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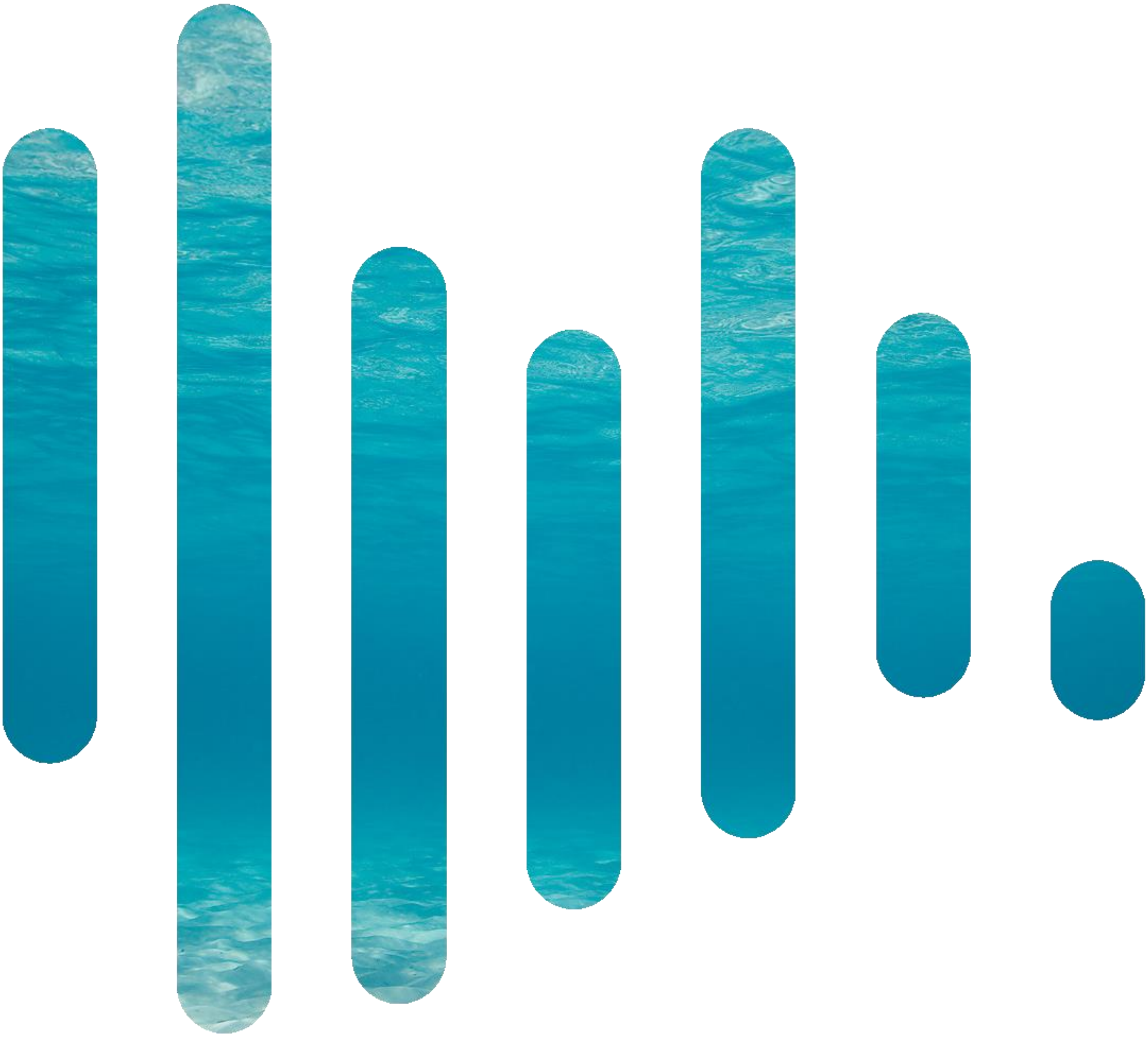

SRI Framework
Methods

Rp001 2017272 (Sound Risk Indicator)

25 March 2020

PROJECT: SOUND RISK INDICATOR FRAMEWORK – METHODS

PREPARED FOR: EQUINOR ASA

ATTENTION: JÜRGEN WEISSENBERGER

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1.0 MOTIVATION

Assessing the impact of underwater noise is a complicated task. There are multiple reasons for this, many of whom relate to the complexity of the marine habitats as well as the fauna within it. For an accurate assessment it is necessary to consider all these factors. We argue that this complexity can cause some confusion along with large variability in the quality of assessment, leading to potential distrust, and therefore disregard for underwater noise assessments. Given the importance of our marine resources such a scenario is highly unfavourable.

As noise propagation modelling can be a cumbersome and slow procedure, we propose the use of a **Sound Risk Indicator** (SRI) value being assigned to a noisy activity early on in the design phase. This value can be used as a guide to rapidly assess what effect changes to the activity have on the environmental acoustic impact of the activity. With changes in the activity the SRI can quickly be updated and will either increase (more noisy) or decrease (less noisy) in response to changes in activity methods. In this way the framework and associated software tool can help in planning activities while continually keeping an eye on the environmental acoustical impact changes.

This report is one part of a two-part framework:

1. SRI Methods (This Document)

The methods described in the Theory document will be applied with suggested marine animal acoustic weightings as well as examples of practical usage. The “SRI-Tool” (software package) will also be presented here.

2. Theory

In the Theory document, the theoretical background for a method to index noisy marine activities is described. The purpose of the Theory document is to guide the reader through the theoretical considerations forming the background of the calculation of a Sound Risk Indicator (SRI).

The reader of this document is asked to remember that the sole purpose of this document is to describe the methods for calculating a Sound Risk Indicator from a rather limited information base, and not to discuss propagation losses nor the ecosystem impacts of anthropogenic noise.

1.2 ABBREVIATIONS

SRI	Sound Risk Indicator
dB	decibel, 0.1 x Bell: logarithmic unit used for sound pressure ratios
SEL	Sound Exposure Level
z-p	“zero-to-peak”
p-p	“peak-to-peak”
RMS	Root Mean Square
TL	Transmission Loss, in dB unless otherwise stated
ICC	Irwin Carr Consulting
NOAA	National Oceanic and Atmospheric Administration (of the USA)
TTS	Temporary Threshold Shift
PTS	Permanent Threshold Shift
Timeseries, TS	A series of pressure values sampled with a constant time interval
dBSea	Underwater noise propagation modelling and visualisation software
SH2019	According to (Southall, et al., 2019)

2.0 INTRODUCTION

In this document we propose that with a highly simplified approach, one can index noisy activities in such a way that a reduction of a calculated index value (Sound Risk Indicator, **SRI**) will result in a real-world reduction of environmental acoustic impact. We also describe the methods and considerations behind this proposal. While we repeatably use theory from the acoustic propagation modelling literature, this is *not an exercise in acoustic modelling*. The methods described here will lead to an index value (SRI), based on a relatively small amount of initial information about the environment and the sound source(s) involved.

This approach assumes a scenario where the user has limited or incomplete information about the activity, the surroundings and the presence of acoustically sensitive species.

In general, the SRI rests on a principle of quantifying the area affected by a noisy activity in a fictitious environment by using simple logarithmic spreading models and absorption. By introducing spectral information of the source, the receiver and a threshold, a corresponding range to that threshold can be calculated.
The area given by this range is used to calculate the SRI.

The use of transmission models is not an attempt to calculate real-world propagation, but solely to have a standardised way of generating an index number from initial values. The logarithmic propagation models were chosen as they ensure that SRI scales well with changes in source level and receiver sensitivity.

This document focuses on the application of the tool and covers the inclusion of suggested thresholds as well as examples of use.

2.1 ADDITIONAL USES

A separate use for the tool, besides the primary goal of assisting comparisons, is that we here use a propagation model that aims to find the minimal realistic transmission loss. This has the effect of providing some real-world reference in the model, and further makes it very unlikely that real-world impacts are larger than indicated in the tool. This is not the main purpose of the tool, but rather a consequence of the applied methods.

2.2 UNITS

Throughout this document we will strive to be consistent and strict in the use of terminology relating to units and here bring an overview of the definitions used:

Table 1. Units used throughout the report. Please see ISO 18405-2017 for more details.

Unit	Definition	Comments
dB_{RMS} ISO 18405-2017: 3.2.1.1	$dB_{RMS} = 10 \cdot Log_{10}\left(\frac{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	Functionally equivalent to deprecated $20 \cdot Log_{10}\left(\frac{RMS}{1 \cdot 10^{-6} Pa}\right)$
$dB_{z\text{-}p}$ ISO 18405-2017: 3.2.2.1	$dB_{z-p} = 20 \cdot Log_{10}\left(\frac{Pa_{max}}{1 \cdot 10^{-6} Pa}\right)$	This assumes that Pa_{max} is equal or greater than $\sqrt{Pa_{min}{}^2}$
$dB_{p\text{-}p}$ ISO 18405-2017: 3.1.2.8	$dB_{p-p} = 20 \cdot Log_{10}\left(\frac{Pa_{max} - Pa_{min}}{1 \cdot 10^{-6} Pa}\right)$	Often[1] equivalent to $dB_{z-p} + 6.02\ dB$
dB_{SEL} ISO 18405-2017: 3.2.1.5	$dB_{SEL} = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	For continuous sound this is equivalent to $dB_{RMS} + 10 \cdot Log_{10}(t_2 - t_1)$

Additional to the above units we might indicate a time associated with the unit. E.g. "$dB_{SEL\text{-}24h}$" is taken to mean the dB_{SEL} value over a 24-hour interval, "$dB_{SEL\text{-}impulse}$" is the dB_{SEL} value of a single impulse and "$dB_{RMS\text{-}1000}$" is the dB_{RMS} value with an averaging window of 1000 milliseconds.

