Framework for assessing ecological and **cumulative effects** *of offshore wind farms*

Cumulative effects of impulsive underwater sound on marine mammals

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Cumulative effects of impulsive underwater sound on marine mammals

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Author(s)	F. Heinis, C.A.F. de Jong & Rijkswaterstaat Underwater Sound Working Group

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Abstract

Piling work on foundations for wind turbines during the construction of wind farms in the North Sea generates high levels of underwater sound that can disturb harbour porpoises and seals. Given the expected developments in the Netherlands and other countries, it cannot be excluded that the accumulated effects of this impulsive sound as a result of multiple initiatives may impact entire populations.

At the request of the Ministry of Economic Affairs, Rijkswaterstaat agreed to develop an ‘Ecology and accumulation of effects assessment framework’ for Round 3 offshore wind energy. As part of that process, the Underwater Sound Working Group developed a 'line of reasoning' (in other words, a staged procedure) for determining the cumulative effects of impulsive underwater sound on relevant populations of marine mammals in the North Sea. In doing so, it used the Interim PCoD model, which was developed recently in the United Kingdom by researchers from the University of Saint Andrews and SMRU Marine.

As a guideline for environmental impact assessments and appropriate assessments for future Dutch Offshore Wind Energy projects, the following phased approach has been recommended:

1. Calculation of sound propagation per piling strike
2. Calculation of disturbance area for harbour porpoises and seals
3. Calculation of number of harbour porpoises and seals possibly suffering disturbance
4. Calculation of number of animal disturbance days (in other words, the number of disturbed animals per day multiplied by the number of impulse days)
5. Estimation of the possible effect on the population on the basis of the number of animal disturbance days using the Interim PCoD model or the estimation formula described in this report
6. Calculation of the cumulative exposure of harbour porpoises and seals in the vicinity of the pile and the determination of the distance within which there is a PTS risk for animals; investigation and description of how this risk will be mitigated.

The staged procedure (the 'line of reasoning') was applied to obtain an initial estimate of the possible extent of the cumulative effects of impulsive underwater sound on the harbour porpoise population of a number of scenarios for both the construction of wind farms on the DCS and in the rest of the North Sea and for seismic surveying in the period 2016-2022.

In addition, this report also discusses a possible approach for seals and provides an overview of the current knowledge gaps and areas of uncertainty in the proposed approach.

Glossary

Animal disturbance days	Product of the number of impulse days per farm multiplied by the number of disturbed harbour porpoises per impulse day (taking the seasons into account) and by the duration of the disturbance per impulse day (=1/3 of a day, 1 or 2 days).
Impulse day	A day upon which impulsive sound is produced, for example by offshore piling or seismic surveying.
Percentile	The *k*th percentile of an ordered statistical data set is the number that separates the *k*% smaller data from the (100−*k*)% larger data.
PTS onset	In this context, we define 'PTS onset' as an increase in the hearing threshold (at any frequency) of 40 dB measured within 4 minutes after the exposure. According to [Southall et al., 2007], there is a major risk of permanent damage to hearing when there is a threshold shift of this size.
Residual days of disturbance	The number of days after the impulse day during which the behaviour of the animals is affected by the impulsive sound.
Sound Exposure Level	10 times $\log_{10}$ of the ratio of the integral of the sound pressure squared during a defined interval of time (or during a defined event) to the reference value E_0 = 1 $\mu Pa^2 s$.
TTS onset	In this context, we define 'TTS onset' as an increase in the hearing threshold (at any frequency) of 6 dB measured within 4 minutes after the exposure
Vital rates	In general, the probabilities of mortality and reproduction used in the population dynamic models. In the Interim PCoD model, disturbance as a result of impulsive sound affects only the probability of mortality in young calves and juveniles and the probability of adult females producing offspring.
Vulnerable sub-population	The part of the population that may be disturbed by impulsive sound from a specific project. The size of the vulnerable sub-population is linked to the mobility of the animals: how many different animals could be within the disturbance area during the course of the project?

Abbreviations

BE	Belgium
CPOD	Continuous Porpoise Detector
DE	Germany
DK	Denmark
EIA	Environmental Impact Assessment
DCS	Dutch Continental Shelf
NL	The Netherlands
AA	Appropriate Assessment
PCAD	Population Consequences of Acoustic Disturbance
PCoD	Population Consequences of Disturbance
PL	Propagation Loss
PTS	Permanent Threshold Shift
RWS	Rijkswaterstaat
SEL_1	Sound Exposure Level for a single impulsive sound (N.B. SEL_{SS} is also used here, with ‘SS’ standing for ‘single strike’)
SEL_{CUM}	Cumulative Sound Exposure Level resulting from multiple impulsive sounds
SL_E	Energy Source Level
SMRU	Sea Mammal Research Unit (University of Saint Andrews)
SPL	Sound Pressure Level
TNO	Netherlands Organisation for Applied Scientific Research
TTS	Temporary Threshold Shift
UK	United Kingdom

1 Introduction

1.1 Background

Large amounts of sound are produced during piling work on foundations for wind turbines and seismic surveying, resulting in very high levels of sound in the surrounding area.[1] Depending upon how far animals are located from the source, this can affect behaviour or induce physiological effects such as a temporary or permanent increase in the hearing threshold (TTS = *temporary threshold shift* and PTS = *permanent threshold shift*).

It is not known whether, and if so to what extent, these sub-lethal physiological or behavioural effects have a quantitative knock-on effect on the populations as a whole of the predominant species of marine mammals found in the North Sea (the harbour porpoise, the harbour seal and the grey seal). These possible population effects have therefore not been quantified in the environmental impact assessments and appropriate assessments that have been published until now.

In the case of the 'Round 2' offshore wind farms (2009), the competent authority decided that it could not exclude the possibility of cumulative and significant negative effects resulting from underwater sound generated by piling for the twelve initiatives receiving permits. It therefore decided to introduce conditions for the permits with the aim of eliminating any significant negative effects. These conditions were:

- the construction of a maximum of one wind farm a year;
- a seasonal restriction on piling activity (construction permitted between 1 July and 31 December).

This approach is no longer adequate for the 'Round 3' wind farms because the Netherlands aims to focus primarily on the construction of offshore wind farms in order to achieve sustainable energy objectives. The objective for 2023 in the SER agreement[2] of September 2013 is to have a total of 4,450 MW operational, possibly increasing to 6,000 MW in subsequent years. In order to achieve that goal, the Dutch government intends to enter into contracts from 2015 onwards for

[1] Piling and seismic surveying result in regularly repeated impulsive sounds. A number of other activities that also produce impulsive sounds have not been included in this report. As pointed out in Part I of the Marine Strategy for the Netherlands (2012), sonar systems in the Dutch Section of the North Sea make only a very minor contribution to the total amount of underwater sound, as is shown by the inventory of sound sources [Ainslie et al., 2009]. The Marine Strategy states that it is not considered necessary to take specific measures in the Dutch section of the North Sea. For the time being, sonar has not been included in this cumulative assessment. In the future monitoring of impulsive sound sources for the Marine Strategy, defence activities will be included and it will therefore be possible to include the possible harmful effects of sonar in a cumulative assessment. The sound associated with clearing ordnance has not been included because this activity always involves a short sound burden in which damage to hearing is a more important factor than disturbance (see also Section 2.3.4 of this report) and because the effects of the sound of explosions will be described in a parallel study conducted by the Ministry of Defence. The continuous sound of shipping has not been included because it is unclear whether, and how, the effects of this other type of sound can be accumulated with the effects of impulsive sound.

[2] https:// http://www.ser.nl/nl/publicaties/overige/2010-2019/2013/energieakkoord-duurzame-groei.aspx

approximately ten new wind farms (3,450 MW) on the Dutch Continental Shelf (DCS). This cannot be achieved in time if the conditions formulated in Round 2 are left in place.

As a result, research is required to determine whether more wind farms can be built annually, and whether additional conditions need to be formulated for the construction phase. Given the expected developments in the Netherlands and other countries, the possibility cannot be excluded of an impact on entire populations as a result of the accumulation of the effects of impulsive sound generated by multiple initiatives.

At the request of the Ministry of Economic Affairs, Rijkswaterstaat agreed to develop an ‘Ecology and Accumulation of Effects Assessment Framework’ for Round 3 offshore wind energy. This is a project that comprises several components. The formulation of an approach for the determination of the cumulative effects of impulsive underwater sound on relevant populations of marine mammals in the North Sea is one of those components. This project is being conducted by the Underwater Sound Working Group that was established in early 2013.[3]

1.2 Objective

The aims of the Underwater Sound Working Group were:
- The development of a staged procedure (a 'line of reasoning') for the quantification of the possible cumulative effects of 'impulsive' underwater sound during the construction of wind farms in the North Sea on the relevant populations of marine mammals (focusing in particular on the harbour porpoise);
- Estimating the size of the cumulative effects of impulsive underwater sound on the harbour porpoise population using selected scenarios for the construction of wind farms on the DCS and in the rest of the North Sea *and* for seismic surveying in the period 2016-2022. Mitigation measures have been included in the scenarios;
- The establishment of an overview of knowledge gaps.

1.3 Boundary conditions

The Underwater Sound Working Group met on a monthly basis between May and November 2014 (on 16 May, 19 June, 15 July, 9 September, 23 October and 7 November). There were informal consultations on 10 September at the ESOMM congress between a few members and John Harwood and Cormac Booth of SMRU Marine about the possible application of the Interim PCoD model. On 10 October, John Harwood presented the results of a number of exploratory calculations with Interim PCoD during the ecologists workshop organised in the context of the activities of the Working Group. During the period that followed, the calculations for the study presented in this report were conducted in a very short time. Given the

[3] The Underwater Sound Working Group was established in early 2013 at the initiative of RWS Sea and Delta. The members of the group come from Rijkswaterstaat Spatial Development and Water Affairs, TNO, HWE, SEAMARCO, IMARES, Arcadis, Royal HaskoningDHV and Deltares. See Annex 1 for a list of the members.

fact that an Interim PCoD calculation takes some hours to complete, the number of different scenarios for which it was possible to conduct calculations was, of necessity, limited. The aim was to select the scenarios in such a way that the possible bandwidth of effects was covered. Given the time limitations, the parameters advised by SMRU for the population model and for the dose-effect relationship were applied without any further investigation of the background to, or the consequences of, this decision. For the same reason, this study calculated only the effects on harbour porpoises.

1.4 Report structure

Chapter 2 describes the procedure ('line of reasoning') for determining the cumulative effects of underwater sound from piling at sea and seismic surveying on marine mammals. That procedure is then implemented in Chapter 3 to determine the effects of the construction of wind farms and seismic surveying in the years 2016 to 2022 on the harbour porpoise population in the southern section of the North Sea. Chapter 4 looks at the possible application of the procedure to the seal populations. In Chapter 5, we present a summary of the procedure in the form of a staged plan/guideline for writers of environmental impact reports. Chapter 6 gives an overview of the knowledge gaps.

2 Staged procedure for the determination of the cumulative effects of impulsive underwater sound on marine mammal populations

2.1 Overview of stages

When determining the cumulative effects of impulsive underwater sound on marine mammal populations, an assessment of relevance is required for all the possible steps in the chain of effects, from the primary abiotic factors – the sound emission – up to and including the effect on population size. When the stages are relevant, an assessment of the effect size is required. The following stages can be distinguished:

1 Quantification of the relevant sources of impulsive underwater sound in time and space: where, when and how long are the various piling activities and seismic surveys, and what does the acoustic field associated with the activities in question look like?
2 Determination of the relevant effect parameters in terms of behaviour and hearing that ultimately affect the vital rates of individual animals.
3 Determination of acoustic threshold values for the occurrence of a change in these effect parameters.
4 Determination of the number of affected animals and the duration of the effect.
5 Determination of the size of the total relevant population.
6 Extrapolation of effects on individuals to the effect on the population with the Interim PCoD model and the principles and assumptions used in the model.

In 2013, the Underwater Sound Working Group drew up assumptions for the first four steps on the basis of the scientific knowledge available at the time. To ensure that the new staged procedure, which was extended to include quantified population effects, included the latest insights, the various assumptions were submitted to and discussed with a group of ecologists at a workshop (see annex 1 for the participants). The focus here was on determining the cumulative effects of the construction of offshore wind farms and seismic surveying on the harbour porpoise population in the North Sea[4]. See Figure 2-1.

It was decided to opt for the harbour porpoise because the probability of this population being impacted by the cumulative effects of impulsive sound is higher than is the case with seals. This is because, at the locations where the activities are planned, the relative population density of harbour porpoises is much higher than in the case of the two seal species, which are primarily found in coastal waters (see Section 2.4 and Chapter 4). The aim of the meeting was to establish a consensus about the ecological principles and assumptions in the proposed staged procedure and to determine the uncertainties (steps 2 to 6 (incl.) of the overview). Given the uncertainties identified by the group, bandwidths were adopted for the model input parameters, the effects of which were later studied using different calculation scenarios (see also Chapter 3).

[4] Taking into consideration activities in the United Kingdom, Denmark, Germany, Belgium and the Netherlands.

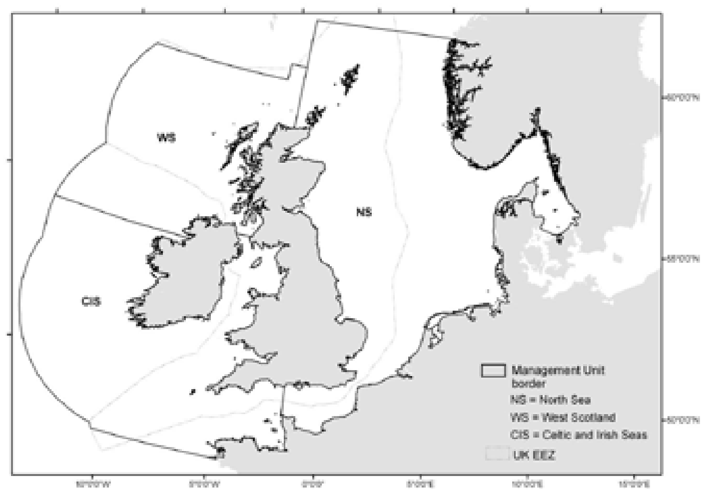

Figure 2-1 Overview of the North Sea 'Management Unit' from [IMMWG, 2013]. See also [Harwood et al., 2014].

Sections 2.2 to 2.5 (inclusive) set out the arguments underlying the selection of the principles and assumptions. Section 2.2 looks at the quantification of sound propagation, Section 2.3 explains the reasons for the selection of relevant effect parameters, together with the associated threshold values for occurrence of the effects (in harbour porpoises *and* seals), and Section 2.4 describes how it is possible to determine the number of affected animals and animal disturbance days for harbour porpoises. Finally, Section 2.5 describes how effects on individuals can be extrapolated to the population as a whole using the Interim PCoD model. This section also looks at the size of the population that may be affected.

