the kurtosis-corrected SEL model (von Benda Beckman et al 2022; Lucke et al 2022). The current consensus is that more evidence and data are needed before we can definitively apply these findings to inform the conclusions in environmental assessments (Finneran 2015; von Benda Beckman et al 2020, 2022; Southall 2021; NMFS 2024). These methods can currently be used in an assessment, but only to provide additional context for informative purposes as they still require further validation.

The modified power law model allows us to predict TTS growth by including hearing recovery between each noise exposure. It can reasonably predict TTS growth for intermittent and continuous sonar sounds of 1-2 kHz. However, it currently tends to underestimate TTS growth from impulsive sound and higher sonar frequencies (von Benda Beckman et al 2020).

The kurtosis-corrected model uses a metric of the impulsiveness of noise (i.e. a measure of "peakiness" of the noise) to apply a correction to the frequency-weighted sound exposure level (SEL). This avoids the need to (arbitrarily) determine whether a sound is impulsive or non-impulsive, as there is a smooth transition between sound types with range (Lucke et al 2022). Von Benda Beckman et al (2022) tested this approach and concluded that a species-specific or hearing group-specific adjustment factor was required for more accurate predictions. They also noted that the model could not adequately explain the differences between continuous and intermittent noise, most probably because it does not account for recovery between pulses.

A PTS framework was developed through the Range Dependent Nature of Impulsive Noise project (Matei et al 2024). This framework consists of an agent based model of an animal moving through a soundscape away from the source and has been made available for use in a public GitHub repository. The framework was used to assess how PTS impact ranges varied across different scenarios (e.g. by varying source levels, transmission loss, piling timeline, swim speed, and specifying the distance at which impulsive sounds transition to non-impulsive). Simulations also indicated that the transition from impulsiveness to non-impulsiveness would need to occur at distances less than 5 km from the source in order to have a meaningful impact on PTS onset ranges, and time between pile strikes and swim speed had a greater impact on PTS onset than the impulsive transition. While follow-up work is being done to expand the framework, we advise that it can be used to help design installation blow patterns to help mitigate impacts at the design or pre-consent stage, thus acting as an embedded mitigation tool (Matei et al 2024), but cannot as yet be used to develop criteria for the transition between impulsive and non-impulsive noise for environmental assessments.

7. Glossary

Some definitions useful for this position statement are given below. Mathematical symbols for levels used in underwater acoustics as defined by ISO18405:2017 are provided with abbreviations in brackets.

- Auditory injury: Damage to the inner ear that can result in destruction of tissue. This may not always result in a permanent threshold shift.
- Cumulative sound exposure level, $L_{E,p,24h}$ (SEL_{cum}): the SEL summed up over the duration of exposure to multiple events such as for a pile driving sequence. NMFS (2024) recommends a 24-hour integration period to account for cumulative sound exposure of an activity. It is intended for individual activities and sources and currently

is not intended for accumulating sound exposure from multiple activities occurring within the same area or over the same time or to estimate the impacts of those exposures to an animal occurring over various spatial or temporal scales. However, NMFS (2024) recognises that there may be situations where the 24-hour accumulation period needs adjustment (e.g., if activities last less than 24 hours, or if receiving individuals are expected to experience unusually long noise exposures) (unit: dB re 1 $\mu Pa^2 s$).