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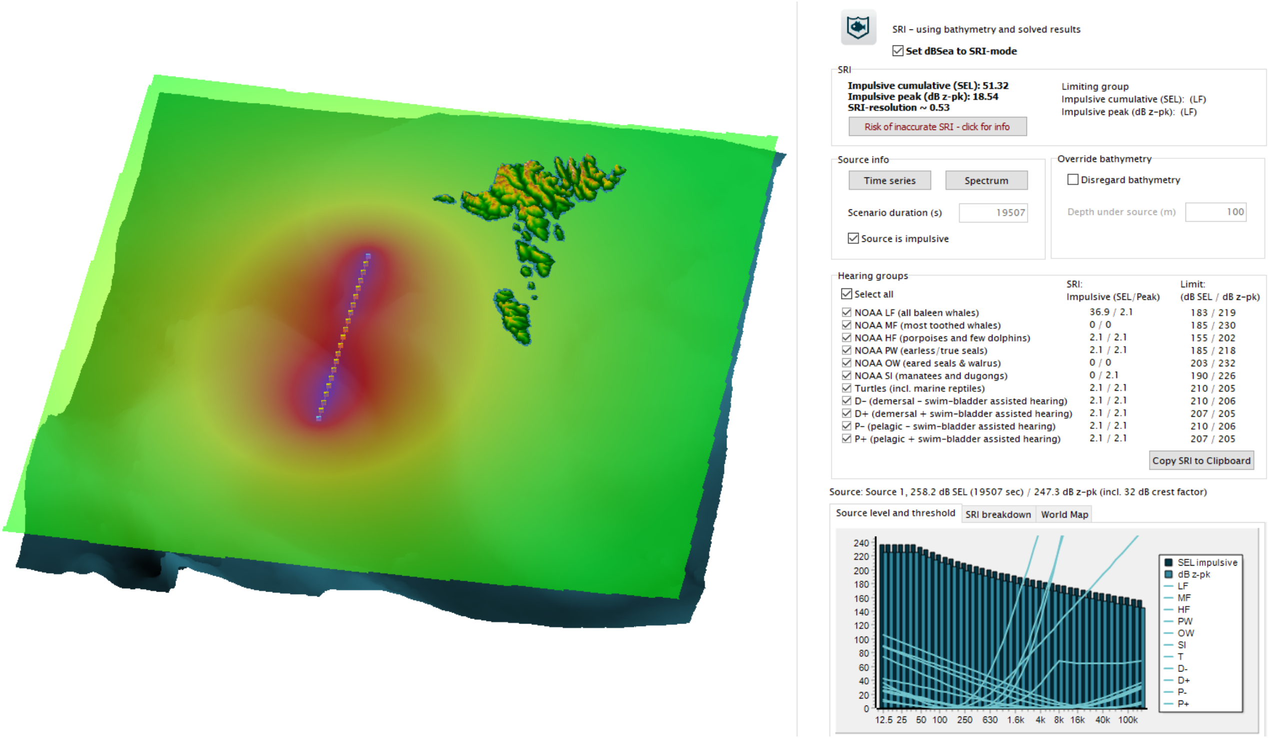
[1] If pulse is below ambient pressure and compression and rarefaction phases are of equal size.

3.0 OVERVIEW OF THE TOOL

The SRI-tool is based on the “dBSea software[2]”, and thus shares basic graphical layout with this. The user is presented witch a large window showing the current environment and a smaller frame allowing settings to be accessed (Figure 1) as well as showing results. General operation of the tool is done primarily through mouse clicking and copy/pasting from spreadsheets or text files.

Figure 1. Example of the SRI-tool user interface, showing a seismic survey track south-east of the Faroe Islands. Note that the SRI has two parts when evaluating impulsive noise sources: Cumulative energy (SEL) and peak pressure (dB $_{z-p}$). Further, the individual SRI values from the different hearing groups are also displayed.



SRI – using bathymetry and solved results

☑ Set dBSea to SRI-mode

SRI

Impulsive cumulative (SEL): 51.32
Impulsive peak (dB z-pk): 18.54
SRI-resolution ~ 0.53

Limiting group
Impulsive cumulative (SEL): (LF)
Impulsive peak (dB z-pk): (LF)

Source info

Scenario duration (s) 19507

☑ Source is impulsive

Override bathymetry

☐ Disregard bathymetry

Depth under source (m) 100

Hearing groups

☑ Select all	SRI: Impulsive (SEL/Peak)	Limit: (dB SEL / dB z-pk)
☑ NOAA LF (all baleen whales)	36.9 / 2.1	183 / 219
☑ NOAA MF (most toothed whales)	0 / 0	185 / 230
☑ NOAA HF (porpoises and few dolphins)	2.1 / 2.1	155 / 202
☑ NOAA PW (earless/true seals)	2.1 / 2.1	185 / 218
☑ NOAA OW (eared seals & walrus)	0 / 0	203 / 232
☑ NOAA SI (manatees and dugongs)	0 / 2.1	190 / 226
☑ Turtles (incl. marine reptiles)	2.1 / 2.1	210 / 205
☑ D- (demersal - swim-bladder assisted hearing)	2.1 / 2.1	210 / 206
☑ D+ (demersal + swim-bladder assisted hearing)	2.1 / 2.1	207 / 205
☑ P- (pelagic - swim-bladder assisted hearing)	2.1 / 2.1	210 / 206
☑ P+ (pelagic + swim-bladder assisted hearing)	2.1 / 2.1	207 / 205

Source: Source 1, 258.2 dB SEL (19507 sec) / 247.3 dB z-pk (incl. 32 dB crest factor)

Accessing the tool puts the dBSea software into “SRI-mode” and lets the user specify sources, movement and receivers. Setting the SRI-mode changes the tool to use the SRI-propagation model and also sets the level types that are displayed to dB$_{SEL}$.

3.1 DEFINING THE SOURCE

The noise source forms the basis of any noise impact assessment, and often we can say a lot about the likely impact of an activity just by knowing the broadband level of the noise source, but the addition of more detailed information on the energy per frequency band, allows a much better impact index to be calculated.

The tool offers two ways for the user to define a source, one is based on octave or 3rd octave band levels, the other on importing a timeseries of the noise event. This could be a recording of a seismic source, a piling impulse or something else the user wishes to use.

3.1.1 Source from spectra or band levels

The user can input a custom level and/or spectrum in the range 12.5 Hz to 168 kHz in octave- or 3rd octave-bands. The user can also choose from a range of predefined noise sources (e.g. generic pile driving, seismic array or a vessel) and then adjust the broadband level to match the desired level.

The source level can be entered as either dB$_{SEL}$, dB$_{RMS\text{-}1000}$ or as intensity, dB re 1 pW, and, if known, a crest factor can be applied as well.

Additionally, two models for generating realistic sound sources are included:

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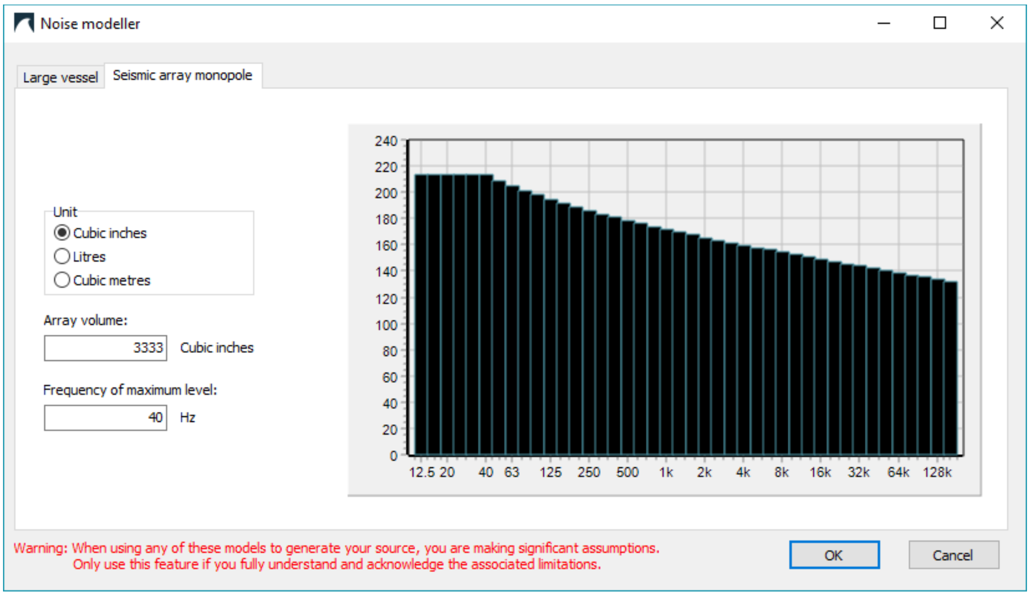
[2] http://www.dbsea.co.uk/

1.1.1.1 Simplified Seismic Source Level Calculator

For seismic sources where just the volume of the array is known we include an option to enter the array volume and the tool will generate an equivalent point source based on this. The method is very crude by design and based on generalising data from published seismic array far-field levels (Cotton, 2003; Sutton, Jessopp, Clorennec, & Folegot, 2014). More details and considerations are available in the “Scientific Remit” document.

The model produces a dB$_{z\text{-}p}$ within 1.3 dB of the observed values (from publications mentioned above) in the frequency range 40 Hz to 63 kHz.

Figure 2. Example of the seismic source model from the SRI software.



Unit
● Cubic inches
○ Litres
○ Cubic metres

Array volume: 3333 Cubic inches

Frequency of maximum level: 40 Hz

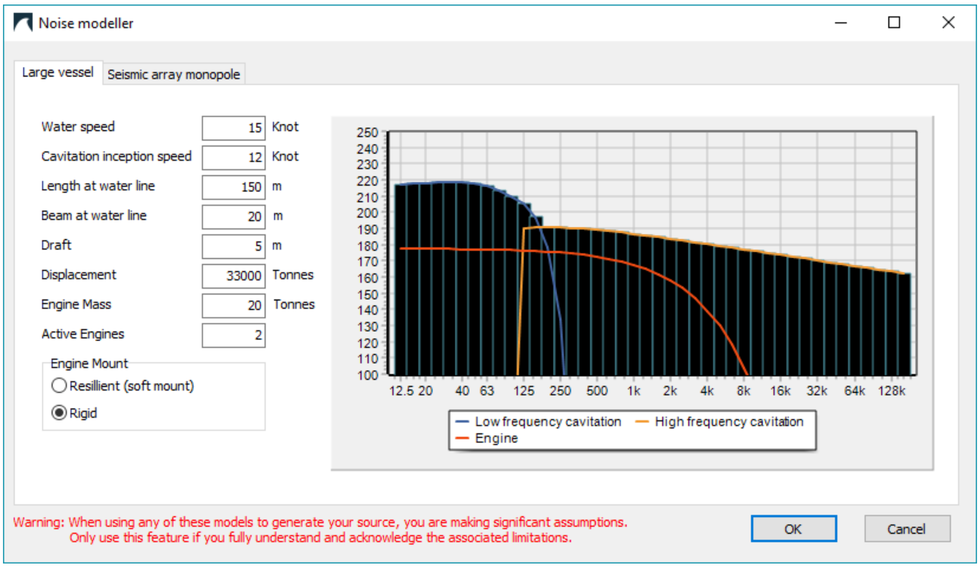
Warning: When using any of these models to generate your source, you are making significant assumptions.
Only use this feature if you fully understand and acknowledge the associated limitations.

Please note that we have limited the level at the lowest frequencies. This is done as the model generally overpredicts levels at very low frequencies (< 40 Hz), these frequencies would otherwise have a large impact on the calculated impact ranges.

1.1.1.2 Large vessel noise model

Additionally, we have implemented a source generator for large vessels following the model by (Wittekind, 2014) to facilitate use of realistic sound sources, should the user not have their own data. This model takes input about the vessel and engine size along with design information about operating speeds and engine mounting method.

Figure 3. Example of a menu letting the user generate a large vessel noise source.