2.2 Quantification of sound propagation

2.2.1 Modelling with AQUARIUS

The AQUARIUS computer model developed by TNO was used to estimate the levels of underwater sound generated during the construction of wind farms or during seismic surveying. That model is based on the method described in Weston [1971, 1976]. It calculates the spatial propagation of the sound using information about the source of the sound, the bathymetry, the sediment and the wind strength. Underwater sound charts are generated, where required for a range of depths in the water column.

2.2.2 Basic principles relating to piling sound

The modelling of the propagation of underwater sound associated with offshore piling is still under development [Reinhall & Dahl, 2011; Lippert et al., 2014]. The hybrid model developed by TNO [Zampolli et al., 2013], which calculates piling sound using detailed data about the pile, the piling hammer and the locality, still requires further validation. In the study described here of the cumulative effects of the construction of wind farms in the future, detailed information of this kind is not yet available.

As a result, this study used the AQUARIUS model to extrapolate the acoustic field using the existing monitoring data at relatively short distances from the pile to larger distances. Although the AQUARIUS model has not yet been validated experimentally for the sound propagation of piling sound over distances of more than approximately 6 km (the maximum distance measured in [De Jong & Ainslie, 2012]), this model is expected to provide a more realistic estimate of sound propagation than models that do not factor in the frequency of the sound, the bathymetry, the sediment or the wind strength.

For the calculation of the propagation of the piling sound, it is provisionally assumed that the piling sound as measured at the Prinses Amalia wind farm (Q7) [De Jong & Ainslie, 2012] can be adopted as a basis for estimating the underwater sound associated with driving monopiles in the North Sea (see [Ainslie et al., 2009]). Using the AQUARIUS model, [Ainslie et al., 2012] estimated the propagation loss PL of the sound between a point source in the middle of the water column at the piling location and the various monitoring locations for Q7 (21 m water depth, 'medium sand' sediment, 4.5 m/s wind at a height of 10 m). Totalling the calculated propagation loss (PL) at the measured sound level (SEL_1) resulted in estimates of the spectrums of an energy source strength SL_E = SEL+PL per piling strike for the various monitoring locations. The upper limit of these estimates (Figure 2-2) is used here as a spectrum for the piling sound in the AQUARIUS calculations. The SL_E per piling strike totalled for the frequency bands is 221 dB re 1 μPa^{2}s m^2. The lowest estimate of the broadband SL_E from the various measuring locations in Q7 is 215 dB re 1 μPa^{2}s m^2. Adopting the upper limit means that the calculated SEL_1 is overestimated by a maximum of 6 dB.

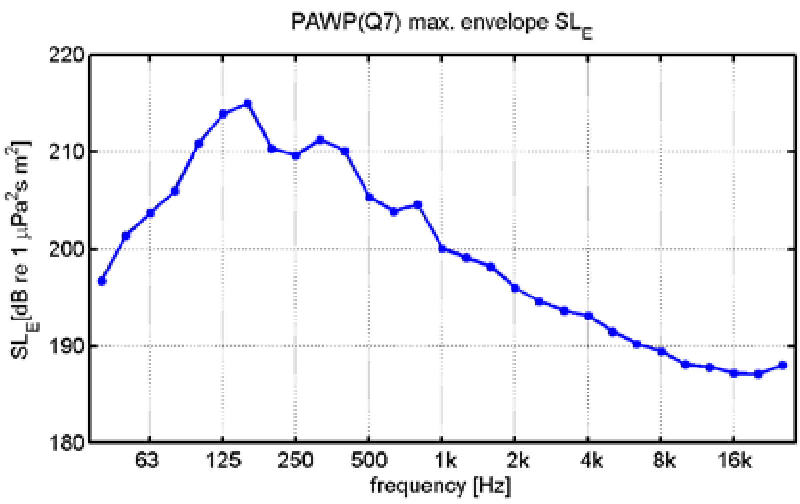

Figure 2-2 Estimated upper limit for the energy source level spectrum (1/3 of an octave) for the underwater sound from piling at sea based on the measurement results obtained during the construction of the Prinses Amalia wind farm (Q7), see the text above.

For the time being, monitoring data for offshore piling for a range of wind-turbine foundations [Ainslie et al., 2009; Betke, 2014; Bellmann et al., 2014] show that the spectrum distribution is not substantially different from this spectrum. The associated level does vary depending on the sizes of the pile and the hammer and on the properties of the seabed where the piling takes place. The level is estimated on the basis of the plausible assumption that a fixed percentage of the hammer strike energy is converted into sound energy. The data in Figure 2-2 apply to a hammer strike energy of 800 kJ. When estimating the SL_E spectrum for a different value for hammer strike energy E_{hammer}, a factor of $10\log_{10}(E_{hammer}/800\ kJ)$ is added to the spectrum from Figure 2-2.

2.2.3 *Basic principles for sound from seismic surveying*

At the request of RWS, an initial estimate was made – in the context of the present study – of underwater sound generated in the North Sea by airgun arrays used in seismic surveying for the purposes of mapping out the seabed in the search for oil and gas. These surveys have been going on for many years [DNZ, 2011]. The underwater sound generated by seismic surveying was estimated to establish a broad picture of the relative importance of this sound with respect to the sound produced during planned piling work for the construction of offshore wind farms.

Underwater sound from seismic surveying was estimated on the basis of highly simplified assumptions. As with piling sound, the calculations were made using the AQUARIUS model. The source strength of the airgun sound was estimated on the basis of the calculations made previously by TNO in a project for Wintershall [Ainslie et al., 2012b]. It was assumed that the source strength of the sound from an airgun array with a volume of 3,090 in^3, a pressure of 2.000 psi and a depth of 6 m is representative for the average configuration used. The estimate of the source strength was based on the results of detailed model calculations conducted by PGS and stated by TNO as an equivalent acoustic point source with the direction dependence relevant for propagation over larger distances. In that way, it was calculated that the most of the sound energy produced by the airguns is directed into the seabed for the purposes of surveying and does not therefore contribute to sound propagation in the vicinity.

2.3 Determining the size of the affected area: effect parameters and threshold values

2.3.1 *Relevant effect parameters*

As a result of the developments associated with offshore wind energy and the associated monitoring and research programmes, we have learnt an enormous amount in recent years about the effects of impulsive sound on marine animals. This is knowledge acquired both in the field and in laboratory conditions about the effect of the sound on the behaviour and the hearing of individual animals (particularly harbour porpoises). See the publications of [Kastelein et al. (2013, 2014)]; [Diederichs et al., 2014]; [Dähne et al., 2013] and [Thompson et al., 2013a]. The effects on individual animals observed in the study can have an impact on the population size, for example because foraging abilities are impaired, with a knock-on negative effect on survival chances or reproductive success because of the animal's condition. Changes in behaviour can also have acute effects on the chances of survival, for example if young animals lose their mothers [Miller et al., 2012].

The staged procedure in recent Dutch environmental impact assessments and appropriate assessments has been based on the latest research results. The staged procedure presented here looks at both the effects on the behaviour (avoiding the sound source) and the effects on hearing (particularly PTS) because it is supposed that these are the effect types that determine the size of the population. See Section 2.3.4.

2.3.2 *Threshold values for avoidance and effects on hearing (TTS/PTS)*

Threshold values for avoidance and TTS or PTS have been derived as much as possible from recent 'peer-reviewed' literature. Table 2-1 contains an overview of the criteria that are important for the determination of effects on harbour porpoises and seals, together with the associated values. For the arguments underlying the values included in the table, the reader is referred to the Intermezzo 'Threshold values for the effects of underwater sound on marine mammals'. An important parameter for the determination of the cumulative SEL is the speed at which animals swim away from the sound source. The assumed speeds are 3.4 m/s for the harbour porpoise and 4.9 m/s for seals. The Underwater Sound Working Group determined these values using a range of sources.

Table 2-1 Threshold values for estimating effects on harbour porpoises and seals. SEL_1 = sound dose as a result of a single piling strike; SEL_{CUM} = sound dose received by the swimming animal as a result of the driving of the entire pile; $SEL_{1/CUM,w}$ = M-weighted SEL for seals in water. See [Southall et al., 2007]

Species	type of effect	value	source
Harbour porpoise	Avoidance	SEL_1 > 140 dB re 1 $\mu Pa^2 s$	see Intermezzo Threshold values[5]
	TTS onset	SEL_{CUM} > 164 dB re 1 $\mu Pa^2 s$	Lucke et al., 2009
	TTS-1 hour	SEL_{CUM} > 169 dB re 1 $\mu Pa^2 s$	TTS onset + 5 dB
	PTS onset	SEL_{CUM} > 179 dB re 1 $\mu Pa^2 s$	TTS onset + 15 dB
Seals	Avoidance	$SEL_{1,w}$ > 145 dB re 1 $\mu Pa^2 s$	Kastelein et al., 2011
	TTS onset	$SEL_{CUM,w}$ > 171 dB re 1 $\mu Pa^2 s$	PTS onset – 15 dB
	TTS-1 hour	$SEL_{CUM,w}$ > 176 dB re 1 $\mu Pa^2 s$	TTS onset + 5 dB
	PTS onset	$SEL_{CUM,w}$ > 186 dB re 1 $\mu Pa^2 s$	Southall et al., 2007

Intermezzo *Threshold values for the effects of underwater sound on marine mammals*

THRESHOLD VALUES FOR AVOIDANCE

Harbour porpoise

In the past few years, relatively large amounts of research data have become available that can be used to derive threshold values for avoidance. These data

[5] The calculations made for this report (Chapter 3) adopted a threshold value for avoidance/disturbance in harbour porpoises of SEL_1 = 136 dB re 1 $\mu Pa^2 s$. These calculations had already been completed when the Underwater Sound Working Group decided to assume a rise of 4 dB in the threshold value to SEL_1 = 140 dB re 1 $\mu Pa^2 s$ in environmental impact assessments in the future.

come from research in both controlled conditions and field studies.

Experimental study

The threshold value for avoidance used in the Dutch environmental impact assessments in 2013 and in the calculations in the present report was derived from the results of research by SEAMARCO [Kastelein et al., 2013e]. In that study, a harbour porpoise with good hearing was exposed to 5 levels of recorded piling sound. A range of behavioural responses were studied, including breathing, jumping out of the water and the average distance from the loudspeaker. Jumping out of the water was seen as the best indicator of avoidance behaviour. Given figure 8b in [Kastelein et al., 2013e], it was then decided to adopt a threshold value of SEL_1 = 136 dB re 1 μPa^2s (SPL = 145 dB re 1 μPa). This value is the average of the lowest sound level at which the animal in the study started to jump out of the water and the sound level at which the frequency of jumping was significantly higher than in the control condition. This is a conservative value based on the results of a controlled experiment in quiet conditions. For example, when harbour porpoises are exposed to sonar sound, it has emerged that masking by background sound can result in a lower response [Kastelein et al., 2011].

Field study

There was also extensive research during the construction of the Borkum West II wind farm[6] looking at the response of harbour porpoises to piling [Diederichs et al., 2014]. That involved the installation of CPODs (Continuous POrpoise Detectors) at 26 stations at a range of distances from the piling locations.[7] This field study did not indicate any statistically significant change in harbour porpoise activity at an SEL_1 of less than 144 dB re 1 μPa^2s. That activity was expressed as the number of 'porpoise positive minutes' an hour with respect to baseline values.[8]

International threshold values

The German *Schallschutzkonzept* [BMU, 2013][9] concludes on the basis of results from a range of studies that the threshold value for disturbance is somewhere between SEL_1 = 134 and 145 dB re 1 μPa^2s. It is not entirely feasible to determine the precise threshold value on the basis of individual differences in response. In addition, the 'context' plays a role. However, it is assumed that a threshold value for disturbance of 140 dB re 1 μPa^2s is plausible [BMU, 2013]. This is higher than the value of SEL_1 = 136 dB re 1 μPa^2s used in the Dutch environmental impact assessment in 2013 and in the calculations for the present report but that it is still well below the value of SEL_1 = 145 dB re 1 μPa^2s at which Kastelein et al. [2013e] observed a significant increase in jumping frequency.

Threshold value for avoidance by the harbour porpoise for future Dutch impact

[6] BW II was built between 3 September 2011 and 28 March 2012, with 40 wind turbines on tripod foundations. The piles have a diameter of 2.4 m and they were driven with a maximum piling energy of 1,200 kJ. The piling time for each pile was an average of two hours.
[7] Harbour porpoises constantly send out high-frequency clicks (echo location) to track their food. These sounds can be recorded with CPODs.
[8] 'Porpoise positive minutes' are minutes during which CPODs detect the clicks emitted by harbour porpoises
[9] This document contains the policy guidelines for granting permits in Germany.

assessments

During the meeting of the Underwater Sound Working Group on 7 November 2014, it was decided to adopt the higher threshold value of SEL_1 = 140 dB re 1 μPa^{2}s for future environmental impact assessments because it has become clear that the value previously adopted of SEL_1 = 136 dB re 1 μPa^{2}s is probably very conservative and the value of SEL_1 = 144 dB re 1 μPa^{2}s may not be conservative enough (in case of doubt, the precautionary principle should apply). Furthermore, the same threshold value will then be used in the Netherlands and Germany, easing the way to international harmonisation in the future.

Seal

The threshold value for avoidance behaviour in seals of SEL_1 = 145 dB re 1 μPa^{2}s is derived from observations of the behaviour of seals when exposed to recorded piling sound [SEAMARCO, 2011]. At SEL_1 = 142 dB re 1 μPa^{2}s, it was found that one of the two harbour seals exposed to the sound swam away and left the pool. Because the other seal did not respond and therefore had a higher threshold for disturbance, the Underwater Sound Working Group decided to adopt an $SEL_{1,w}$ of 145 dB re 1 μPa^{2}s.

THRESHOLD VALUES FOR EFFECTS ON HEARING

In the calculations for the Round 2 wind farms, three thresholds with increasingly higher values for the size of the effect were used to study the occurrence of effects on the hearing sensitivity of harbour porpoises and seals. These thresholds were values for the occurrence of a temporary or permanent increase in the hearing threshold: TTS (Temporary Threshold Shift) and PTS (Permanent Threshold Shift) respectively. They are based on the following criteria:

1. TTS onset: in exposed animals, an increase in the hearing threshold of 6 dB at any frequency is measured between 1 to 4 minutes after exposure.
2. TTS (1 hour): in exposed animals, an increase in the hearing threshold of 18 dB at any frequency is measured between 1 to 4 minutes after exposure. Given a trend estimated on the basis of measurements in the recovery of hearing, TTS falls to 6 dB after 1 hour. With a trend estimated using measurements in the increase in the threshold shift, this threshold value is 5 dB higher than the threshold value for 'TTS onset' (see Annex 2).
3. PTS onset: the level at which a rise in the hearing threshold of 40 dB is thought to occur in exposed animals after 1-4 minutes (for ethical reasons, this is not actually measured). Given data relating to land mammals, this threshold is estimated to be 15 dB above the value for 'TTS onset'.