- Duty cycle: how much time a sound source is “on” or “off”, usually expressed as a percentage. This term is often used when describing active acoustic sources such as sonar.
- Equal energy rule: the assumption that threshold shifts depend only on the total sound exposure regardless of how the sound is distributed in time. For example, if the cumulative sound exposure of two sources is the same, a lower level source over a longer duration is predicted to cause the same amount of hearing loss as a higher level source over a shorter duration.
- Frequency weighting / auditory weighting: a process where the frequency content of a sound is weighted according to a weighting curve to obtain the sound level experienced by an animal. They are applied to SEL values but not SPL. The most up to date weighting curves (e.g. NMFS 2018; Southall et al 2019; NMFS 2024) are based on the audiograms of animals, which are graphs that show the detection threshold (y-axis) against frequency (x-axis) for a species, or group of species with similar hearing capabilities. Essentially, a weighted sound level mimics the filtering effect of a mammalian ear, where some acoustic energy is filtered out for frequencies which an animal is less sensitive to. For harbour porpoise, for example, the most commonly used weighting is the very high frequency (VHF) group audiogram in NMFS (2024). Similarly, for bottlenose dolphin, the high frequency (HF) group audiogram is used, and for grey seal the phocids in water (PW) group audiogram is used. Other weightings exist such as M-weightings from Southall et al (2007), and type II weightings from Finneran and Jenkins (2012).
- Impulsive noise: a pulsed short-duration broadband sound that has a sudden onset and is often loud. Sources can include pile-driving, airguns, and detonation of unexploded ordnance (UXO). For simplicity, here we define impulsive noise sources based on their characteristics at the source, despite known effects that take place at greater ranges (over several kilometres) where impulsive noise gradually loses its impulsive characteristics.
- Kurtosis: a statistical measure of how “peaky” or “pointy” a data distribution is. When applied to a sound signal, it can be used to characterise the impulsiveness of sound in an objective way – the greater the kurtosis, the more impulsive a sound is.
- Non-impulsive noise: sounds where the acoustic energy is spread over a significant time, from seconds to hours. The amplitude of the sound can vary, however it does not fall to zero for any significant amount of time. The sound may contain broadband or tonal noise at specific frequencies, and can be brief or prolonged, continuous or intermittent. It typically does not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do. Sources can include shipping, dredging, or operational noise from turbines.
- Peak sound pressure level, $L_{p,pk}$ or $L_{p,0\text{-}pk}$ (L_{pk}, commonly used notation: SPL_{pk}): the unweighted peak sound pressure level is the absolute maximum noise level at any one time, and is often used to characterise impulsive noise. Peak sound pressure level is determined by measuring the maximum variation of pressure from the positive peak to zero within the wave. This is referred to as zero to peak, or $L_{p,0\text{-}pk}$. Similarly, the peak-

to-peak sound pressure level is obtained by measuring the difference between the maximum and minimum variation of pressure within the wave. This is referred to as peak to peak, or $L_{p,pk-pk}$. While we are aware that the abbreviation peak SPL has been deprecated in ISO18405:2017 (with L_{pk} suggested as the alternative abbreviation), for the purpose of this guidance we have retained the more commonly known used notation SPL_{pk} (unit: dB re 1 μPa).

- Permanent threshold shift (PTS): A permanent and irreversible loss of hearing sensitivity (i.e. increase in the hearing threshold) at a specified frequency or portion of an animals hearing range.
- Power law: a mathematical expression where something is proportional to a constant power of something else. When additional parameters are included, it is then referred to as a modified power law.
- Sound exposure level, $L_{E,p}$ (SEL): the sound exposure level is a measure of the sound energy of exposure accumulated over a specified time interval or event. Often this metric is normalized to a single sound exposure of one second, although ISO 2017 indicates that the time duration be specified with this metric e.g. $L_{E,P,100ms}$. Where a specific frequency weighting function is applied, this should be indicated by appropriate subscripts. It is used to assess noise from both impulsive and non impulsive sources (unit: dB re 1 μPa^{2}s).
- Sound Pressure Level, L_p / $L_{p,rms}$ (SPL): is considered to be a measure of the average unweighted level of sound over a given measurement period (by taking the root-mean-square of the pressure of a sound signal), and is typically used to characterise noise from a non-impulsive / continuous source (unit: dB re 1μPa).
- Temporary threshold shift (TTS): A temporary and recoverable loss of hearing sensitivity (i.e. increase in the hearing threshold) at a specified frequency or portion of an animals hearing range.

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