Water speed	15	Knot
Cavitation inception speed	12	Knot
Length at water line	150	m
Beam at water line	20	m
Draft	5	m
Displacement	33000	Tonnes
Engine Mass	20	Tonnes
Active Engines	2	

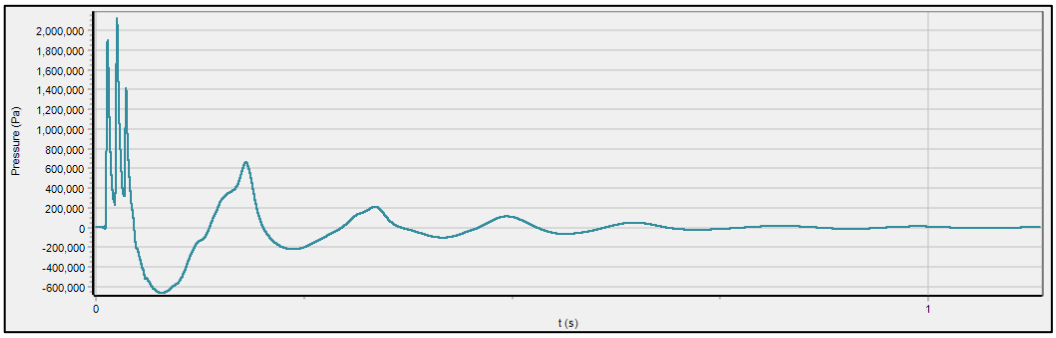
Engine Mount
○ Resilient (soft mount)
● Rigid

Warning: When using any of these models to generate your source, you are making significant assumptions.
Only use this feature if you fully understand and acknowledge the associated limitations.

3.1.2 Source from timeseries

The user can choose to import a timeseries of an event to evaluate the SRI of that event. The imported signal will be band filtered to generate a dB$_{SEL\text{-}impulse}$ and a crest-factor that will be used to calculate the impact ranges that form the basis for the SRI. (for details on the calculations see the “Scientific Remit” report).

Figure 4. Example of timeseries of a seismic array impulse.



4.0 SRI WEIGHTINGS

A large part of the SRI framework rests on the idea of using the acoustic sensitivity of marine species groups to give the user some insight into species groups that are more likely to be at risk from the proposed activity or be affected most by changes in that activity.

The tool has eleven species groups built-in:

1	LF	NOAA LF cetaceans (all baleen whales)
2	MF	NOAA MF cetaceans (most toothed whales, incl. Ziphiidae & Physeteridae)
3	HF	NOAA HF cetaceans (porpoises, few dolphins & Kogiidae)
4	PW	NOAA PW (earless/true seals)
5	OW	NOAA OW (eared seals, walrus, otter & polar bear)
6	SI	NOAA sirenians (manatees and dugongs)
7	T	Turtles (incl. marine reptiles)
8	D-	Fish, Demersal, no swim-bladder assisted hearing
9	D+	Fish, Demersal, swim-bladder assisted hearing
10	P-	Fish, Pelagic, no swim-bladder assisted hearing
11	P+	Fish, Pelagic, +swim-bladder assisted hearing

The six NMFS/NOAA weightings and thresholds are defined and justified in (NOAA, 2016; NOAA, 2018) and will not be justified further[3]. These weightings are identical to the weighting suggested by Southall et al in 2019, only the names differ (Southall, et al., 2019).

In this framework we initially adopt a “threshold-type” version of the curves[4], as it allows us to have a consistent approach to all hearing groups using the general equation on page 13 of the NMFS guidance document (NOAA, 2018) but adjusting the most sensitive region to the levels given in table A7, page 77 of the document (NOAA, 2018).

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[3] These limits coincide with the proposed limits in the unpublished revision of (Southall, et al., 2007) due to be published in 2019, albeit under different names.

[4] We are aware that the NOAA curves are wider than their actual hearing threshold counterparts, but applying this framework allows some consistency between fishes and mammals.

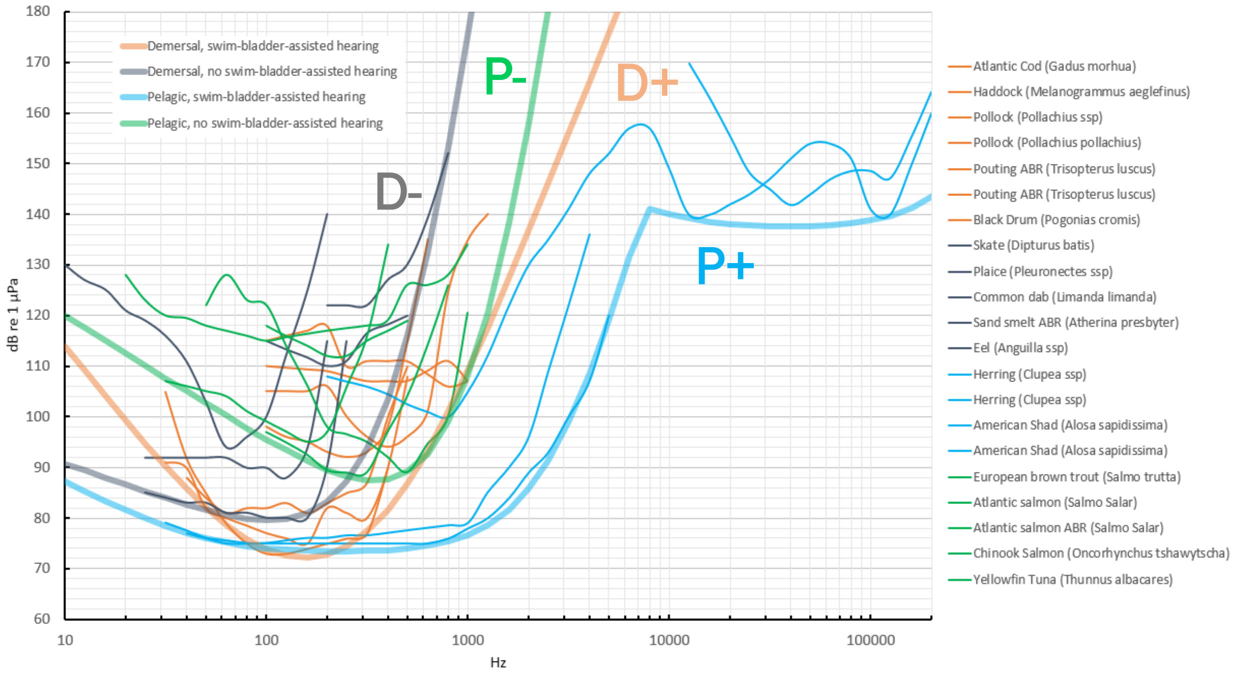
$$E(f) = K - 10\cdot\log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2a}}{\left(1+\left(\frac{f}{f_1}\right)^2\right)^a\cdot\left(1+\left(\frac{f}{f_2}\right)^2\right)^b}\right) \tag{2}$$

“E” is detection limit in $\text{dB}_{\text{RMS-1000}}$ at a specified frequency. “K” is a vertical offset to adjust the minimum sensitivity. “a” determines low-frequency roll-off in sensitivity (20 · a dB/decade). “b” determines high-frequency roll-off in sensitivity (20 · b dB/decade). Lower and higher “limit” of best hearing are given by “f_1“and “f_2”.

4.1 FISH

Of the remaining five groups, four are fishes (D-, D+, F-, F+), and the weightings are derived from composites of auditory thresholds from fish separated into groups depending on their auditory thresholds, habitats and hearing mechanism (turtles are dealt with later). These groups have audiograms defined by the most sensitive species[5] in each group and curves for each group were adapted from the NOAA curve equations by curve fitting[6] to give generalised thresholds. Other authors (BOEM, 2014) have made similar suggestions for hearing groups, but with an approach to grouping based solely on the spectral sensitivity of the species. The groups proposed here are based also on habitat affinity as we found that this was an easier metric for a user of the tool to determine.

Figure 5. Thresholds for the four fish groups part of the framework. The four groups are based on the normal habitat of the fish along with information on whether the fish’s swim-bladder is an important component for hearing. Also see Figure 7 for comparison of all thresholds and weightings.



Note that certain species of soldierfish (*Myripristis kuntee*) and fresh-water fish have been omitted even though data was available for these species. The soldierfish live in tropical regions, and are highly specialised and should be assessed as a specialised case with a separate threshold. Fresh-water fish live in habitats that are of smaller interest to the industry and therefore to this framework (i.e. very few seismic surveys are done in lakes). This is not meant as a de-prioritisation of fresh-water fish, but rather the result of a wish to make the hearing groups representable of species most likely impacted by industry.

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[5] In this respect we deviate from the NOAA method of adopting the median level.

[6] Parameters in Eq. 11 were changed until R^2>0.95 or until no further increase in R^2 could be achieved.

Table 2. Constants used in Eq. 12 to obtain the curves for fish and turtles. See explanation under equation (2) for description of constants. Note: to include the clupeiformes high-frequency hearing, the "P+" group has a composite hearing threshold.

	D+	D-	P+		P-	T
	Demersal, swim-bladder-assisted hearing	Demersal, no swim-bladder-assisted hearing	Pelagic, swim-bladder-assisted hearing		Pelagic, no swim-bladder-assisted hearing	Turtles
			< 8000 Hz	>= 8000 Hz		
a	2.5	0.7	1	1	1.25	1
b	5	15	8	10	15	20
f_1	0.09	0.3	0.05	10	1	1
f_2	0.4	0.5	3	500	1.2	2
K	-1	-2.11	73	137	70	67

4.2 TURTLES

Turtles are harder to establish a weighting for as the data is very sparse indeed. We have based weightings and thresholds on available data (Ketten & Bartol, Functional Measures of Sea Turtle Hearing, 2005; Popper, et al., 2014; Christensen-Dalsgaard, et al., 2012; Piniak, Mann, Harms, Jones, & Eckert, 2016; Piniak, Eckert, Harms, & Stringer, 2012; KJ, SC, & JC, 2012) and chosen the minimum values to represent turtle hearing thresholds (Figure 6 below).

Figure 6. Summary of hearing data for turtle species.