Harbour porpoise

The threshold value for TTS onset assumed for harbour porpoises is based on the results of the research of Lucke et al. (2009). The exposure levels reported in that study for TTS onset are expressed as an unweighted SEL_1 caused by a single pulse. Because, among other things, the recovery of hearing between strikes is not taken into account, this can be seen as a conservative threshold for 'TTS onset' after the cumulative exposure to the 2500-3000 piling strikes involved in driving one pile. Recent, as yet unpublished, research [Kastelein et al., 2014] shows that the threshold values for the occurrence of TTS and PTS upon exposure to a series of pulses (recorded piling sound) are probably a lot higher than assumed here (see below, Section 2.3.4). In other words: the hearing of the harbour porpoise has proven to be less sensitive to the accumulation of a series of pulses than to a single pulse with the same exposure level.

Seals

The threshold adopted for TTS onset in the harbour seal is the one derived indirectly in [Southall et al., 2007] from the data of Kastak et al. (2005). In a harbour seal, they found a 6 dB TTS onset after exposure to continuous sound at a SEL_{CUM} of 184 dB re 1 μPa^2s (25 min, SPL 152 dB re 1 μPa^2). On that basis, Southall et al. estimated a threshold value for TTS resulting from impulsive sound by deducting the difference of 13 dB between the threshold values measured in bottlenose dolphins for TTS as a result of continuous sound and TTS caused by impulsive sound. As is also stated in [Southall et al., 2007], that is probably a conservative estimate. This threshold value is used for the cumulative unweighted $SEL_{CUM,W}$, totalled for all pulses to which an animal is exposed during the driving of a single pile.

PTS onset

The threshold value adopted for PTS onset is, in line with [Southall et al., 2007], 15 dB above the threshold for TTS onset (see also the considerations in the TNO memorandum included as Annex 2 to this report). The threshold for PTS is therefore SEL_{CUM} = 179 dB re 1 μPa^2s for the harbour porpoise and $SEL_{CUM,W}$ = 186 dB re 1 μPa^2s for the seal. Adopting this threshold implies that PTS in seals will, in addition to a form of permanent damage, also imply severe TTS in which recovery will take days.[10]

Frequency weighting

For the harbour porpoise, given the data from [Lucke et al., 2009] and [Kastelein et al., 2013e], we assume unweighted threshold values that do not take hearing sensitivity as a function of the frequency into account. In the case of the seal, in line with [Southall et al., 2007], Mpw-weighted SELW values have been used, with ‘pw’ standing for ‘pinnipeds in water’. This weighting takes a bandwidth for hearing underwater of between 75 Hz and 75 kHz into account. At the distances at which avoidance can occur, the effect of this weighting for impulsive sound from piling and seismic surveying is small because the sound at the frequencies covered by the weighting is also weakened by propagation effects. Frequency weighting is discussed in further detail in conjunction with the knowledge gaps in Section 6.3 and Section 6.4.

2.3.3 Application of threshold values in the determination of the sizes of the affected area

In the environmental impact assessments and appropriate assessments drafted in 2013, the effects of piling sound on behaviour were calculated with underwater sound charts generated using AQUARIUS, which showed the distribution of the

[10] In recent research, Kastelein et al. (2013a) have shown that a harbour seal nevertheless recovered from a very high TTS (44 dB) after 4 days. Because of the possible ecological consequences of a chronic threshold shift and because 1 measurement in which the limit of 40 dB TTS is exceeded is not yet enough to exclude the possibility of PTS, the definition of PTS used in Southall et al. (2007) has been adopted (Underwater Sound Working Group).

spatial sound imissions as a result of a single piling strike (SEL_1). It was assumed that the sound energy from a single, maximum, piling strike determines behavioural changes. In the next step, the distance from the piling location at which the threshold values for **avoidance** are exceeded was determined for harbour porpoises and seals.

In addition, the possible cumulative sound burden during the driving of a single pile was calculated for harbour porpoises and seals that are in the proximity of the piling location and then swim away at a given speed. The total sound burden on the animal as a result of the cumulative energy generated by all piling strikes for a single foundation (SEL_{CUM}) was compared with limit values above which the sound could lead to a **temporary or permanent threshold shift** (TTS and PTS respectively) in harbour porpoises and seals.

2.3.3.1 Determining the avoidance area (effect on behaviour)

An example of the calculated distribution of the sound during piling for the construction of a wind farm off the Dutch coast, taken from [Arends et al., 2013], can be found for harbour porpoises in Figure 2-3. The distribution at 1 m below the water surface can be found on the left of the figure, with the distribution at 1 m above the seabed being on the right. The black lines show the contour within which a threshold value for avoidance by harbour porpoises of 136 dB re 1 $\mu Pa^2 s$ is exceeded. The sound tails off faster towards the coast because of the reduction in the depth of the water. The figure shows that, at local average wind conditions (= 6.5 m/s) and a piling energy of 1,200 kJ, the piling location could be avoided by harbour porpoises near the seabed in an area of 2,028 km^2. At 1 m below the surface of the water, this area is 290 km^2. The avoidance distance is shorter closer to the surface because sound tails off more higher in the water column than deeper down. See the example in Figure 2-4. In Figure 2-3, the maximum distances at which avoidance of the piling location is found are approximately 27 km (close to the seabed) and 10 km (1 m below the surface).

In this procedure proposed in this report, we have decided to use disturbance in the bottom part of the water column as the basic assumption for the determination of the disturbance area because we assume that the natural behaviour of harbour porpoises is to dive when foraging and that they can be disturbed in that behaviour by the higher sound levels found deeper in the water column.

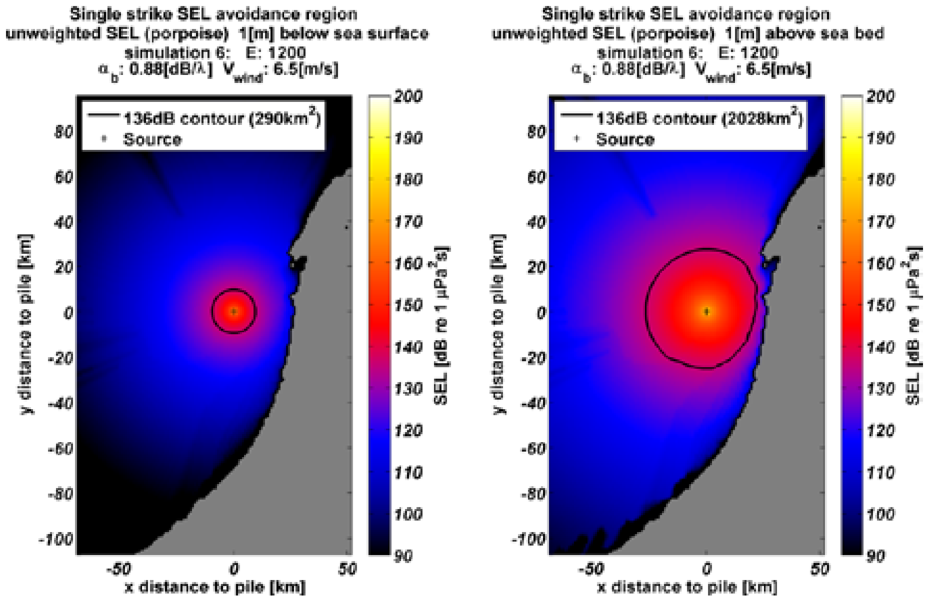

Figure 2-3 Calculated distribution from [Arends et al., 2013] of SEL_1 around a piling location (+) in the North Sea at a depth of 1 m below the surface (left) and 1 m above the seabed (right). Wind speed 6.5 m/s. The black lines show the contour within which the threshold value for avoidance (see Table 2-1) is exceeded for harbour porpoises. The grey area shows the Dutch coast.

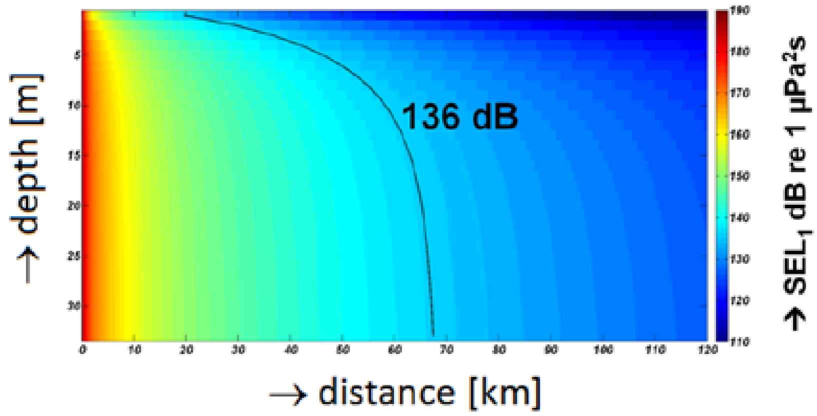

Figure 2-4 Example[11] of an SEL_1 distribution as a function of distance from the pile and depth in the water column calculated by AQUARIUS. The black line is the contour at which the SEL_1 is 136 dB re 1 μPa^{2}s.

2.3.3.2 *Determining the area in which TTS or PTS can occur*

In addition to the calculation of avoidance distances, it is also possible to calculate the total sound dose (SEL_{CUM}) to which harbour porpoises are subjected if they are exposed to several piling strikes during the driving of a single pile. Their location when the piling starts and assumptions about their behaviour in response to the piling sound determine the total sound dose received and therefore the occurrence

[11] N.B. The example in Figure 2-4 relates to a location other than the example in Figure 2-3.

of TTS and PTS. The following assumptions apply to this calculation for this example:

- a maximum of 1,200 kJ piling energy / a maximum of 3,500 piling strikes;
- piling complies with a realistic ‘soft start’ scenario, based on current practice for driving monopiles for wind turbine foundations;
- when piling starts, the animals are located close to the seabed (*worst case scenario*);
- animals within the contour line in which avoidance occurs swim quickly to the surface of the water during the first two piling strikes;
- these animals then swim in a straight line away from the piling location at a depth of 1 m below the surface as piling continues;
- animals stop swimming as soon as they reach a point away from the piling location at which the sound dose as a result of 1 piling strike is lower than or equal to the threshold value at which avoidance occurs.

Figure 2-5 states, for the same example as in Figure 2-3, the results of the calculations for harbour porpoises in average wind conditions. It can be seen from the figure that TTS may occur in harbour porpoises near the seabed when piling starts within a radius of approximately 16 km. The distance within which PTS may occur in a harbour porpoise is 0.5 km. N.B. The results shown here have been calculated for a specific farm at a specific location and they are not generally applicable.

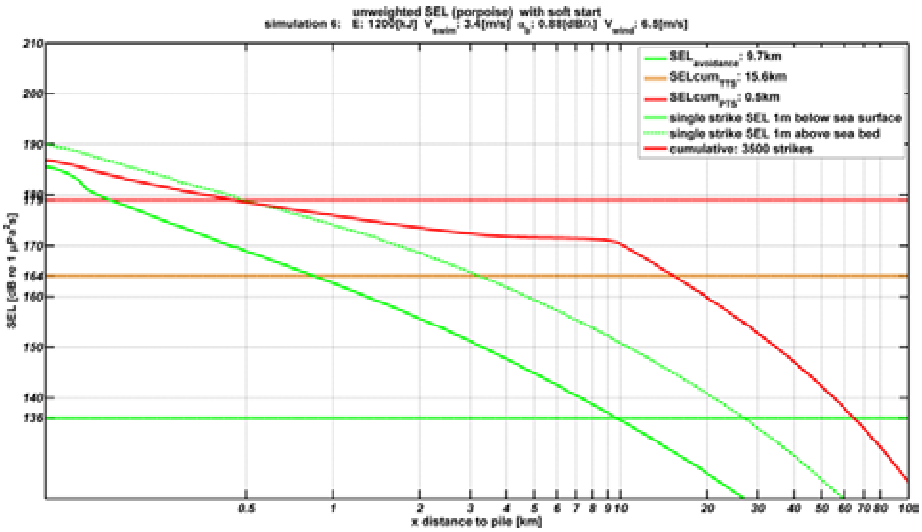

Figure 2-5 Calculated distribution from [Arends et al., 2013] of SEL_1 at a depth of 1 m below the surface (continuous green curve) and at 1 m above the seabed (dotted green curve) and the SEL_{CUM} to which a harbour porpoise is exposed during the complete piling scenario for a single wind turbine foundation (continuous red line) as a function of the distance to the pile at which an animal is located when piling starts at 1 m above the seabed (*worst case scenario*). The horizontal lines show the threshold values for avoidance behaviour (green), TTS onset (orange) and PTS onset (red) for harbour porpoises (see also Table 2-1). The intersections of the green curves (SEL_1) with the green horizontal line show the avoidance distance for harbour porpoises at 1 m below the surface (~10 km) and at 1 m above the seabed (~27 km). The intersections of the red line with the red and orange dotted lines show the ‘PTS distance’ (~0.5 km) and the ‘TTS distance’ (~16 km).

2.3.4 *Assumptions for determining population effects*

To determine the effects of piling sound on the populations of marine mammals, the approach for Round 3 wind farms takes the approach developed in early 2013 further. In effect, the staged procedure developed at that time was supplemented by the Interim PCoD 'population module'.

The approach underlying the Interim PCoD model is used internationally, making our results and approach comparable with those of other countries. Furthermore, the Interim PCoD model is currently the only model available.

On the basis of ongoing developments and research results published recently, the Underwater Sound Working Group concluded that the previous staged procedure requires some amendments in terms of the effect parameters and the threshold values in order to allow the most recent insights to be taken into account:

- In the Interim PCoD model, the primary effect to be entered in the model is expressed by the number of animals disturbed by sound; an animal is considered to be 'disturbed' if there is a 'significant behavioural response' [Harwood et al., 2014]; the Interim PCoD model defines this ‘significant behavioural response’ as a behaviour with a score of 5 or higher on the behaviour response scale in [Southall et al., 2007]; these are behaviours such as changes in swimming behaviour and breathing, avoiding a particular area and changes in vocal behaviour (for the purposes of communications and foraging). In the workshop for ecologists referred to above, it was concluded that the threshold value used in the past for avoidance is based on similar principles. The concept of ‘significant behavioural response’ (disturbance) as used in the Interim PCoD model can therefore be considered to be equivalent to the concept of ‘avoidance’ as used thus far in the staged procedure for the effects of underwater sound on marine mammals;
- The calculations made for this report adopted a threshold value for avoidance/disturbance in harbour porpoises of SEL_1 = 136 dB re 1 $\mu Pa^2 s$. These calculations had already been completed when the Underwater Sound Working Group decided to assume a rise of 4 dB in the threshold value to SEL_1 = 140 dB re 1 $\mu Pa^2 s$ in environmental impact assessments in the future. See the arguments given in the Intermezzo ‘Threshold values for the effects of underwater sound on marine mammals’ in Section 2.3.2;
- Effects on behaviour (disturbance/avoidance) probably determine the effects on populations. On the basis of the arguments described below, the calculations of the cumulative effects of the construction of several wind farms in the North Sea no longer take into account any knock-on effects of TTS and PTS on the population as a whole.