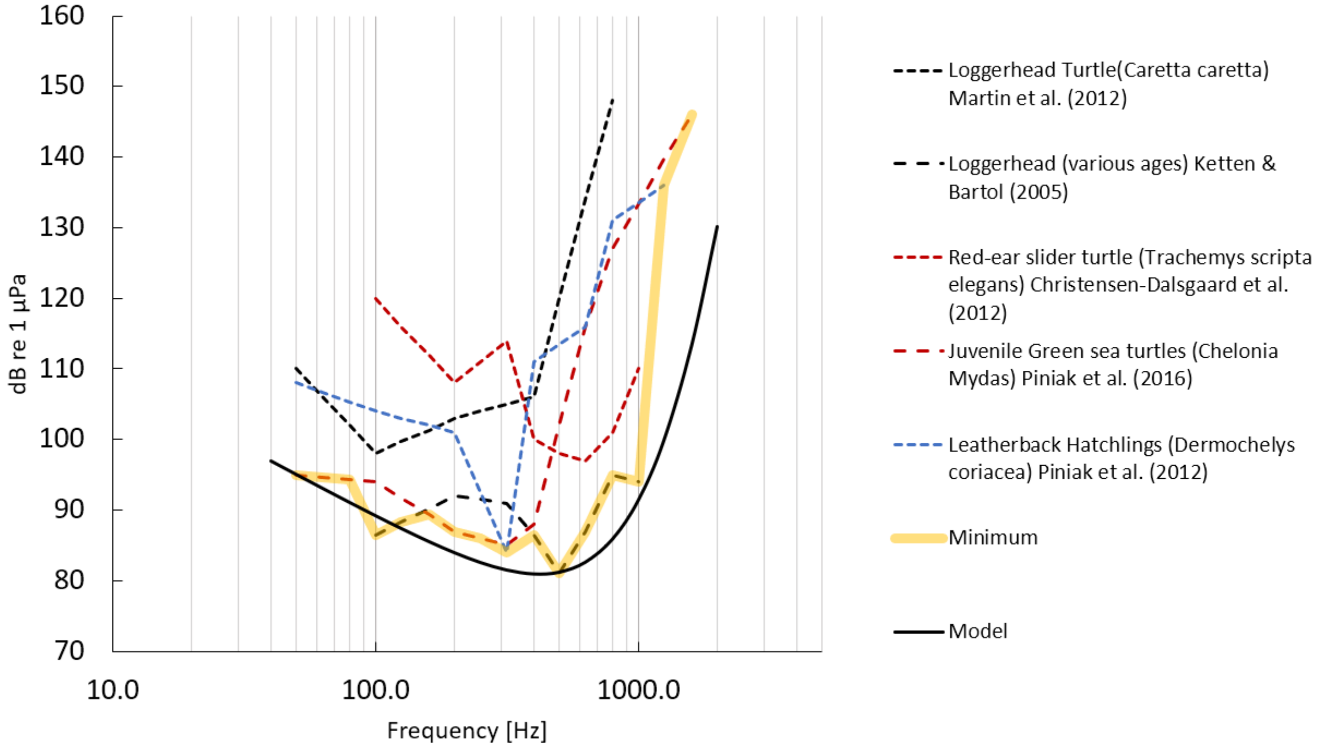
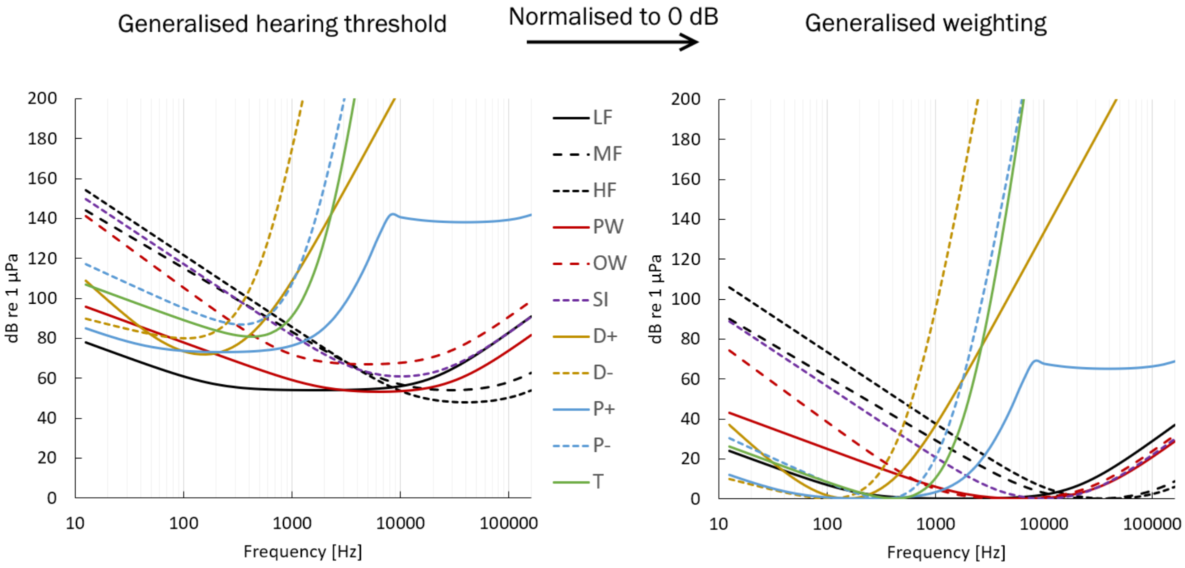


Figure 7. Generalised group hearing thresholds are normalised to generate weightings. Weightings can then be subtracted from non-dB$_{z\text{-}p}$ noise levels to achieve weighted noise levels, dB$_{wgt}$.



4.3 TTS/PTS LIMITS

For the six marine mammal groups (NOAA, 2018; Southall, et al., 2019), TTS and PTS thresholds are summarised below (Table 4, p. 15). For the fish groups and turtle group, the same framework for limits cannot be applied as easily. In the following we hope to make our choices and consideration clear.

PTS in mammals is associated with irreversible damage to the hearing, but fish can often repair the structures associated with their hearing (Lombarte, Yan, Popper, Chang, & Platt, 1993; Smith, Kane, & Popper, 2004). This suggest that conventional PTS, as understood for mammals[7], does not exist for fish, and further implies that any auditory system damage to fish really is temporary, and therefore TTS.

While the TTS onset limit is often set for mammals at noise levels resulting in 6 dB TTS (NOAA, 2018), there is no such agreed value for fish that we could find. A linear relation between threshold shift and received levels has been proposed (Smith, Kane, & Popper, 2004) and suggests that a TTS of 6 dB occurs at 38 dB above hearing threshold for the fish tested in that study. Adopting this approach would lead to TTS thresholds of 90 dB$_{RMS}$. This limit is very low compared to limits for TTS published in, or derived from other studies (DFO Canada, 2006; Carlson, Hastings, & Popper, 2007; Popper, et al., 2014), and we consequently use a different approach.

It is possible that a complete framework for fish TTS and PTS can be developed on the basis of a linear function TTS-onset threshold methodology, but as we here wish to have *one* similar approach for all hearing groups we propose a different set of thresholds for fish based on results from a variety of in vivo exposures and guidelines (DFO Canada, 2006; Carlson, Hastings, & Popper, 2007; Popper, et al., 2014).

From the DFO study (DFO Canada, 2006) we have gathered all results that state the received level with less than 6 dB uncertainty and summarised the impacts from those 39 studies / 50 experiments. We have categorised the effect of the noise exposure into six categories depending on severity (Table 3, p. 14). The mean level from each effect group has been used as the limit.

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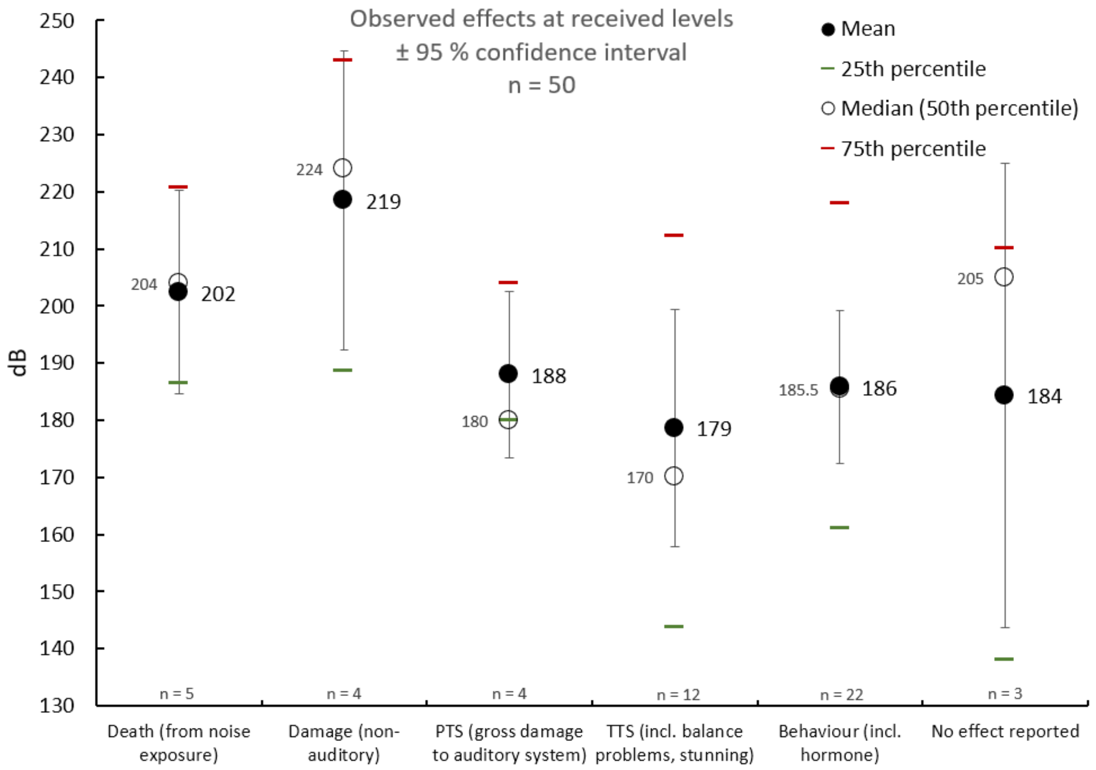
[7] Permanent worsening of hearing, understood to be caused by structural damage to the auditory pathway.

Figure 8. Summary of reported results from (DFO Canada, 2006). Mean (solid dots), median (circles), 25th percentile (green line), 75th percentile (red line) and 95 % confidence interval (error bars) show that the data has high variation for all categories. “n” numbers refer to number of experiments.



As the data is based on studies with various foci, meaning that not all effects with relevance for noise limits were checked. As a consequence several studies only reported directly observable changes, with no evaluation of e.g. hormone levels or of possible non-visible injuries. Therefore, the data only represents effect-*presence* and does not provide robust grounds for determining effect-*absence*.

The data does not show clearly the expected correlation between noise level and severity of impact, but rather shows that large variation in impact exist between experiments, species and source types. A clear example of this is evident in the mean from effect groups “Death” and “Damage” where group “Death” has a lower limit than “Damage”, contradicting what one might expect from increasing exposure levels. Keep in mind that there are few studies and that many mortality studies only focussed on mortality, while some damage/injury studies did not report mortality.

Table 3. Summary of part of the data used to generate TTS and PTS limits for fish. Please note that while it can seem counterintuitive that the limit of "Physical injury" is higher than the "Death" limit, this reflects the observations of the authors of the studies and emphasise the variability in these types of experiments, as well as the consequence of not specifying *absence of effects* (Notice the large confidence intervals).