The arguments for disregarding **TTS** are as follows:

- The calculated TTS onset contours are much smaller than the maximum avoidance contours, which means that the number of harbour porpoises with hearing that is temporarily affected is also smaller than the number of harbour porpoises disturbed;
- On condition that mitigation measures are implemented to prevent PTS (see below), all the harbour porpoises that may be affected will recover their hearing in full (with the vast majority of them doing so within a few hours after leaving the area affected or after piling ceases);

- The threshold value adopted for ‘TTS onset’ in harbour porpoises is based on the results of the experimental exposure of harbour porpoises to airgun sound by Lucke et al. (2009). This is the sound dose (SEL_{CUM}) at which a temporary increase in the hearing threshold of 6 dB is measured (in other words, hearing is 6 dB less sensitive). However, it has emerged from the results of recent research by SEAMARCO that, with recorded piling sound, a minor TTS of 2.3 – 4 dB can be observed in harbour porpoises at a SEL_{CUM} of 180 dB re 1 $\mu Pa^2 s$ [Kastelein et al., 2014]. This value is much higher than the value assumed in the calculations and this could imply that the effect areas for TTS are much smaller than those calculated until now, which assume a threshold value for SEL_{CUM} of 164 dB re 1 $\mu Pa^2 s$;
- The frequencies at which TTS can occur in harbour porpoises after exposure to piling sound are not in the frequency range that is important for finding food using echo location. In the case of a harbour porpoise exposed to recorded piling sound, it has emerged that the shift is limited to a relatively small band of low frequencies [Kastelein et al., 2014]. A statistically significant TTS was found only at frequencies of 4 kHz and 8 kHz, and not at the higher measured frequencies (16 kHz and 125 GHz, the echo-location frequency) and the lower frequency (2 kHz). It is striking that, at frequencies in which most of the sound energy of the delivered piling sound is located, namely the 600 – 800 Hz frequency band, there is no TTS. These observations are important for the assessment of the ecological relevance of a predicted hearing threshold shift. A temporary shift in the low-frequency range of the hearing spectrum is probably much less relevant for harbour porpoises in terms of foraging than it is in the high-frequency range. High-frequency sounds of about 125 kHz and the audibility of those sounds are essential in this species for locating prey (using echo location).

As for the possible effects of **PTS**, it has been assumed that the effects will be prevented by mitigation measures. At present, this is safeguarded by means of a regulation in the existing permits. It emerges from the calculations made for various wind farms that the distance at which harbour porpoises could suffer PTS is relatively small. This distance is approximately 500 m at an average wind speed and approximately 1.5 km in windless conditions. At distances of this kind, the effect can probably be prevented by piling with a ‘soft start’ and by using an ‘acoustic deterrent device’ (ADD)[12]. This will probably drive harbour porpoises away to a distance outside the PTS contour line. If this were not to be done, one or two harbour porpoises per driven pile could suffer PTS given the population densities on the DCS.

2.4 Quantification of the number of affected animals and animal disturbance days

2.4.1 Calculation of the number of harbour porpoises affected by piling sound

It has been assumed in the calculations of the number of animals affected by piling sound that these are all the animals present inside the contour line where the threshold value for disturbance/avoidance is exceeded in the lower half of the water column (*worst case scenario*). The lower sound levels near the surface have not been taken into account in the estimate of effect distances in the supposition that

[12] Because ADDs produce sound in another frequency range than piling sound, the possibility of cumulative effects on hearing is negligible.

the normal behaviour of harbour porpoises will be affected if they cannot use the entire water column. In addition, it has been assumed that all the animals located inside the contour line when sound production starts are disturbed for the same length of time. This means that it is also assumed that an animal located at a distance of one kilometre from the sound source when piling starts will be disturbed for the same amount of time as an animal located ten kilometres from the source. German and Danish field research looking at the construction of wind farms suggests that these assumptions are highly simplified (see Intermezzo ‘Effects of impulsive sound on harbour porpoises in field conditions’). However, it is not yet possible to make more realistic assumptions based on these observations.

Intermezzo *Effects of impulsive sound on harbour porpoises in field conditions*

The research of [Brandt et al., 2011] shows that it takes 1-3 days before harbour porpoise activity in the area around a piling location recovers completely. Recovery is gradual: near the piling location, it takes longer before harbour porpoise activity is observed than further away. [Dähne et al., 2013] monitored harbour porpoise activity with CPODs at 12 stations before, during and after piling for the construction of the Alpha Ventus wind farm. At 8 of the 9 stations located less than 11 km from the piling location, harbour porpoise activity fell significantly after piling started and activity at 2 of the 3 stations located more than 23 km from the piling location increased significantly. No data are available about developments in harbour porpoise activity at distances between 10 and 23 km since no monitoring stations were located in this area. The return of the harbour porpoises (whether these are the same animals or other animals) was measured using the 'first waiting time'.[13] The authors state that this depended on the distance from the piling location and that it varied from a median value of 81 minutes at a distance of 25.2 – 26 km from the piling location to 24 hours at 0.5 – 2.5 km.[14] Inside a radius of approximately 25 km, it took an average of 16.5 hours after the start of piling before harbour porpoise activity was observed again. The maximum waiting time measured in this study was almost 6 days and this was observed at a distance of 2.3 – 4.7 km.

There was also extensive research during the construction of the Borkum West II wind farm[15] (where tripod foundations were used) looking at the response of harbour porpoises to piling [Diederichs et al., 2014). CPODs were installed here at 26 stations at different distances from the piling locations. The picture to emerge from that study was as follows:

- At an SEL_1 of less than 144 dB, no disturbance was observed in harbour porpoises; disturbance was derived from the changes in the number of 'porpoise positive minutes' per hour with respect to baseline values;
- The calculated disturbance distance at this sound level was 15 km;
- There was an almost directly proportional relationship between the sound

[13] ‘Waiting time’ (in minutes) defined as the time interval of more than 10 minutes in which no harbour porpoise activity is observed.
[14] The ‘gap’ in the figures at distances of between 10 km and 23 km means that this conclusion cannot be drawn without reservation.
[15] BW II was built between 3 September 2011 and 28 March 2012, with 40 wind turbines on tripod foundations. The piles have a diameter of 2.4 m and they were driven with a maximum piling energy of 1,200 kJ. The piling time for each pile was an average of two hours.

level and disturbance effects;

- At SEL_1 > 160 dB, the authors found that all animals were driven away (with some animals being driven away at levels between 144 dB and 160 dB);
- 9-12 hours after piling ceased, harbour porpoise activity was still significantly lower than previously; the lowest values were measured up to 4 hours after piling, after which they increased again gradually;
- By contrast with the results from the studies of Brandt et al. (2011) and Dähne et al. (2013), it was found that the animals returned within a period that was much shorter than 24 hours; throughout the area affected, it took no more than 13 to 16 hours before harbour porpoise activity returned to a level that was comparable to that prior to the start of piling; in addition, it also emerged that there was no clear correlation with the distance to the piling location;
- Given the results, the authors concluded that, inside the SEL_1 = 144 dB contour line, approximately 40% of the harbour porpoises present were driven away. N.B. The staged procedure in the present report assumes that disturbance occurs in all harbour porpoises inside the contour line where the threshold value is exceeded.

The observations of Brandt et al. (2011), Dähne et al. (2013) and Diederichs et al. (2014) lead to the following conclusions:

- Near the piling location, all the harbour porpoises present when piling starts leave the area; harbour porpoise activity returns to a normal level within 12 to 24 hours and it has even been found that activity returns to normal only a few days after piling ceases. N.B. It is not known whether these are the animals driven out of the area that are returning or animals from the surrounding area swimming into the affected area;
- Further away from the piling location (but within the maximum area where an observable response occurs), there is a response in some of the harbour porpoises present. The proportion of the harbour porpoises that respond depends on the distance to the piling location;
- In this transitional area, the pattern for the recovery time varies: Diederichs et al. (2014) state that it also takes 12 hours in this area before the situation returns to normal. Dähne et al. (2013) believe that this depends on the distance to the piling location and state that the situation on the edge of the affected area recovers faster (in 1 hour and 20 minutes) than close to the piling location (24 hours). Brandt et al. (2011) sketch a similar picture.

The results from the studies in Danish and German wind farms described above nuance the method currently used, in which it is assumed that the effect on all the animals inside the contour line calculated for disturbance is the same. In the case of the construction of Borkum West II, it was found that this was not the case in field conditions [Diederichs et al., 2014]. However, it is unclear how the observed effects should be interpreted for application in effect calculations for the construction of wind farms in the future involving piling.

Recently, information became available about the response of harbour porpoises to seismic sound [Thompson et al., 2013a]. The results of aerial surveys and CPOD data showed that there was a fall in harbour porpoise activity (relative population density and clicking) at SEL_1 values between 145 and 151 dB re 1 μPa^{2}s. The research also showed that a resumption of harbour porpoise activity could be observed in the affected area within a few hours.

The number of affected harbour porpoises was calculated by multiplying the disturbance areas by the average harbour porpoise population density at the time of year when the disturbance took place. For the DCS, the calculation is based on the results of aerial surveys reported by [Geelhoed et al., 2011, 2014]. In addition, the population density assumes the estimated average density in each separate area (see Figure 2-6). The estimates cover a bandwidth of ± 50% centred on the average. Data for the entire DCS are available for the spring of 2011, 2012 and 2013, with data also being available for 2010 (C, D) and 2009 (D) in two individual areas. The availability of information about densities varies. For the purposes of determining harbour porpoise numbers in the summer (July) and the autumn (October/November), data are available for 2010 only. For information about harbour porpoise numbers outside the Netherlands (DCS), the reader is referred to Section 3.1.4.

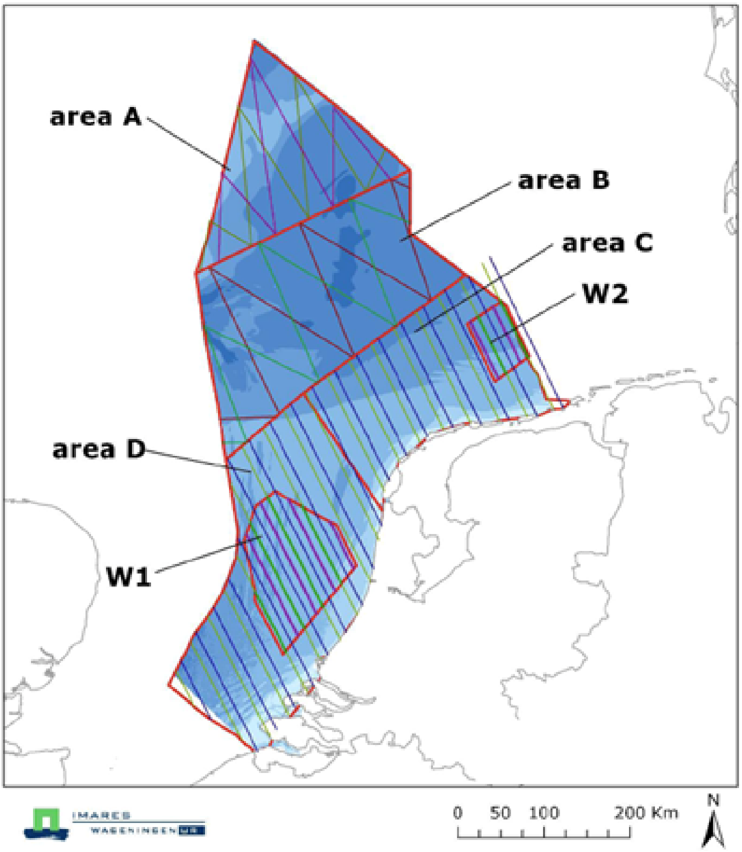

Figure 2-6 Chart after Geelhoed et al. (2011) of the DCS showing areas A (Dogger Bank), B (Offshore), C (Friesian Front) and D (Brown Bank). W1 and W2 show the areas relevant for wind energy at the time. The lines represent the transects flown and the colours represent the various surveys.

2.4.2 *Animal disturbance days*

The total number of animal disturbance days is calculated by multiplying the number of animals that may be disturbed on one day by the number of disturbance days. In principle, the Interim PCoD model assumes that each day on which piling takes place counts as a single disturbance day, regardless of how long piling lasts. This is a pragmatic approach because the information known at present about how long disturbance lasts does not provide us with an unequivocal picture. For example, in the SEAMARCO pools, it was found that the harbour porpoise reverts to normal behaviour immediately after the exposure ceases. On the other hand, some field observations suggest that animals stay away from an area for one to three days after being disturbed by piling [Brandt et al., 2011]. However, harbour porpoise activity has been observed just a few hours after disturbance by seismic surveying [Thompson et al., 2013a]. It is reasonable to suppose that the disturbance time depends on the exposure level and the context (season, location, gender, weaning, and so on), but adequate detailed information is lacking given the small number of studies. The Interim PCoD model can take the disturbance time into account by adding one or more ‘residual days’ after a disturbance day during which there has been piling activity, or by shortening the disturbance time.

2.5 Extrapolation of effects on individuals to the population

2.5.1 *Determination of the total relevant population size*

The selection of a specific population size plays a role in the extrapolation of effects on individuals to the population. In line with [IMMWG, 2013], it has been assumed for the calculation of effects on harbour porpoises that the relevant population is the population in the ‘North Sea Management Unit’ (see Figure 2-1 for the boundaries of this area): 227,298 animals. It has also been assumed that the size of the population not suffering disturbance is stable.

2.5.2 *PCAD and PCoD models*

Figure 2-7 describes the PCAD model developed at the initiative of the National Research Council (USA) [NRC, 2005]. It shows how behavioural changes in marine mammals resulting from anthropogenic sound can affect the population as a whole.

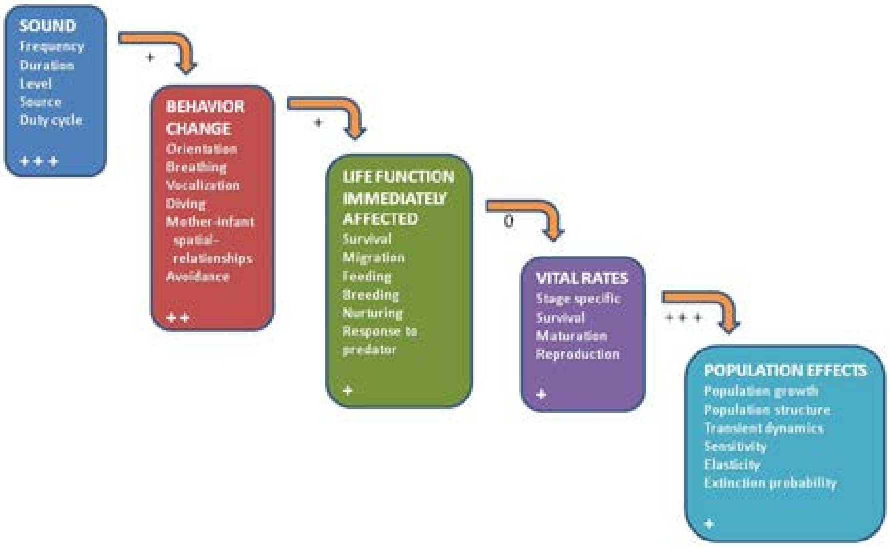

Figure 2-7 The *Population Consequences of Acoustic Disturbance* (PCAD) framework developed by the National Research Council's panel on the biologically significant effects of sound. After Figure 3.1 in (NRC, 2005). The number of + signs provides an indication of the panel's estimate of the level of scientific knowledge about the connections between the boxes; 0 indicates that this knowledge is lacking.

The structure of the PCAD model was amended in a working group established by the US Office of Naval Research. Parameters were estimated using results from case studies looking at five species of marine mammal. During this process, the scope was also extended to include all possible forms of disturbance and the possible influence of the physiological effects of disturbance was also included. The amended model – the PCoD model (Population Consequences of Disturbance) – can be found in Figure 2-8 and it has been described in detail by New et al., (2014). It can be seen in the figure that disturbance can affect both the behaviour and the physiology of individuals and that changes in these factors can have a direct effect (an 'acute effect') on survival and reproduction (*vital rates*) in that individual or impact the individual indirectly by affecting health (this is a chronic effect).

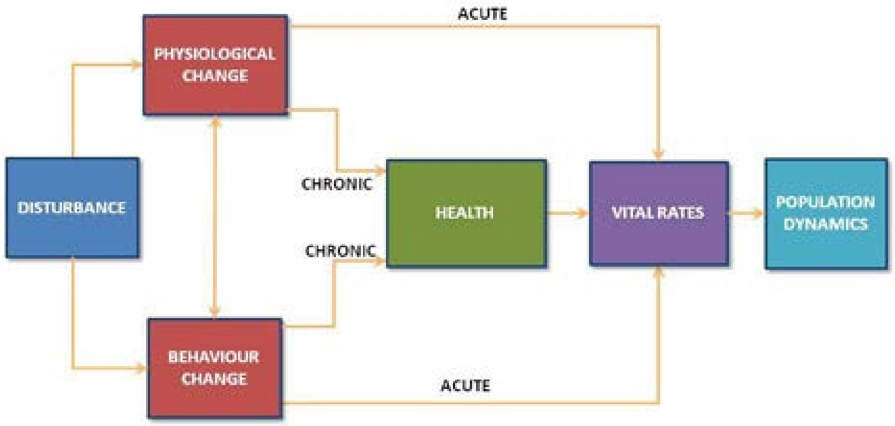

Figure 2-8 The PCoD framework for modelling the '*Population Consequences of Disturbance*' developed by the ONR PCAD working group (adapted after Figure 4 in New et al., 2014). The term *health* is used for all aspects of the internal condition of an individual that can affect the health of that individual. This may be, for example, the fat reserves or resistance to disease. *Vital rates* refers to all components of individual health (*probability of survival and producing offspring*, *growth rate*, and *offspring survival*).

Despite the fact that the PCoD model presented in Figure 2-8 is already a major simplification, it is not yet possible to make an estimate of all the required parameters for many marine mammal species. This also applies to the species we focus on in this study: the harbour porpoise, harbour seal and grey seal. The knowledge gaps relate primarily to the quantified effects of changes in behaviour and/or physiology, the knock-on effects on condition/health and the resulting probability of survival/reproduction (*vital rates*).

The PCoD model has therefore been simplified yet further for certain species when the required knowledge is not available. This is the 'Interim PCoD framework' in Figure 2-9 [Harwood et al., 2014]. In this approach, the parameters for the relationship between physiological and/or behavioural changes and the vital rates are obtained by bringing in experts to estimate them in an *expert elicitation process* (see Intermezzo 'Expert Elicitation' for an overall description and [Harwood et al., 2014; Donovan et al., in press] for details).

The *Interim PCoD framework* was developed in 2013 by SMRU Marine and the University of Saint Andrews to predict the possible effects on marine mammal populations resulting from disturbance, damage to hearing and collisions as a result of the construction and operation of offshore renewable energy structures (including wind energy). As far as is known, this is the only instrument currently operational that establishes a quantitative link between disturbance and consequences for populations as a whole. That means that it is also the only instrument that can be used to determine the cumulative effects of disturbance by various types of activity. The framework has been described by Harwood et al. (2014) and the associated software written in *R* (www.r-project.org) can be downloaded from the website of The Scottish Government (see www.smru.co.uk/pcod and www.scotland.gov.uk/Topics/marine/science/MSInteractive/Themes/pcod).

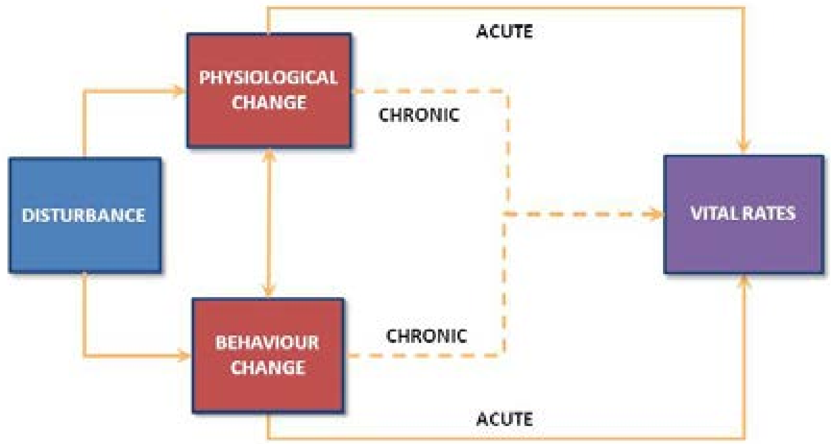

Figure 2-9 Simplified version of the PCoD framework from Figure 2-8 as applied in the Interim PCoD model. Due to the lack of empirical data about the effects of changes in physiology and behaviour on individual health (*health*), the links indicated by the dotted lines between the chronic effects of changes of this kind and *vital rates* were determined in an 'expert elicitation process' [Harwood et al., 2013/2014]. The term *vital rates* here refers to all the components of individual health (*probabilities of survival and producing offspring*, *growth rate*, and *offspring survival*).

Intermezzo *Expert elicitation*

The Interim PCoD model establishes a quantitative relationship between the disturbance of behaviour and 'vital rates'. That relationship was established by consulting experts in a formal 'expert elicitation' process because of the lack of observational data. That process involved the use of a range of techniques to weight the experts' opinions independently and to provide a numerical estimate of the uncertainty in the relationship. See Harwood et al. (2014) for details.

In the implementation of the Interim PCoD model for the purposes of this study, 'disturbance' (in other words, 'significant behavioural response') was defined as a change in behaviour that can have an adverse effect on the probabilities of survival, reproduction and nurturing of offspring. This corresponds, in broad terms, to a score of 5 or higher on the 'behavioural response severity scale' for marine mammals in Southall et al. (2007).

A group of 13 international experts, who were selected on the basis of recent relevant publications, participated in the 'expert elicitation' process for harbour porpoises. They were asked to make estimates of the three parameters A, B and C for the relationship shown in Figure 2-10 between the number of disturbance days in a year and two specific dominant 'vital rates':

1. the survival probability for offspring (calves and juveniles);
2. the probability of adult females giving birth.

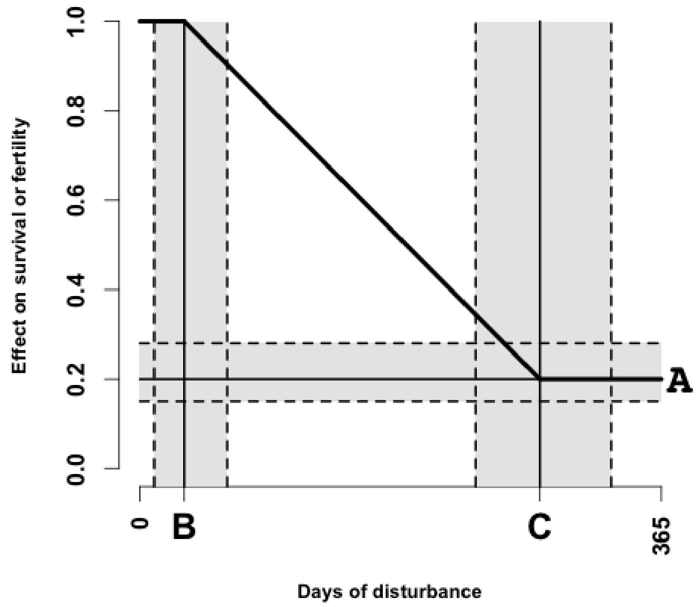

Figure 2-10 From [Harwood et al., 2014]: The hypothetical relationship between the number of days of disturbance experienced by an individual marine mammal and its effect on the probability of survival or fertility. A is the maximum effect of disturbance on this probability (in this case, the actual probability will be the population survival rate multiplied by 0.2), B is the number of days of disturbance an individual can tolerate before its survival or fertility is affected, and C is the number of days of disturbance required to cause the maximum effect. The shaded areas indicate the likely range around the best estimates of A, B and C provided by each expert.

The answers of the various experts, including an indication of the confidence interval, were combined to produce a two-dimensional probability distribution function, as shown in Figure 2-11.

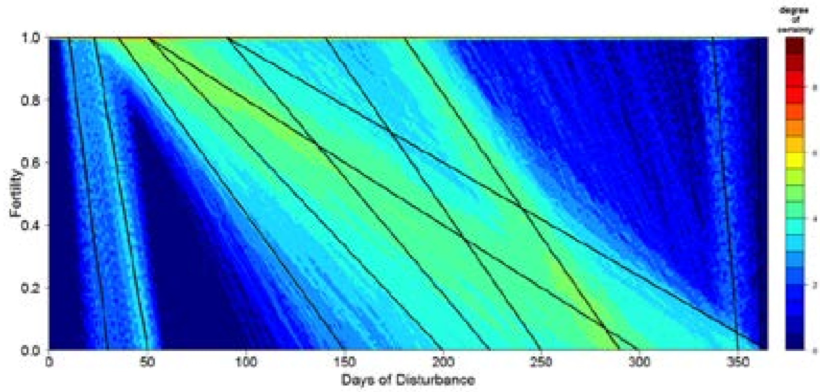

Figure 2-11 From [Harwood et al., 2014]: Probability density function for the relationship between the number of days of disturbance experienced by an adult female harbour porpoise and the effect of that disturbance on her fertility. The black lines indicate the relationships suggested by individual experts. They are superimposed on a map that shows the overall support amongst the experts for particular combinations of values - 'hot' colours (reds and yellows) indicate combinations for which there was a lot of support, and 'cold' colours (various shades of blue) indicate combinations for which there was little or no support.

Given these probability distributions, a random 'virtual' expert opinion was derived for each simulation run in a stochastic population dynamic model that extrapolates the calculated number of disturbance days for individuals in ten age categories to 'vital rates' and demographic development (see also [Harwood et al., 2014]).

Other relevant parameters in the Interim PCoD model are:

- The total size of the population;
- The ‘vulnerable sub-population’: the part of the total population that may be disturbed for a given period of time by underwater sound from a specific project. If the total population is highly mobile, this may be a large proportion of that population. However, the project may also be located in a habitat that is critical for a small part of the population;
- The duration of the disturbance. The basic assumption in the Interim PCoD model is that the effect of a disturbance that lasts for part of the day continues for at least one whole day. It has emerged from field studies that this duration can be longer or shorter (see also Intermezzo in Section 2.4.1 and Section 2.4.2). As a result, the Interim PCoD model includes an option for factoring in an anomalous duration of the disturbance using a *residual days of disturbance* parameter.

There are uncertainties relating to the correct selection of these parameters because research results are lacking or equivocal. It would therefore be advisable to study the sensitivity of the model calculations to realistic variations in these parameters. Chapter 3 describes, for harbour porpoises, the possible effect of variations in these parameters on the model outcomes.

The Interim PCoD model assumes that the harbour porpoise population is stable and that demographic development does not depend on the population density. This means that, after the one-off inclusion of an effect on the population, in other words a fall in numbers as a result of the activities, the population in the model outcomes will not recover after the activities cease and that it will stabilise at a lower level. This is an unrealistic simplification. We need to know more about the population-density-dependent effects on demographic developments in order to arrive at a more realistic estimate of changes in the population during the years when there is disturbance, but above all after the disturbance ceases. The available knowledge in this area relating to the harbour porpoise is very limited (see Chapter 6).

2.5.3 *Application of Interim PCoD in RWS project*

Rijkswaterstaat Sea and Delta asked John Harwood and his colleagues to make calculations in September 2014 for a range of provisional scenarios applying to the Dutch situation. At the request of the Underwater Sound Working Group, a number of adjustments were also made to the *R* scripts[16]. John Harwood presented the results of this exercise at the ecologists workshop and described them in [Harwood et al., 2014b].

[16] *R* script: a command written in the *R* programming language for a specific procedure

The results of these initial calculations made by SMRU were discussed at the ecologists workshop. In the light of this discussion, and discussions about the variations in input parameters requiring study, a range of scenarios were developed. TNO then studied the effect of those scenarios on the harbour porpoise population using the Interim PCoD model. That study looked at the effect on the harbour porpoise population of a range of scenarios for both the construction of wind farms and for seismic surveying in the North Sea. Chapter 3 describes the results.

3 Application to harbour porpoises

The staged procedure described in Chapter 2 was used here to determine the cumulative effects on the harbour porpoise population in the southern section of the North Sea of a number of generic scenarios for the construction of wind farms and for seismic surveying in the years 2016 to 2022.