Effect	Mean level (n = number of studies[8]) (± 95 % confidence interval)	Comment
Death	202 (± 17.8, n=5)	Death attributed to sound exposure by original author.
Physical injury	219 (± 26.2, n=4)	Injury to structures not related to the inner ear. Swim bladder damage included here.
PTS[9]	188 (± 14.5, n=4)	Gross damage to auditory system
TTS	179 (± 20.8, n=12)	incl. balance problems and stunning
Behavioural	186 (± 13.4, n=22)	Behavioural changes and changed in hormone levels
No reported effect[10]	184 (± 40.7, n=3)	Original author reported no effect or didn't investigate

4.3.1 TTS limit

We used the mean from the categories PTS and TTS in Table 3 to establish a TTS limit. The choice to combine these two groups is based on their large overlap and a desire to make sure that the PTS limit continues to be perceived as a "hard limit", above which there is serious risk of significant permanent injury to the animal (i.e. fatal or near-fatal). As mentioned earlier there is evidence suggesting that fish can recover, even from structural damage to their acoustic system, and this form of injury is therefore not permanent.

From a view that PTS is serious permanent injury to marine mammals, and that the level we set as "PTS" for fish should indicate similar serious permanent injury and potential impact on a population, the PTS used for fish refers to levels likely to give rise to permanent damage. We have kept the nomenclature, for ease of comparison, although, for fish, the limit could be named "injury threshold". Injuries to the acoustic system that are not permanent are therefore referred to here as TTS, and PTS is reserved for permanent injuries and death.

Combining the two categories yields a TTS level of 181[11]. This level is somewhat lower than the 205 $dB_{z\text{-}p}$ mentioned in (Carlson, Hastings, & Popper, 2007), but given the documented effects of seismic-type exposures and the fact that the 205 $dB_{z\text{-}p}$ level given in Carlson et al 2007 is based primarily on *one* study (Popper, et al., 2005) using estuarine/freshwater fish, we feel justified to set the threshold at the lower value, as it represents a larger number of experiments, with primarily marine species.

4.3.2 PTS limit

Combining categories "Death" and "Physical injury" to form a PTS threshold, yields a level of 210 dB. This limit is 4-5 dB higher than the limits set as interim limits for impulsive noises in North America (Popper, Carlson, Hawkins, Southall, & Gentry, 2006; Carlson, Hastings, & Popper, 2007) and 3 dB higher than the limit for fish with swim bladder from (Popper, et al., 2014) guidelines. We

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[8] The actual number of fish were not available from the original texts.

[9] As fish can regenerate hearing structures, this is not strictly PTS as understood for mammals, but we wish to emphasise that the loss of fitness is thought to be greater in this category than for "conventional" TTS.

[10] "No reported effect" does not mean there was no effect (e.g. many fish were not checked for hormone levels), just that the report did not mention effects.

[11] This is an average off all the data from PTS and TTS categories, not an average of the two category limits.

adopt the lower limit from these to arrive at 205/206 dB$_{\text{z-p}}$ (depending on group, see Table 4, p. 15).

The keen reader will notice the lack of units in the previous section. This is due to a lack of available information from the original authors.
As the sources in the collated data were either seismic sources or imitations of such, we assume the unit to be dB$_{\text{Z-P}}$. If a level was in fact dB$_{\text{RMS}}$ or dB$_{\text{SEL}}$ it will have lowered our limit, as the RMS- or SEL-level of an impulse will have a lower value than that of the peak level.

As we could find no better data for cumulative impulsive exposures (dB$_{\text{SEL}}$) we adopt the limits from the North American interim pile driving guidance (Carlson, Hastings, & Popper, 2007) and from the Sound Exposure Guidelines for Fishes and Turtles (Popper, et al., 2014) (whichever is lower), for dB$_{\text{SEL}}$ type limits.

Limits for cumulative non-impulsive exposure were set to match the limits for impulsive exposure. The following reasoning is used to justify this:

1. Lack of available knowledge leads us to adopt the assumption of the “Equal energy hypothesis” that equal incident energy causes similar impact regardless of its other characteristics (Smith M. E., 2008).
2. To account for noises that are wholly or partially outside the hearing range of the fish we apply weightings when assessing noise exposure for the relevant groups. These weightings are the same as the generalised thresholds found in Figure 5, p. 10 & Figure 7, p. 12, but normalised to have their most sensitive region be zero.

We are faced with a choice of whether to adjust the thresholds for fish further, according to their relative limit of hearing at the region of best sensitivity. E.g. the “D+” group have a lowest threshold of 72 dB at 160 Hz, while “P-“ has best hearing of 87 dB at 300 Hz (i.e. a 15 dB difference in sensitivity). We have chosen not to adjust for this disparity, as the limits we use have been derived from a mix of the hearing groups, and we did not find a trend indicating that groups with lower hearing thresholds are more impacted at equivalent exposures. In other words, there was insufficient data to justify raising thresholds for groups with less acute hearing.
Keep in mind that for groups with a narrower hearing bandwidth, their weighting function will in practise serve to lessen the received level.

Table 4. TTS and PTS thresholds for the 10 hearing groups. Upon application, noises described by their peak level are unweighted while SEL based noise levels are weighted according to relevant hearing group.

	TTS (recoverable)			PTS (non-recoverable)		
Receiver type	dB$_{\text{SEL-24}}$ Non-impulsive	dB$_{\text{SEL-24}}$ Impulsive	dB$_{\text{Z-P}}$ Impulsive	dB$_{\text{SEL-24}}$ Non-impulsive	dB$_{\text{SEL-24}}$ Impulsive	dB$_{\text{Z-P}}$ Impulsive
NOAA LF	179	168	213	199	183	219
NOAA MF	178	170	224	198	185	230
NOAA HF	153	140	196	173	155	202
NOAA PW	181	170	212	201	185	218
NOAA OW	199	188	203	219	203	232
NOAA SI	186	175	220	206	190	226
D+	185^{b}	185^{b}	181^{c}	207^{a}	207^{a}	205^{b}
D-	186^{a}	186^{a}	181^{c}	210^{a}	210^{a}	206^{b}
P+	185^{b}	185^{b}	181^{c}	207^{a}	207^{a}	205^{b}
P-	186^{a}	186^{a}	181^{c}	210^{a}	210^{a}	206^{b}
T[12]	185^{a}	185^{a}	181^{c}	210^{a}	210^{a}	205^{b}

a. Limits from Sound Exposure Guidelines for Fishes and Turtles (Popper, et al., 2014).
b. Limits from North American interim pile driving guidance (Carlson, Hastings, & Popper, 2007)
c. Limits from our work based on data from (DFO Canada, 2006).

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[12] All TTS levels for turtles are copied from fish limits, this is done following an argument from (Popper, et al., 2014, p. 43) stating that turtle hearing is likely less sensitive than for fish, and so this is sufficiently conservative.

While the mammal limits are directly from the NOAA report (NOAA, 2018) the fish limits are generated from collated data (overview in Table 3 above) from (BOEM, 2014; DFO Canada, 2006; Ketten, Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions, 1995; Mann, higgs, Tavolga, Souza, & Popper, 2001; Subacoustec, 2004; Carlson, Hastings, & Popper, 2007; Popper, et al., 2014).

To evaluate "$\mathrm{dB}_{\mathrm{SEL\text{-}24}}$" for fish we have adjusted the constant "*K*" in Eq. 2 section 4.0 so that the most sensitive region of the weighting curve is zero.

PTS limits form the basis of the SRI.

4.4 BEHAVIOURAL LIMITS

The tool focuses on a standardised method of evaluation sources to yield and index. This means a certain rigidity in terms of evaluation parameters. The user can however add any additional weightings and limit levels to the tool. Doing this will mean that the tool will no longer produce an SRI value, but rather the user has veered away from an indexing exercise towards an impact assessment (which the tool is not designed for).

4.5 MINIMUM SENSITIVITY

The absolute minimum sensitivity (highest threshold) is set relative to the depth at the source so that any level over ambient pressure plus 57 kPa will be the threshold. A positive pressure of 57 kPa has been shown to have serious or lethal effects in some mammals and fishes (Ketten, Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions, 1995). A threshold like this has been adopted as the equations for the weighting curves will generate very large, and unrealistic, threshold values at frequencies far from any hearing group's most sensitive region. Depending on the depth the tool will limit the maximum weighting level at any frequency.

Table 5. Example of highest threshold values for a range of depths.

Depth [m]	Ambient pressure [Pa]	Ambient pressure [dB re 1 µPa]	Limit (Ambient pressure + 57 kPa) [dB re 1 µPa]
0	101,300	220	224
5	151,950	224	226
10	202,600	226	228
20	303,900	230	231
50	607,800	236	236
100	1,114,300	241	241
200	2,127,300	247	247
500	5,166,300	254	254
1,000	10,231,300	260	260
2,000	20,361,300	266	266
5,000	50,751,300	274	274

Note that this is a limit applied for practical reasons and does not affect the result of the tool, but rather affects how the interface is presented.

5.0 EXAMPLES

To increase the readers understanding of the tool and its use it’s relevant to provide examples of its application.

Here follows a few examples of situations where the SRI is used to inform the activity design on choices regarding source configuration, mitigation measurements and vessel control.

Lastly we include a step by step example, in the hope that this will serve to address any questions that have not been addressed in the previous examples.

5.1 SEISMIC – ENERGY VS PEAK

Seismic survey design can face a range of choices in regards to operating pressure, firing sequence, timing and shot number, to name a few. These will all affect the way the survey will impact the acoustically sensitive fauna in the area, and while technicians have very good understating of the effects on the array output, it can be harder to estimate the environmental impact.

For this example, we will assume that we have a choice between two different seismic array setups:

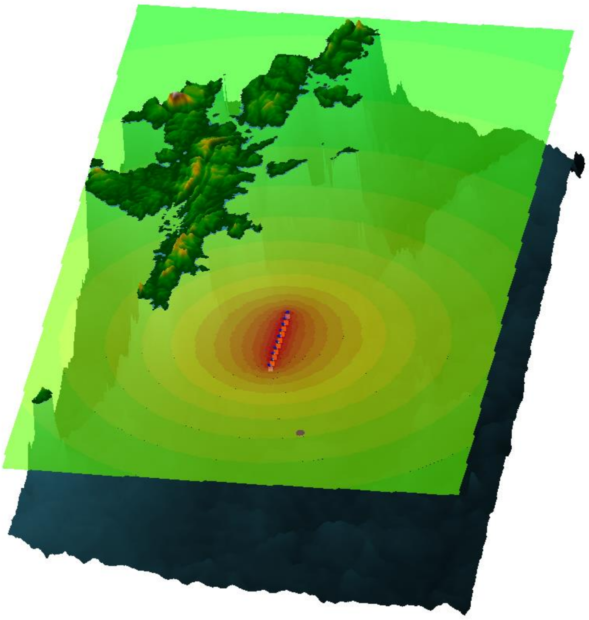
A. Array A has *less* total energy, but a *higher* peak level
210 $\mathrm{dB_{SEL\text{-}single\ shot}}$ / 30 dB crest factor (240 $\mathrm{dB_{z\text{-}p}}$)

B. Array B has *more* total energy, but a *lower* peak level
220 $\mathrm{dB_{SEL\text{-}single\ shot}}$ / 10 dB crest factor (230 $\mathrm{dB_{z\text{-}p}}$)

Both arrays were set up with the inbuilt seismic source model (section 1.1.1.1, p.8)

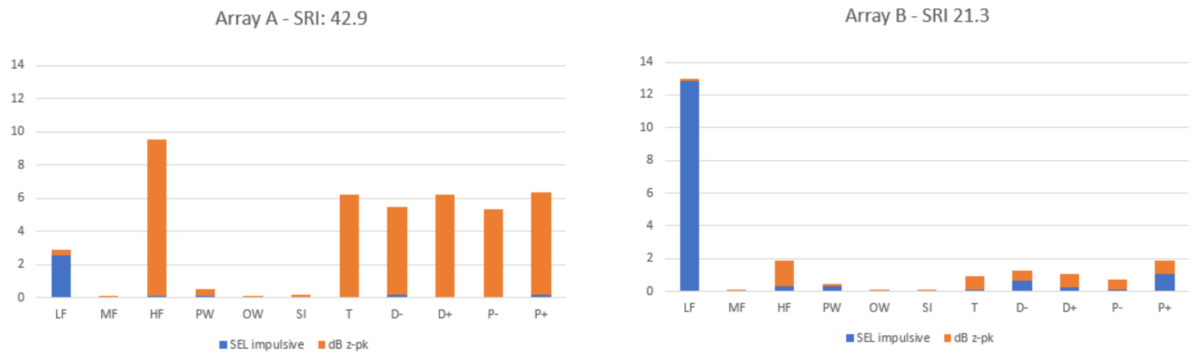
We let the array move 20 km at a speed of 2.5 m/s, with a shot every 10 seconds.

Figure 9. Example of simple survey line south-east of Shetland. Colours represent max levels projected to the surface.



The SRI tool will use information about the depth, shot count, activity duration and receiver sensitivity to establish an SRI value for both arrays. For this example, with impulsive noise, we are given two SRI values: one for the cumulative energy content of noise (SEL) and one for the peak level ($\mathrm{dB_{z\text{-}p}}$). Here we present the graph view of the SRI as it allows us to see what hearing groups are more sensitive to the noise from our activity.

Figure 10. The main impact of Array A is due to the high peak levels (orange), while the SRI from Array B is dominated by the energy content of the source (blue).



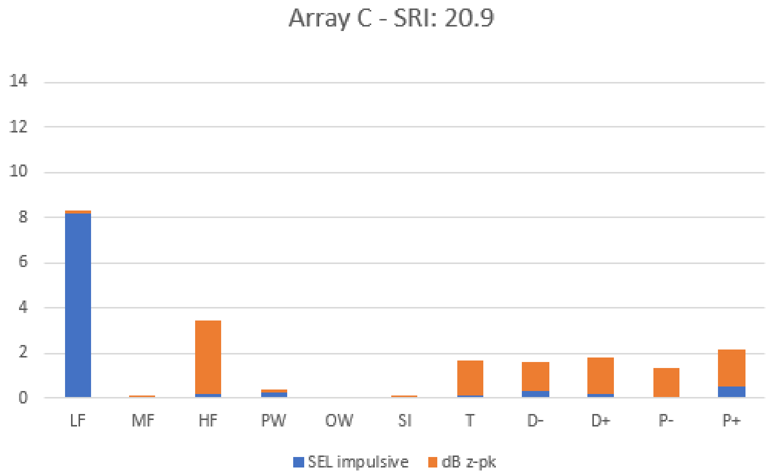
The two activities produce very different SRI values of 42.9 (A) and 21.3 (B) respectively, and the tool shows us that the contribution from the peak levels in A (orange bars) is much higher than in B, but that the increased energy content in B (blue bars) has an increased impact on the Low Frequency cetaceans (LF group).

We now introduce Array C where we have tried to balance shot energy with peak pressure based on the information from A and B:

- 217 dB$_{\text{SEL-single shot}}$ / 16 dB crest factor (240 dB$_{\text{z-p}}$)

This has half the impulse energy of Array B, but double peak pressure.

Figure 11. A separate array with modified energy and peak level, to minimise SRI.
SRI from cumulative energy: 9.8
SRI from peak: 11.1



This has helped "balance" the impact so than no groups have a very high SRI, while still retaining a high outgoing level from the source.

The previous figures also provide some insight into what animal groups we expect to be most sensitive to the activity, so while we can see that Array C seems to have lower impact, it's spread over all groups hearing groups. If we know that there are no members of the HF, SI and T groups present in our area, array A will comparatively have its SRI lessened most (down to 27).

While this is not an accurate indication of actual real-world impact, the use of weighted spectra for SRI calculation means that we can rely on the information that Array A has a comparatively high impact on the HF hearing group while Array B has a comparatively high impact on baleen whales, and we should keep this in mind as we proceed to later stages in the project (thinking about mitigation measures).

5.2 SEISMIC – SPECTRAL DIFFERENCE

For another seismic scenario we compare two vertical seismic profiling (VSP) setups with different distribution of band energy. The two sources have the same energy and peak pressures.

Array A – low frequency source, SEL 221.4 $\text{dB}_{\text{SEL-single-shot}}$ / 241 $\text{dB}_{\text{z-p}}$

Array B – standard source, SEL 221.4 $\text{dB}_{\text{SEL-single-shot}}$ / 241 $\text{dB}_{\text{z-p}}$

We assume 1000 impulses from both sources.

Figure 12. VSP example south of Madeira. colours represent levels, all depth layers are visible.

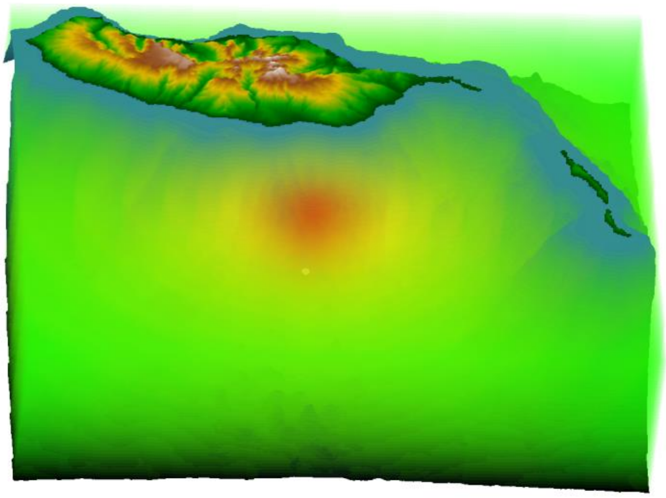
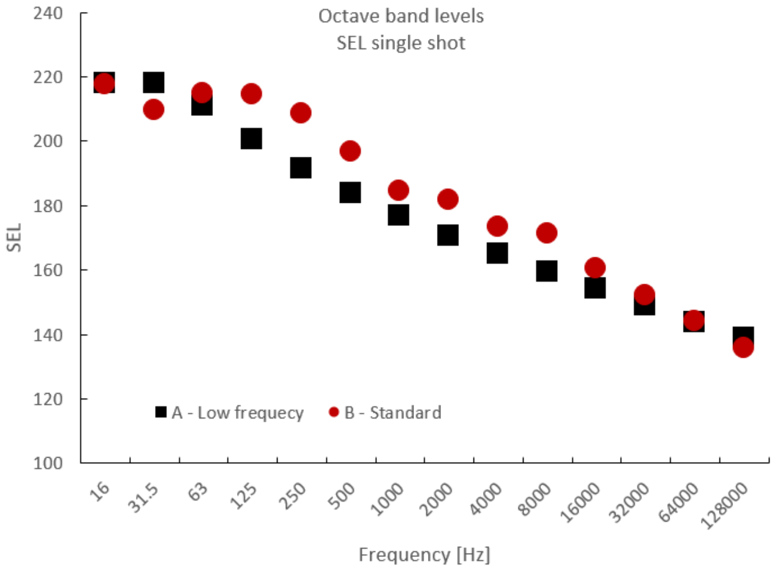
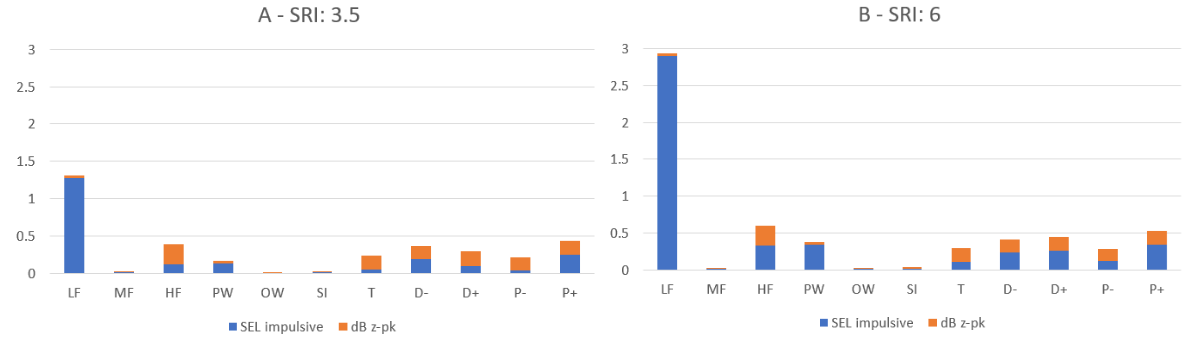


Figure 13. Band levels for the two VSP sources.



Running the SRI tool for both scenarios/sources we get the following results:

Figure 14. SRI for two different sources used for VSP. Source A has SRI of 3.5 – source B SRI of 6.0.



The different between the two sources lies in the slight difference in levels between the 63 Hz and 1000 Hz band, where source B has more energy, while source A has more energy at very low frequencies, 16-32 Hz. Even though the LF group is sensitive to low frequencies in general (<500 Hz), they are less sensitive[13] to very low frequencies (<100 Hz, Figure 7, p.12 LF). Keeping most of the energy in this very low range, will lessen the impact of the VSP. Also note that the SRI from peak pressure does not change as this is based on the maximum pressure of each impulse, and not the frequency-weighted band level.

We have thus gotten a quick indicator that using a source with more emphasis on the very low frequencies is beneficial in terms of acoustic impact, even though the two sources have the same energy and peak pressure level.

5.3 PILE DRIVING

For a piling scenario in Bristol channel we wish to compare and evaluate what species groups should be the focus of our mitigation efforts at an early planning stage.