The following steps were completed for each scenario:

1. Calculation of sound propagation per piling strike or seismic airgun pulse using TNO's AQUARIUS model
2. Calculation of the area of sea in which harbour porpoise behaviour is disturbed by piling strikes or seismic airgun pulses on the basis of the relevant acoustic threshold value
3. Calculation of the number of animals that may suffer disturbance by multiplying the disturbance area by an estimate of the local animal population density in the season during which the activity takes place
4. Calculation of the number of animal disturbance days per offshore project by multiplying the calculated number of disturbed animals a day by the number of disturbance days, taking the seasons and the duration of disturbance per calendar day into account
5. Calculation of the statistics for the possible development of the harbour porpoise population over the years using SMRU Marine's Interim PCoD model (see www.smru.co.uk/pcod)

A range of parameters were selected in accordance with the best current practice and in consultation with the working group for the specific implementation of these steps. The reasons underlying the selection of these parameters are given in this chapter and the previous chapter (Sections 2.3 and 2.4).
The aim of the scenario calculations for the effects of underwater sound during the construction of wind farms in the North Sea in the years 2016 to 2021 was to establish an insight into:

- The extent of the effect on the harbour porpoise population predicted by the Interim PCoD model;
- The sensitivity of the Interim PCoD calculations to the selected input parameters;
- The consequences of mitigation measures (such as the current seasonal restriction on construction on the DCS and the sound standard introduced in Germany) on the extent of the effect on the harbour porpoise population predicted by the Interim PCoD model.

3.1 Piling

3.1.1 Scenarios for the construction of wind farms in the North Sea

The procedure proposed in this document was used with a number of specific scenarios for the construction of wind farms in the North Sea between June 2016 and May 2022 (years in the Interim PCoD model are from June to May).

This process was based on the memorandum supplied by RWS Sea and Delta [Hazenoot, 2014] and the Excel file ‘Which foreign wind farms qualify for inclusion’ of 5/8/2014. These documents contain information about the planned locations in the Netherlands, Germany, United Kingdom, Belgium and Denmark: the planned capacity for the farms, the year (sometimes the month as well) when the start of the work is planned and whether the project involves monopile or tripod/jacket foundations.

Because of the uncertainties affecting the timetable for the future construction of offshore wind farms, a range of assumptions had to be made when drawing up the construction scenarios. The results of this study therefore primarily provide a picture of parameter dependencies and relative effects. In the Dutch scenarios, the focus here was primarily on the effect achieved by the introduction of a seasonal restriction on construction work, or by the introduction of a sound standard (SEL_1 at 750 m from the pile ≤ 160 dB re 1 $\mu Pa^2 s$), as in Germany [BMU, 2013]. The idea is that the proposed approach for future environmental impact assessments will be based on more up-to-date and detailed information.

In the case of the construction of the Dutch offshore wind farms, the current timetable[17] in the route map (in the letter to the Dutch parliament) implementing the SER agreement (www.energieakkoordser.nl) was adopted:

Start of construction	Location	Capacity
2017	**Borssele**	**2 × 350 MW**
2018	**Borssele**	**2 × 350 MW**
2019	**Dutch Coast South Holland**	**2 × 350 MW**
2020	**Dutch Coast South Holland**	**2 × 350 MW**
2021	**Dutch Coast North Holland**	**2 × 350 MW**

This approach included four timetables for the construction of the Dutch wind farms:

A. The construction of two wind farms a year in the spring, without a sound standard (*worst case scenario*);
B. The construction of two wind farms a year in the spring, with sound standard (at 750 m from the pile: 'SEL_1 = 160 dB re 1 $\mu Pa^2 s$);
C. The construction of one farm a year in the spring and one in the autumn, without a sound standard;
D. The construction of two wind farms a year in the autumn, without a sound standard.

In addition, one hypothetical timetable was generated for the construction of wind farms abroad (UK, DE, DK, BE) using the following data and assumptions:

- Year/month when construction starts in the Excel file supplied by Rijkswaterstaat;
- No piling in the winter months (December, January, February);
- When only the year is known, a random starting date was selected between 1 March and 30 November;
- When the starting date in the Excel file was between 1 January and 1 March, 1 March was selected as the starting date;

[17] In the case of the Interim PCoD calculations in this study, the total planned capacity is particularly important. Any changes to the proposed schedule for construction will not alter the conclusions in this study.

- When an overview had been drawn up of all the construction activities in the North Sea, it emerged that an unrealistically large number of farms were sometimes due to be built at the same time, even though the required capacity is probably lacking. It was therefore assumed that a maximum of six piling installations would be available at the same time for construction work in the North Sea, two of which would be used in the Netherlands: construction work was assumed to start on farms scheduled to start earlier; the others were postponed until the completion of an ongoing project. As a result, a total of seven farms on the list were postponed until after June 2022, the final days of the period covered by the calculation. These farms were therefore not included in the calculations.

In addition, the following additional assumptions were made during the elaboration of the scenarios:

- All planned turbines have a capacity of 6 MW;
- The number of turbines per farm is determined in line with the estimated maximum capacity of the farm divided by 6 MW;
- In all cases, it is assumed that one foundation (monopile, tripod or jacket) is installed every 48 hours: every piling day is followed by one day without piling, during which, for example, the piling vessel is moved.

Figure 3-1 gives an overview of the timetable drawn up in this way for the years covered by the international scenario, with scenario A for the Dutch wind farms.

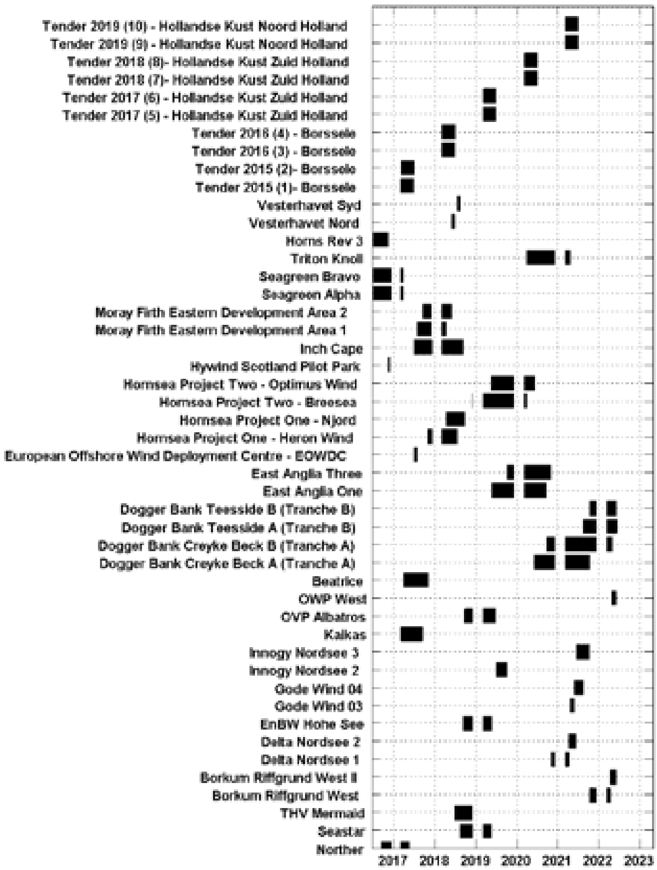

Figure 3-1 Example of the construction timetable used for wind farms in the North Sea, with the construction of two wind farms a year in the spring for the Netherlands, without a sound standard (*worst case scenario*: scenario 11. See Section 3.1.7).

3.1.2 *Calculation of sound propagation*

Sound propagation is calculated for each location using the current version of TNO's AQUARIUS model. In other words, given the estimated hammer energy and local parameters (bathymetry, soil conditions and disturbance of the water surface by wind), the SEL_1 at 1 m above the seabed in the locality is calculated. This measure is representative for the SEL_1 in most of the water column in which harbour porpoises can be found (see also Section 2.4.1).

The calculations were made using the following assumptions:

- In almost all cases, the turbines are installed on monopile foundations (assumed pile diameter approximately 8 m) driven using an estimated maximum hammer energy of 2 MJ. When the available information indicates that tripod or jacket foundations will be used (maximum pile diameter 4 m), the assumed hammer energy is 800 kJ.
- In the case of the 800 kJ hammer strikes, the maximum point-source energy is adopted from the monitoring data for the construction of the Prinses Amalia wind farm (Q7): SL_E = 221 dB re 1 $\mu Pa^2 s\ m^2$. In the case of the 2 MJ hammer strikes, this value is scaled up to SL_E = 225 dB re 1 $\mu Pa^2 s\ m^2$.

- For the construction of wind farms in Germany (and as an alternative in some scenarios), it is assumed that sound mitigation measures are implemented to comply with the sound standard: at 750 m from the pile SEL_1 = 160 dB re 1 $\mu Pa^2 s$. In that case, the appropriate point-source energy for the project location is back-calculated with AQUARIUS on the basis of this limit value;
- The AQUARIUS calculations assume the same sediment parameters (‘medium sand’) for all locations because specific information for each location is not immediately available;
- The AQUARIUS calculations are made for realistic conditions with wind (6.5 m/s at 10 m above the water surface) and (*worst case*) no wind (0 m/s).

When two wind farms are being built with possibly overlapping disturbance areas, it is assumed that the piles are driven alternately so that one pile is driven every 24 hours. This means that (in the *worst case scenario*), there will be no spatial overlapping of the disturbance areas of each pile. Nor is the possibility of a spatial overlap with disturbance areas of foreign farms taken into account.

3.1.3 Calculation of the harbour porpoise disturbance area

The AQUARIUS calculations determine the ‘harbour porpoise disturbance area’: the area in which the calculated SEL_1 at 1 m above the seabed exceeds the threshold value for the disturbance of behaviour.

- In the absence of better information, we have adopted a discrete threshold for disturbance for the time being. As alternatives, we have selected (see Intermezzo ‘Threshold values for the effects of underwater sound on marine mammals’ in Section 2.3.1) the following:
  a. SEL_1 = 136 dB re 1 $\mu Pa^2 s$ on the basis of [Kastelein et al., 2014]
  b. SEL_1 = 144 dB re 1 $\mu Pa^2 s$ on the basis of [Diederichs et al., 2014]
  c. SEL_1 = 140 dB re 1 $\mu Pa^2 s$ on the basis of the German Schallschutzkonzept [BMU, 2013]
- As the harbour porpoise disturbance area, we adopt the linear average for the calculated disturbance areas with and without wind. From the results from AQUARIUS calculations conducted previously for piling sound in the North Sea, it emerges that the disturbance areas for situations without wind are approximately twice as large as with wind. By adopting the linear average, we opt for an estimate with an uncertainty of ±50%, depending on the prevailing wind during construction.

Figure 3-2 shows an example of the calculated harbour porpoise disturbance areas for the construction of wind farms in the scenario (Section 3.1.1) for 2017.

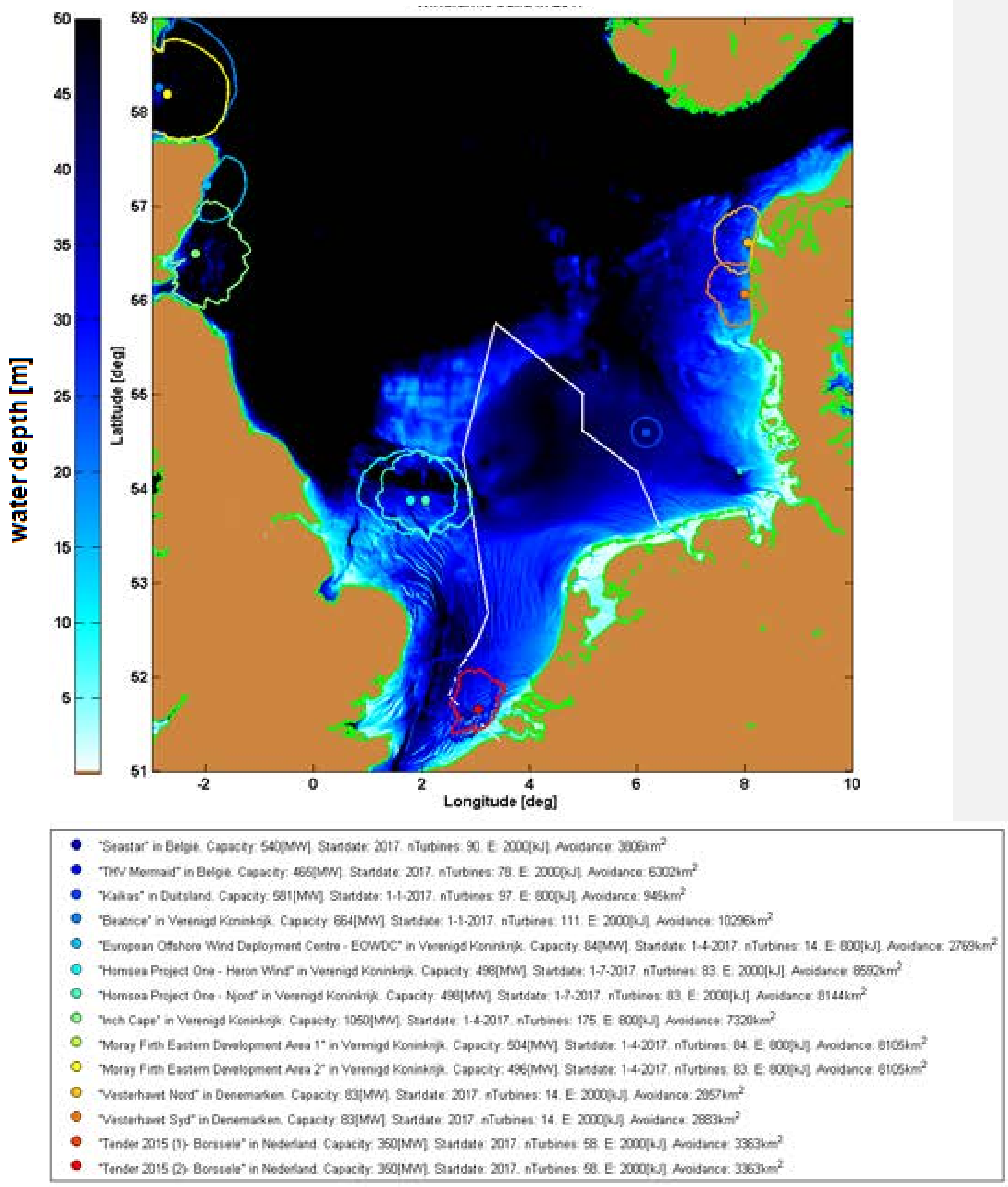

Figure 3-2 Example of the calculated disturbance areas for the construction of wind farms in 2017 (in accordance with the scenario described in Section 3.1.1). This example shows the results of calculations for a situation without wind and without a sound standard (except in Germany, where a sound standard has been included in the calculations). These disturbances do not all occur at the same time in the construction timetable.