Figure 15. Piling location in Bristol channel.

Here we will use a recording of a piling impulse that has been scaled to reflect the sound pressure at 1 meter from the source – the standard for underwater noise measurements.

Source level: SEL 200.5 $dB_{SEL\text{-}single\text{-}strike}$ / 231.6 $dB_{z\text{-}p}$

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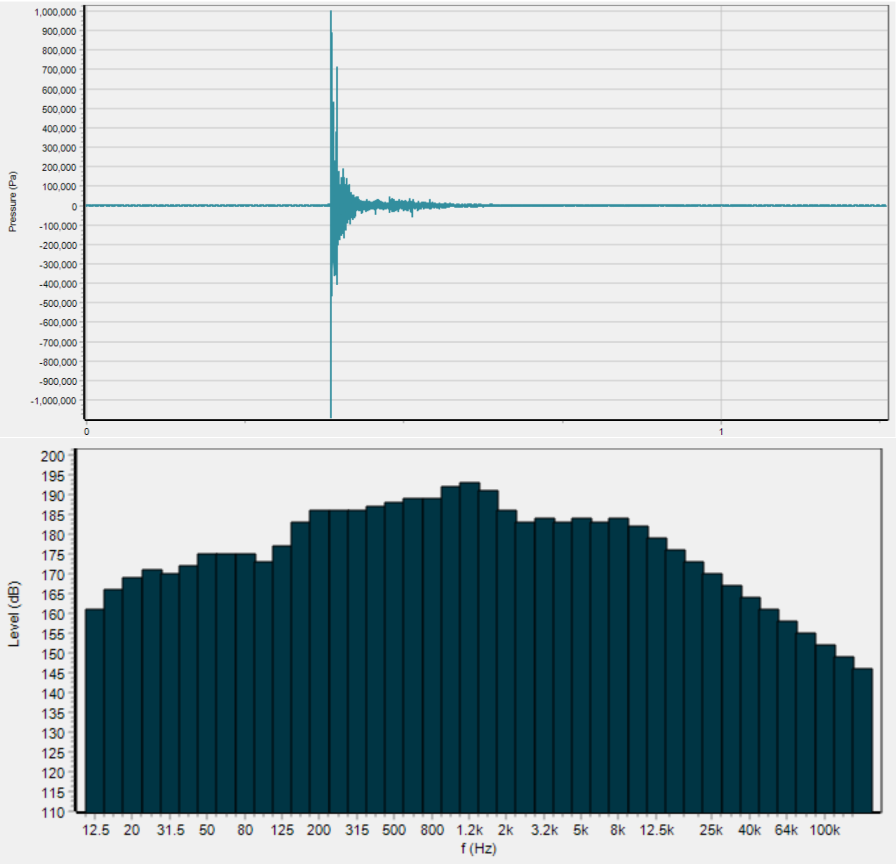
[13] According to (NOAA, 2018)

Figure 16. Timeseries and band levels of a single piling strike. Peak pressure is 231.6 $dB_{z\text{-}p}$ and SEL for one strike is 200.5 $dB_{single\text{-}impulse}$.

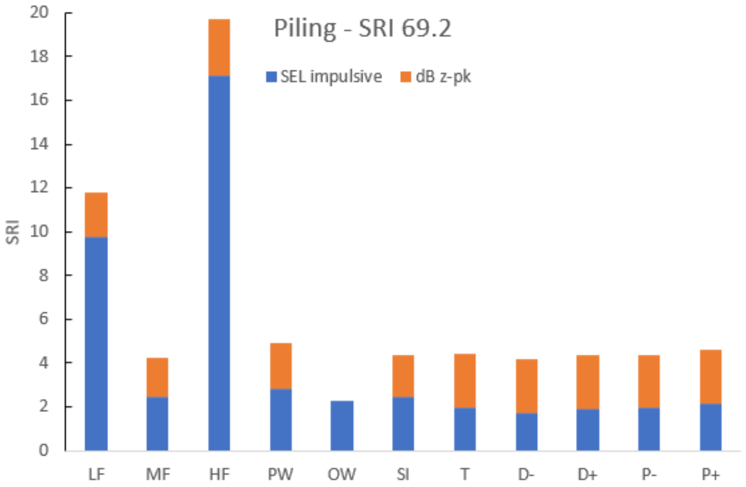


When importing a timeseries into the tool, the crest factor is calculated as well as the band levels as it's needed to evaluate against impulsive thresholds (Table 4, p.15).

The SRI for 1000 strikes is 69.2, with a highest impact on the HF group.

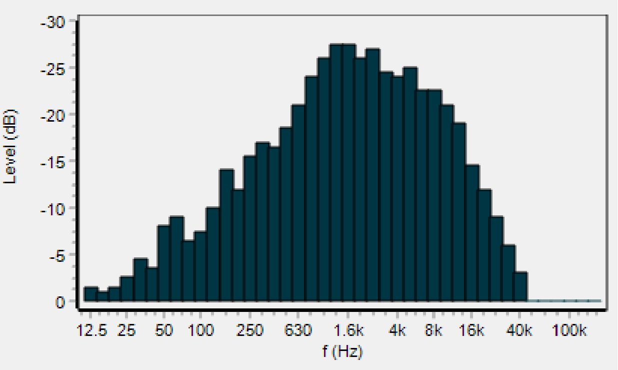
Note here that this is somewhat higher than what we saw in previous examples and highlights how the tool should not be used to compare dissimilar scenarios. The difference stems primarily from the lower predicted transmission loss as a consequence of shallow water, and the assumption of a highly reflective seabed.

Figure 17. SRI breakdown of a sample piling scenario. For impulsive noises the Total SRI is broken into two qualitatively different measures, cumulative (SEL impulsive, blue) and peak (dB $_{z\text{-}p}$, orange).



From the database we can either enter our own mitigation or pull information on previously defined mitigation measures, e.g. a bubble curtain:

Figure 18. Dampening per 3rd octave band of a bubble curtain (example from (Nehls, et al., 2015))

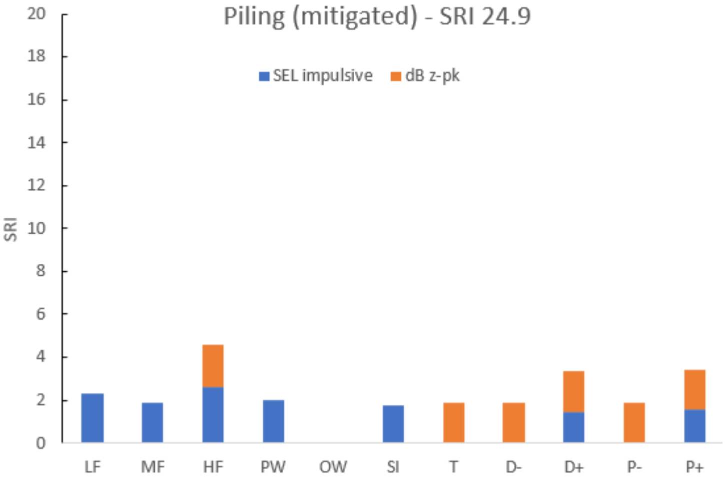


After applying the bubble curtain mitigation, the tool lets us know that we have greatly improved (lowered) the impact on the HF group, an almost reduced the SRI by two thirds.

This lowering will correspond to real-world reduction in exclusion zone of a similar factor due to the way the tool is designed and the nature of transmission loss calculations.

We can furthermore use the knowledge about the transmission loss model used in the tool to say something about the maximal ranges of impact from the activity. Because of the transmission loss model used (see “Scientific Remit” report) it is extremely unlikely that the tool overestimates transmission losses. This means that for this scenario we can be confident that we have a PTS risk zone smaller than 2.6 km (tallest single bar in figure below), and that this is likely an overestimate (as the sediment in Bristol channel is softer than solid rock).

Figure 19. SRI after mitigation measures.



5.4 CONTINUOUS NOISE SOURCES

In a scenario where we look at the relative impact of two ferries to service the Dover-Calais ferry route, we find again that frequency is important for determining impact.

Ferry A is modelled[14] on the ship “MS Spirit of Britain”, and Ferry B on its sister ship “MS Spirit of France”. The vessels here have the same overall SEL, but while A has a lower maximum band level, its hull shape[15] causes more energy in higher frequency bands.

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[14] Using the inbuilt vessel noise modelling tool (Figure 3, p.8) – Vessel dimensions from Wikipedia.

[15] In the model used, length, width and displacement vs engine size, cavitation speed and operating speed all affect frequency distribution of the emitted noise.

Figure 20. The band wise noise as dB$_{SEL-24}$ for two ferries on the Dover-Calais route.

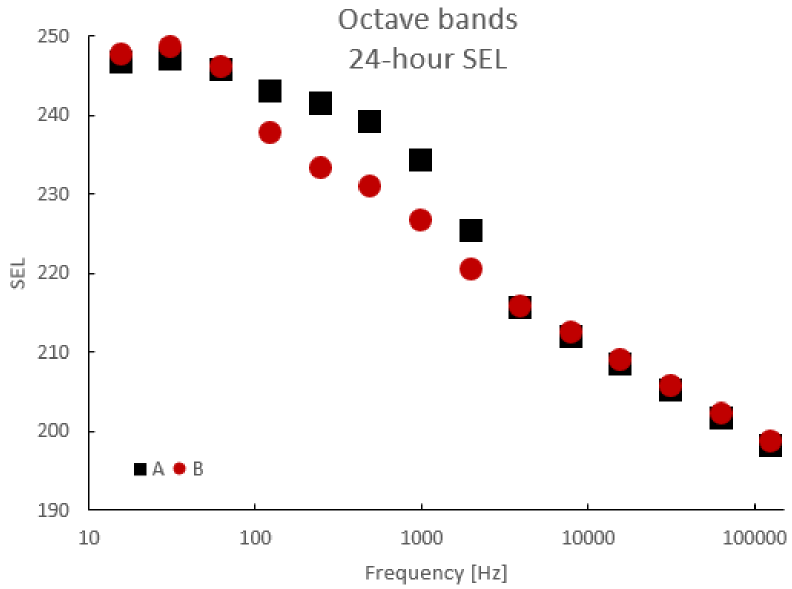
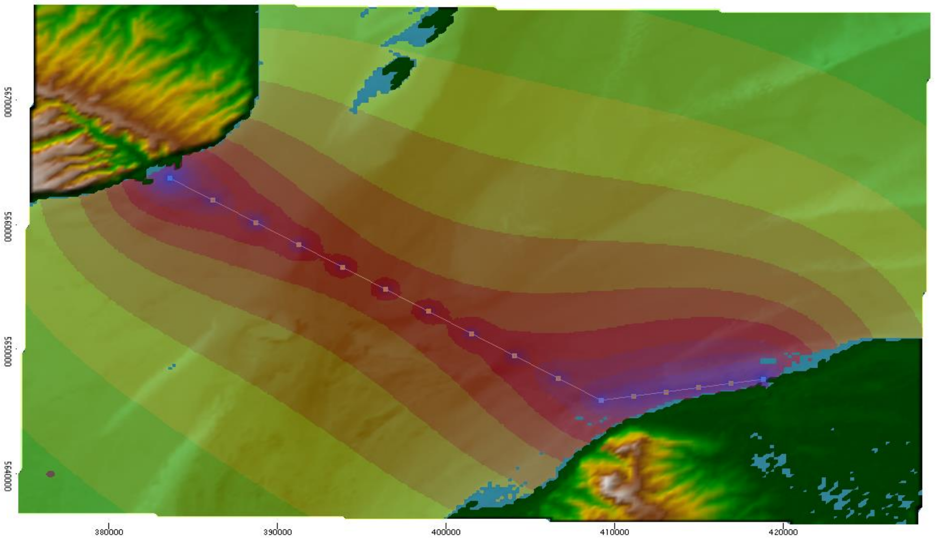
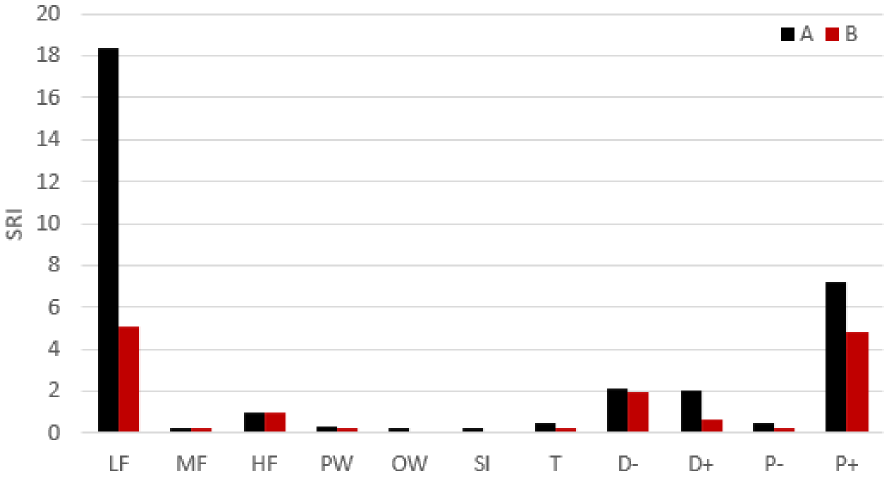


Figure 21. Colours corresponds to levels. Example of the levels forming the basis for the SRI calculation for a Dover-Calais ferry route.



Similar to the VSP example in section 5.2, (p. 19) noise at very low frequencies does not affect SRI as much as noise over 100 Hz. This is in keeping with the generalised weighting curves for the different species groups in the framework (section 4.0, p.9).

Figure 22. SRI of Vessels A and B. Even though the total SEL of the two vessels are equal the difference in distribution across frequency bands, means that vessel A has greater impact on especially the LF and P+ hearing groups.



Facing a choice between the two vessels we should thus choose ferry B for this activity, as much of the noise it produces is outside the range of best hearing for most species. As for the VSP example the majority of the noise from ferry B is below the region of best hearing of the LF and P+ hearing group.

5.5 STEP-BY-STEP WALKTHOUGH

Here we will follow a step-by-step recipe to create a scenario with a moving source and multiple impulses.

Please ensure you have downloaded the following files:

Timeseries (txt file, 500 kB):
https://drive.google.com/open?id=1iB77mEgilKZd6iWpymtI3UQ0QzvBp3pH

Bathymetry: “Madeira.asc”
https://drive.google.com/open?id=1YqpQ96bY0G8Jh_0E0VTFpkZiUf690gyV

& “MadeiraCropped.asc”

https://drive.google.com/open?id=1phxM-hUpas2n-JzDZ14E0XNpZH3OoScF

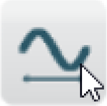
Steps:

1. Open the SRI tool
2. Click button “Load Bathymetry” and find the Bathymetry file “Madeira.asc”.
3. Press “Reset view” button to view from above (“ctrl + left mouse” allows 3D rotation)

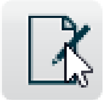
4. Click the SRI logo (Far right on tool bar), and accept changing to “SRI-mode”

5. To make a moving source, go to “Sources”.

6. Tick the checkbox “Moving source” and click button labelled “Motion”.
7. In the new window, top row under “x” enter “300,000”, and under “y” enter “3,600,000”
8. Press “Add” to add a second row, and change the number of “Sections” from “1” to “9”.
9. Now change the x value in row “2” to “320000”
   Distance travelled is now 20000 m or 20 km.
10. Press radio button “Set speed (m/s) and set the speed to “2”.
11. Press “OK” (you might get an info box, read it and confirm).
12. Go to the “Frequencies and solvers” tab



13. Set “Master spectrum frequencies to 16 Hz to 16 kHz by using the arrows (the source we will be using is sampled at 50 kHz, so we are limited to < 25 kHz[16]).
14. Go to the “Setup Project” tab



15. Press “Set to map resolution”
16. Set “z depth points” to 44
17. Set “Range points” to “500”
18. Press “OK”
19. Go back to the SRI tab (see step 4)
20. Tick check box “Source is impulsive”

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[16] This is explained by the Nyquist-Shannon sampling theorem (see e.g. https://en.wikipedia.org/wiki/Nyquist%E2%80%93Shannon_sampling_theorem)

21. Press button “Time series” (and accept the change to impulsive).
    If you wish to use “Spectrum” to set your source level and time, please feel free to do so, the rest of this step by step guide will work, but your numbers will not be identical.
22. Press button “Open text file” and find the downloaded txt file “Seismic source 50 kHz”
23. Set the “Sample rate (Hz)” to 50000
24. Remember that we are travelling 20 km in total at 2 m/s.
    We are shooting once every 10 seconds / once every 20 m.
    This means that we have 1000 shots in total, set “Count” to “1000”[17].
25. Press “OK”.
26. SRI is now calculated for your activity using the “Geometric mode”. This is the quickest way to get an indication of SRI, but it doesn’t take land and certain cumulative effects into account (see Theory Report section named “The Sound Risk Indicator”) and is generally a bad way to get an indication for a moving source (52/4.2/1).
27. This next step will take a while (1-10 minutes depending on your machine)
    Press “Solve project”
28. After the solve has finished and the SRI calculated for all groups, you can now explore the SRI tab.

    Note: SRI values are either “3.6”, “0.3” or zero (and the “SRI-accuracy” is estimated at ± 62 %!).

    This is a sign that we have imported bathymetry of an area that is too large compared to the activity we want to index.

    We can increase the calculation resolution (increase the numbers in step 14-18) to get a better resolution, but this will make the calculations much more resource-consuming. So, we will here opt for the alternative, import a smaller bathymetry file.

29. Import bathymetry file “MadeiraCropped.asc”
30. You might have to re-enter the movement of you source (see step 6-11)
31. Also go to the “Setup Project” tab (step 14) and change the calculation grid so that the step sizes (dx & dy) and range step are only 50 meters:
    “x points”: 512
    “Y points”: 342
    “Z depth points”: 36
    “Range points”: 511
    Click “Step sizes” to see the resolution on the current scenario.
32. Press “Solve project”
33. Go to the SRI tab. SRI will recalculate for a total SRI of 6.1
    5.4 from the SEL (cumulative) and 0.7 from the $dB_{z\text{-}p}$ (peak pressure).

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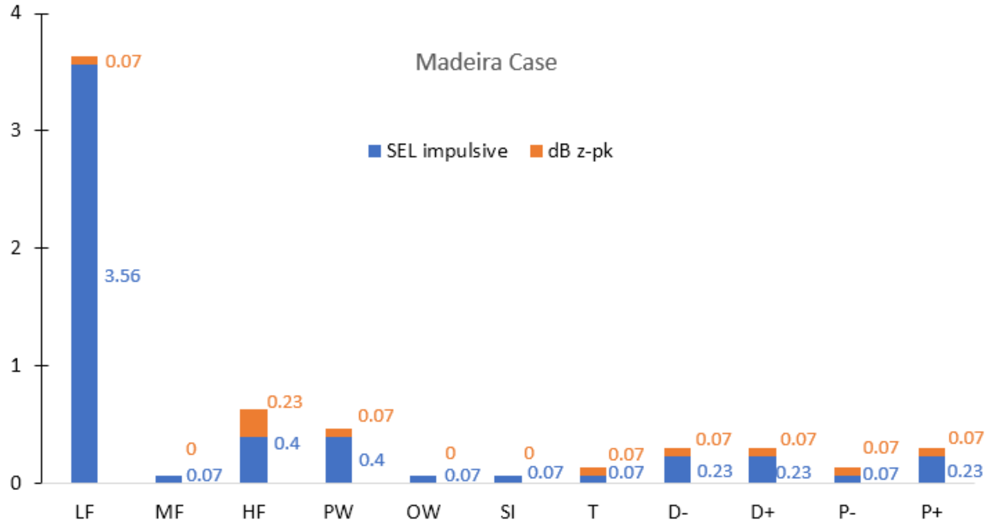
[17] In “SRI mode” the total number on impulses for the whole survey is entered

34. You will see the following breakdown of SRI values:



35. Things to note:
   (a) A warning has appeared "* Warning: SRI values may be limited by the scenario size" This warning will show when an SRI value is larger than the shortest distance from any source point to the edge of the scenario. To validate that it's not an issue for our current example go to the "Marine species weightings" tab

   From the dropdown list, choose "NOAA LF Cetaceans (low frequency)". This will apply the LF weighting across the scenario.
   Now go to tab "Overall sound levels"

   Click "Change limits", tick box "Show exclusion zone" and set Exclusion zone level to "183" (this is the LF limit for impulsive SEL)
   Click "OK"
   You will now see a read area, showing the extend of the area where levels exceed the limit. Note that this area is not restricted by the scenario size.
   Undo the "show exclusion zone" and change the "Marine species weighting" to "none".
   (b) Due to the high energy of the low frequencies this is likely to impact LF cetaceans far more than other marine macrofauna.
   (c) The "SRI-accuracy" is reports as 49 %, meaning that the lowest SRI value can be up to 49 % away from the estimated[18] "true" SRI value for this scenario. Increasing the resolution will decrease this value. As most SRI values are rather small (<1) for this scenario, this is not critical.
36. From here you can try to change the number of impulses (count) or maybe the track path.

Good luck!

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[18] We try to estimate the difference between an area of rectangular cells and that of an areas with rounded borders.

6.0 CONCLUDING REMARKS

The example above concludes this report, describing the theory of the framework used to compress and integrate noisy activity information into a single Sound Risk Indicator. It is not intended as a replacement for impact assessments, but rather to serve as an indexing tool to let industry and regulators easily compare various scenarios by assigning a single number to them.

We invite readers of this document to send comments and questions to:

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