3.1.4 *Calculation of the number of disturbed harbour porpoises per project day*

- The number of disturbed harbour porpoises per project day[18] is calculated by multiplying the harbour porpoise disturbance area by the estimated local harbour porpoise population density in the season when construction takes place (see Table 3-1).

[18] This report also uses the term ‘impulse day’.

- The scheduling of the project days during the years and seasons follows from the scenarios for the construction of wind farms.
- Local harbour porpoise population densities for each location and season are estimated using data from the SCANS surveys [Hammond et al., 2002/2013], surveys conducted by IMARES on the DCS [Geelhoed et al., 2011/2014], data from the SMRU [Harwood et al., 2014; Verfuss et al. 2014] and data from the various environmental impact assessments for the planned farms in the UK. See Table 3-1.

Table 3-1 Estimated local harbour porpoise population densities in each area and season

	Spring (individuals/km^2)	**Summer (individuals/km^2)**	**Autumn (individuals/km^2)**
The Netherlands, Belgium, and East Anglia	1.42	0.48	0.398
Germany	0.98	0.98	0.98
Denmark	1.3	2.9	1.6
United Kingdom Dogger Bank	1.8	1.8	1.8
United Kingdom Scotland	0.2 – 0.7	0.2 - 0.7	0.2 - 0.7
United Kingdom Hornsea projects	1.4	1.8	1.3

3.1.5 *Calculation of harbour porpoise disturbance days*

The total number of harbour porpoise disturbance days per project is estimated by multiplying the number of project days by the estimated number of harbour porpoises disturbed per project day in the season when construction takes place. The Interim PCoD model can also factor in the duration of the disturbance.

- In the basic scenario, we assume one disturbance day per pile (24 hours, no ‘residual day of disturbance’).
- Because it takes much less than an entire day to drive a pile, an alternative was also examined in which disturbance is limited to a maximum of 8 hours (roughly speaking, 4 hours for the piling and another four hours for the harbour porpoise to revert to normal behaviour). In that case, the disturbance of a single harbour progress during one impulse day is considered to be one third of a harbour porpoise disturbance day (8 hours).
- On the other hand, there are indications that harbour porpoises are disturbed (or stay away) for more than one day. That effect was studied by factoring in one extra ‘residual day of disturbance’ per disturbance day (24 hours + 24 hours ‘residual day’). See Intermezzo in Section 2.4.1 and Section 2.4.2 for the background to these decisions. Because it is assumed that piling takes place on alternate days and because spatial overlapping of the disturbance areas when farms are being constructed at the same time has not been included, there is an effective doubling of the number of harbour porpoise disturbance days per project.

The calculated disturbance area and the associated number of possibly disturbed harbour porpoises per project for the years 2016 to 2022 for the basic scenario: construction of all foreign farms combined with scenario A for the Dutch farms, (no. 11 see Section 3.1.7) is:

Table 3-2 Planned 'impulse days' (total number of days on which piling takes place totalled for all projects in accordance with international basic scenario 11 see Section 3.1.7) and the associated calculated number of 'harbour porpoise disturbance days'

	impulse days		harbour porpoise disturbance days	
	number	percentage	number	percentage
Total (NL, UK, BE, DE, DK)	3709	100%	16439945	100%
Proportion NL	580	16%	2326049	14%

3.1.6 *Interim PCoD calculations*

In addition to the harbour porpoise disturbance days per offshore project, the Interim PCoD uses the following input parameters:

a. Total harbour porpoise population (North Sea);
b. 'Vulnerable sub-population' per project: the proportion of the total population that may be affected;
c. Demographic parameters.

The first assumption is that the total relevant harbour porpoise population is stable. This value is not varied. Here, we assume the total estimate of 227,298 harbour porpoises, the 'North Sea Management Unit', from [IMMWG, 2013].

- In the case of the Dutch and Belgian farms, we adopt the IMARES 'Area D' population (estimated at 30,000 individuals [Geelhoed et al., 2011/2014]) as the *vulnerable sub-population* (see Figure 2-6).
- In the case of the southern United Kingdom ('East Anglia'), which is close to the edge of the DCS, we assume the same 'Area D' population as for the Dutch farms.
- For the other farms in the United Kingdom, Germany and Denmark, we assume the estimated population[19] of 99,329 individuals in the SCANS II blocks H, U and Y. See Figure 3-3.

[19] Upon further consideration, the size of the *vulnerable sub-population* may have been underestimated by approximately 45,000 animals given the fact that some of the farms planned in the UK are located in area V. This may have had some effect on the outcomes of the calculations. However, it emerges from a comparison of the calculation results (Section 3.1.7) for the basic scenario 1 with scenarios 5 (in which the *vulnerable sub-population* is approximately twice as large) and 6 (in which the *vulnerable sub-population* is approximately 5 times smaller) that the model outcomes are relatively insensitive to variations in the size of the *vulnerable sub-population*.

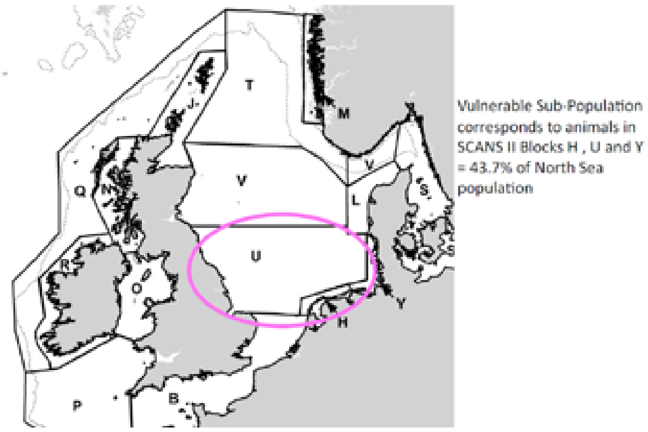

Figure 3-3 Classification of the North Sea in terms of 'SCANS' blocks (from J. Harwood's PowerPoint, 10/10/2014)

The Interim PCoD model assumes that the harbour porpoise population is stable and that demographic development does not depend on the population density. This means that, after the one-off inclusion of an effect on the population, in other words a fall in numbers as a result of the activities, the population in the model outcomes will not recover after the activities cease. The population then stabilises at a lower level.

The model calculations in this respect assume a relatively low *adult survival* rate (0.85) in order to factor in effects like by-catch, and relatively high *fecundity* (0.96). See [Harwood et al., 2014]. According to SMRU Marine, previous tests showed that adopting a higher *adult survival* rate (0.925) in combination with lower *fecundity* (0.48) led to comparable calculation results.

SMRU Marine implemented the Interim PCoD model in the '*R*' statistical software package (www.r-project.org. See also Section 2.5.1). On the basis of a calendar of disturbance days per project (see Figure 3-4), 500 'trials' were conducted for virtual individuals in each scenario. See also [Harwood et al., 2014]. A statistical estimate (median and percentiles) of the development of the size of the population during the years emerges from the 500 outcomes.

The calendar of impulse days runs from June 2016 to May 2022 (Figure 3-1). The population levels have been calculated until the end of May 2024. Because the model does not describe any recovery in the population and because the construction of wind farms will, in reality, continue after May 2022, the calculation results for the 2023 and 2024 are not very realistic. We use these results to arrive at a more robust estimate of the reduction in the population after six years of exposure to impulsive sound. We do this by determining, as the end result, an average of the estimates of the population size (median and percentiles) for the period 2022 - 2024.

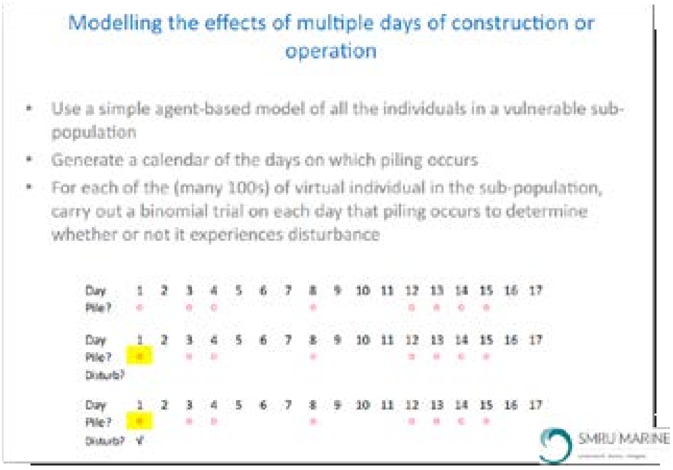

Figure 3-4 The Interim PCoD calculations are based on a calendar of disturbance days per project.

The next figure (Figure 3-5) shows the changes in the harbour porpoise population over the years for scenario 11 (Section 3.1.7), as calculated with the Interim PCoD tool.

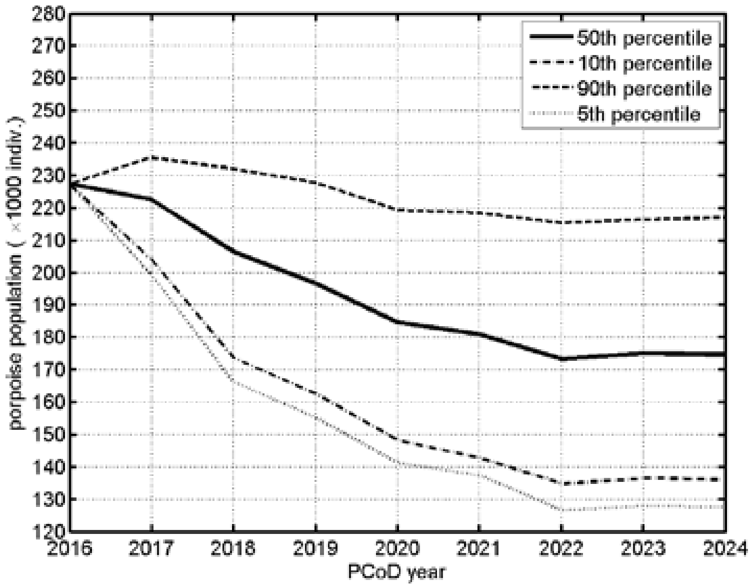

Figure 3-5 The changes in the harbour porpoise population in the North Sea, as calculated with the Interim PCoD, as affected by wind-farm construction in line with an international scenario for the construction of offshore wind farms (in the years 2016-2022) combined with scenario A for the Dutch farms (scenario 11 in Section 3.1.7). A PCoD year runs from 1 June to 31 May. The bold line shows the median (50th percentile) and the lines for the 10th and 90th percentiles show the limits of the range for 80% of the 500 simulation results. In 95% of the simulations, the harbour porpoise population is larger than indicated by the 5th percentile line.

These simulations predict an average reduction (median or 50th percentile) in the harbour porpoise population from 227,298 to 174,406 animals (average for the years 2022-2024) as a result of all the construction projects in the North Sea from June 2016 to June 2022 that have been included in the calculations. That is a reduction of 52,892 animals and therefore ~23% of the total North Sea population considered.

The spread in the results of the 500 calculations is the result of the spread in the stochastic population model, in combination with the spread as a result of the statistical estimate of the dose-effect relationship from the *expert elicitation* (Figure 2-11). The Interim PCoD model offers the possibility of making a distinction between the spread in the results resulting from the stochastic population model and the spread in the estimates of the additional population reduction resulting from disturbance by underwater sound (among other things as a result of the spread in the results of the *expert elicitation*. See also Section 3.1.6). To this end, the changes in both the disturbed and the undisturbed populations are calculated for each individual simulation. The difference is noted as an 'additional reduction in the population'. Figure 3-6 shows the development in that additional reduction in the population resulting from disturbance by piling sound for the same international scenario for which the population change is shown in Figure 3-5.

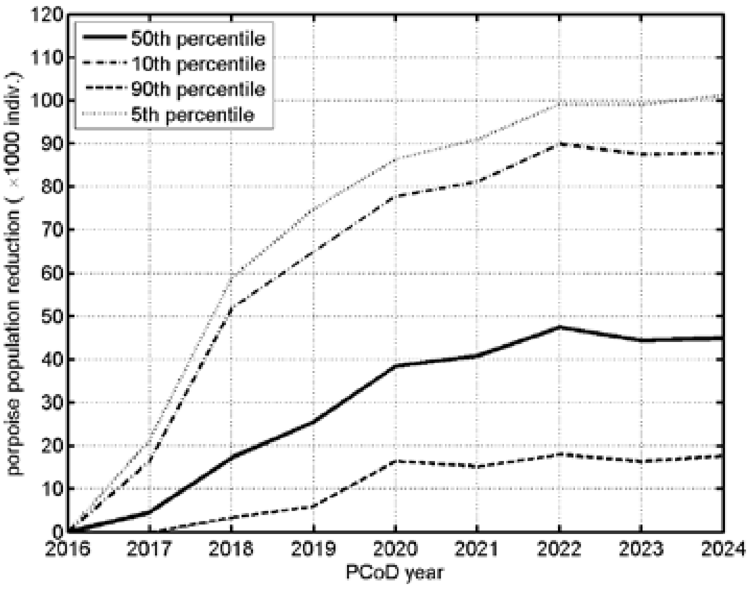

Figure 3-6 The reduction in the harbour porpoise population in the North Sea calculated with Interim PCoD and caused by piling sound in an international scenario for the construction of offshore wind farms (in the years 2016-2022) in combination with scenario A for the Dutch farms (scenario 11 in Section 3.1.7). A PCoD year runs from 1 June to 31 May. The bold line shows the median (50th percentile) and the lines for the 10th and 90th percentiles give the limits of the range for 80% of the 500 simulation results. In 95% of the simulations, the reduction in the harbour porpoise population as a result of sound disturbance is smaller than indicated by the 5th percentile line.

Figure 3-7 shows the associated probability distribution. The vital rates in the population model were selected in such a way that the probability of a decline in the undisturbed population is almost the same as the probability of an increase and so the probability of a reduction in the population exceeding 0 is approximately 50%. The spread in the stochastic population model is symmetrical: in 10% of the simulations, the undisturbed population falls by more than 40,000 individuals, but there is also a probability of 10% that the population will increase by more than 40,000 individuals.

Disturbance by underwater sound results in all cases in a positive additional population reduction. Figure 3-7 shows that, in the international scenario in question, there is a probability of 10% of an additional reduction in excess of ~88,000 individuals, a probability of 50% of an additional reduction in excess of ~46,000 individuals and a probability of 90% of an additional reduction in excess of ~17,000 individuals.

In the final assessment of the risks of disturbance by underwater sound for the harbour porpoise population, an estimate of the maximum effect with a high level of certainty is required. The recommendation here is therefore to assume a 5% probability of an exceedance of the maximum permissible population reduction.

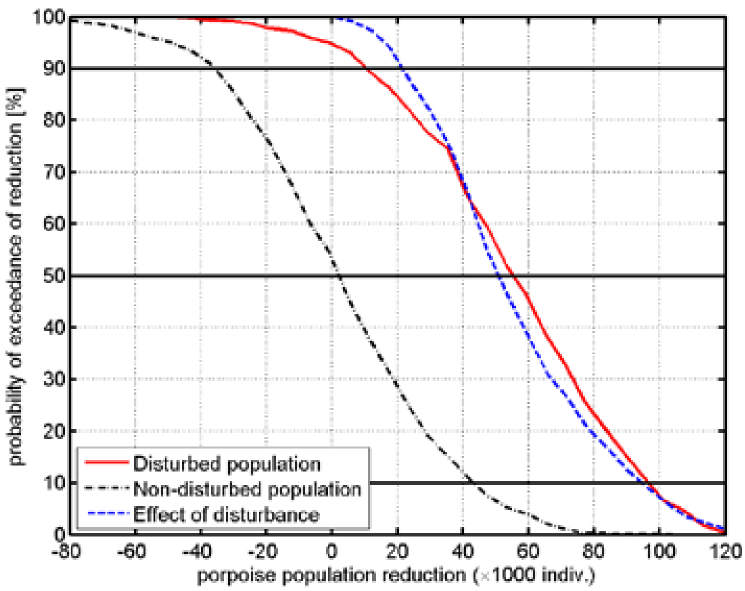

Figure 3-7 Cumulative distribution (for the scenario from Figure 3-5) of the results after 6 years of the 500 Interim PCoD simulations. This shows the probability of the population reduction being larger than the value shown by the curve. The intersections of the 'disturbed population' line with the 10%, 50% and 90% probability lines corresponds to the points for 2022 in Figure 3-5. The blue dotted line shows the added effect of the disturbance by underwater sound determined on the basis of the differences between the disturbed and the undisturbed population in each individual simulation.

3.1.7 *Calculation scenarios*

In addition to the international and national planning scenarios referred to above for the construction of wind farms in the North Sea in the years 2016-2021, calculations were made for a number of extra scenarios in order to establish a picture of the bandwidth of the calculation results. All these scenarios assumed the Dutch worst case scenario A: the construction of two wind farms at the same time in the spring of each year (see 3.1.1, scenarios A to D, for a description).

The 14 scenarios below were then modelled in succession for offshore piling:

Variations in Dutch scenarios: (sub-population 30,000 animals)

1 Dutch farms only, scenario A: 2 farms in the spring

2 Dutch farms only, scenario B: 2 farms in the spring with sound standard SEL_1(750 m) = 160 dB re 1 μPa^2s

3 Dutch farms only, scenario C: 1 farm in the spring and 1 in the autumn

4 Dutch farms only, scenario D: 2 farms in the autumn

Model tests; sensitivity to parameters:

5 Dutch farms only, scenario A, with a larger vulnerable sub-population: the DCS population (66,000 animals)

6 Dutch farms only, scenario A, with a smaller vulnerable sub-population: the affected population (6,518 animals[20])

7 Dutch farms only, scenario A, with 2 disturbance days per impulse day (one residual day of disturbance)

8 Dutch farms only, scenario A, with 1/3 disturbance day per impulse day (8 hours)

9 Dutch farms only, scenario C, with 2 disturbance days per impulse day (one residual day of disturbance)

10 Dutch farms only, scenario A, with higher disturbance threshold value of SEL_1 = 144 dB re 1 μPa^2s

International accumulation of effects:

11 All foreign farms combined with scenario A for the Dutch farms (basic scenario)

12 All foreign farms only, without the Dutch farms

13 All foreign farms combined with scenario A for the Dutch farms, with a higher disturbance threshold value of SEL_1 = 144 dB re 1 μPa^2s (basic scenario with higher threshold value)

14 All foreign farms combined with scenario A for the Dutch farms, with a higher disturbance threshold value of SEL_1 = 144 dB re 1 μPa^2s and with sound standard SEL_1(750 m) = 165 dB re 1 μPa^2s

15 Seismic scenario. See Section 3.2

Additional variations in Dutch scenarios: (sub-population 30,000 animals)

16 Only the Dutch farms, 2 farms in the spring with sound standard SEL_1(750 m) = 165 dB re 1 μPa^2s

17 Only the Dutch farms, 2 farms in the spring with sound standard SEL_1(750 m) = 168 dB re 1 μPa^2s

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[20] The size of this site-faithful sub-population was estimated by multiplying the largest calculated disturbance area for the Dutch farms (4538 km^2), together with an estimated farm area of 52 km^2, by the highest animal population density (Spring, Table 3-1)

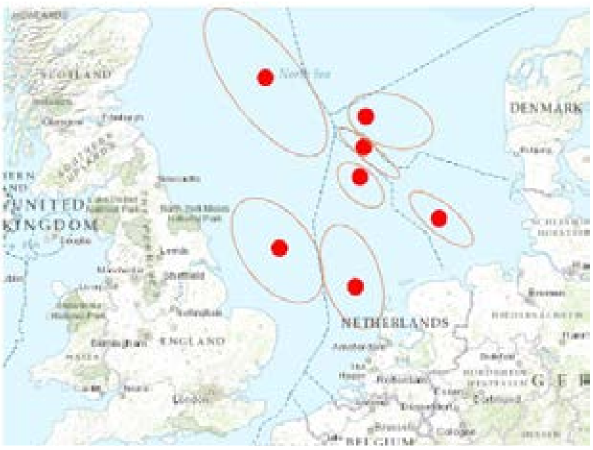
3.2 Scenario calculation for seismic surveying

The procedure proposed here was also applied to one specific scenario for seismic surveying in the North Sea in the years 2016 to 2022. This scenario was not included in an accumulation in Interim PCoD with the scenarios for the construction of wind farms because the effects of seismic surveying have probably already been discounted in part in the population dynamic model, given the fact that this effect has already been present for many years (albeit with major year-on-year variations). The scenario (sites and associated timetable for surveying days for the years 2016-2022) was supplied by Royal HaskoningDHV using publicly available information[21] about seismic surveying in the southern North Sea.

In addition, the following basic principles were applied:

- Every year, 3D seismic surveying is conducted covering 20,000 km^2 in the southern North Sea (Netherlands, Germany, Denmark and UK collectively);
- It takes 6 weeks to survey an area of 1,000 km^2 (including 20% downtime during which the airgun is turned off), regardless of the method, type of airgun or resolution;
- Seismic surveying is conducted from March to October (inclusive);
- A maximum of 8 surveys are conducted at the same time in the North Sea;
- The majority of the surveys are conducted in the spring (this matches the scenario for wind farms).

In a ‘realistic’ scenario, approximately 8 seismic surveys will be conducted at the same time in the entire southern North Sea in the areas shown in the figure below. This assumption is based on information about 3D seismic surveying in the past. The figure is a highly simplified picture of the actual areas where seismic surveying takes place. In this single realistic scenario, it was decided to include the seven areas where most seismic surveys had taken place in the previous year. The table shows the coordinates of the red points taken from the figure.



	Lon	Lat
VK North	1.4	56.7
VK South	1.8	53.8
DK	4.2	56.1
DE North	4.2	55.6
DE South	6.3	54.4
NL North	4.1	55.1
NL South	3.9	53.3

[21] UK charts: www.ukoilandgasdata.com; NL charts: www.nlog.nl; DE charts: www.gpdn.de
Ministry of Economic Affairs, Delfstoffen en aardwarmte in Nederland. Jaarverslag 2013
LBEG. Jahresberichten Erdöl und Erdgas in der Bundesrepublik Deutschland 2010-2013;
Danish Energy Agency, Oil and Gas production in Denmark 2013.

Figure 3-8 Locations in the North Sea for the seismic surveying scenario.

The proposed annual timetable for seismic surveying in these areas is shown in the following table. This proposal is based on the principles listed above. Given the fact that no data are available for seismic surveying about where, when and how much surveying will be conducted in the years to come, this is the best available option at present. This scenario is repeated annually in the Interim PCoD calculation between June 2016 and May 2022. This is an overall scenario that is intended exclusively for the purposes of a comparison of the relative impact of seismic surveying with the impact of piling for wind farms.

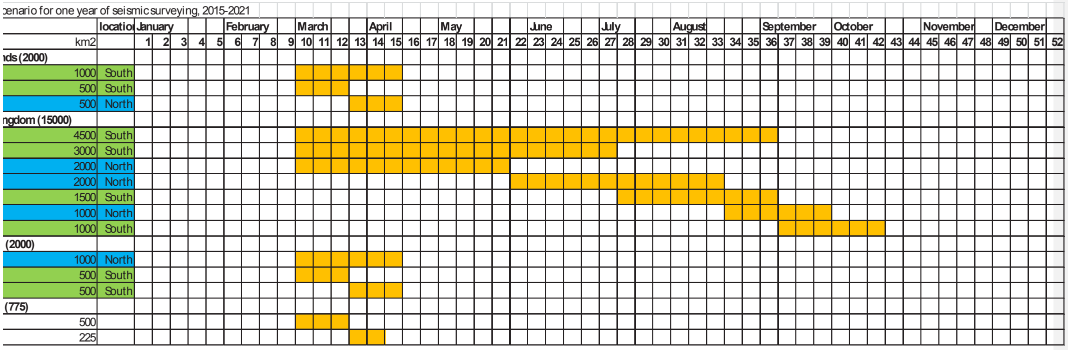


Figure 3-7 Annual timetable for the seismic surveying scenario.

The calculation of the disturbance areas takes the typical daily movement of a survey vessel into account. We calculate the disturbance area for harbour porpoises for one shot in each location. We treat that surface area *A* as a circle and calculate the effective disturbance distance $R = (A/\pi)^{1/2}$. We add this distance *R* in all directions to the daily area surveyed consisting of the track length × area width [km^2], in which the area width is determined by the distance between the various track lines sailed on a particular day. The total disturbance area a day is therefore ~(track length + 2*R*) x (area width + 2*R*) [km^2].

The number of disturbed animals a day follows from the multiplication of this surface area by the local population density of harbour porpoises in the season.

This 15th scenario calculation also makes the following assumptions:

- A survey takes 6 weeks for an area of 1,000 km^2. Assuming 20% downtime, that surface area is covered in ~34 days. This is an area of approximately 30 km^2 a day;
- The 20% downtime is calculated by skipping one day in a random pattern (with a probability of 20%).
- If the track length is ~25 km, an area width of ~1.2 km a day will be surveyed.
- The assumed source level from the airguns is based in all cases on the data used by TNO in a study for Wintershall [Ainslie et al., 2012b] (see Section 2.2.3).
- A threshold value for disturbance of SEL_1 = 136 dB re 1 $\mu Pa^2 s$, which is equal to the threshold value selected for disturbance by piling sound in the international scenario (Section 3.1.7).

- A disturbance effect lasting 24 hours per surveying day (in other words, there are no 'residual days of disturbance'). Because shooting is almost daily during surveys, the number of harbour porpoise disturbance days always increases less when a residual day is factored in than in the case of piling for wind farms on alternating days (Section 3.1.1).
- The vulnerable sub-population adopted for the seismic surveying scenario is the estimated population of 99,329 individuals from the SCANS II blocks H, U and Y (Figure 3-3), with the exception of the 'NL south' projects, where we, as with piling, adopt the estimated 'area D' population of 30,000 animals.

The estimated local harbour porpoise population densities per project and season are:

Table 3-3 Estimated local harbour porpoise population densities per area and season (see also Table 3-1)

	Spring (individuals/km^2)	**Summer (individuals/km^2)**	**Autumn (individuals/km^2)**
UK North	0.2	0.2	0.2
UK South	1.4	1.8	1.3
DK	1.029	0.396	0.391
DE North	1.029	0.396	0.391
DE South	0.98	0.98	0.98
NL North	1.029	0.396	0.391
NL South	1.42	0.48	0.398

3.3 Calculation results

Table 3-3 summarises the calculation results for all scenarios. Here, the number of harbour porpoise disturbance days is equal to the number of harbour porpoises disturbed during one day of piling or seismic surveying, multiplied by the number of days upon which that disturbance occurs for the sum of all projects in all the scenario years. Any residual days of disturbance are factored in as additional disturbance days and, in the scenario in which the duration of disturbance is limited to 8 hours a day, the number of disturbance days is one third of the number of impulse days.

Table 3-4 Interim PCoD calculation results for the 14 scenarios for the construction of wind farms in the southern North Sea in the years 2016-2022. 'Impulse days' is the total for the years and the farms of the number of days on which piling takes place. 'Harbour porpoise disturbance days' are the product of the number of impulse days multiplied by the number of disturbed harbour porpoises per impulse day per farm (taking the seasons into account) and by the duration of the disturbance per impulse day (=1/3 of a day, 1 or 2 days). The calculated additional population reduction is expressed as percentiles of 500 simulation results averaged for the years 2022-2024. Negative numbers indicate that the stochastic model calculates that an increase in the population is not very probable.

			ADDITIONAL population reduction (individuals)			
scen ario	impulse days	harbour porpoise disturbanc	median (50th percentile)	5th percentile	10th percentile	90th percentile

		e days				
1	580	2,326,049	7,418	19,344	15,872	924
2	580	203,668	4	2,645	1,000	-15
3	580	1,572,572	5,274	16,303	13,361	4
4	580	802,261	1,422	8,960	7,025	-6
5	580	2,326,049	5,954	28,363	20,840	-4
6	580	2,326,049	3,748	5,370	5,038	2,608
7	580	4,652,098	11,304	23,358	20,683	5,131
8	580	77,535	563	8,797	6,902	-10
9	580	3,145,144	9,365	20,723	18,893	3,432
10	580	905,803	1,938	9,595	7,525	-10
11	3,709	16,439,945	45,633	99,794	88,388	17,377
12	3,129	14,112,896	41,528	92,437	83,834	16,798
13	3,709	6,052,801	21,851	65,746	50,488	150
14	3,709	388.435	0	3,174	585	-16
15	3,425	21,808,285	53,498	97,453	88,160	30,790
16	580	419,877	54	5,263	3,300	-11
17	580	633,702	516	7,229	5,854	-10

In the basic international scenario (11), the Dutch farms account for approximately 14% of the harbour porpoise disturbance days in the period 2016-2022. The result of scenario 1 (Dutch farms only) shows that the average calculated population reduction associated with the Dutch farms (median of 7,418 animals) is approximately 16% of the total reduction associated with all farms in scenario 11 (median of 45,633 animals). This suggests that the number of harbour porpoise disturbance days is a good indicator of the calculated population reduction in line with the basic principle underlying the Interim PCoD model that is based on a statistical relationship established in expert elicitation between the number of days of significant behavioural response and vital rates.

Figure 3-9 shows the trend for population reduction as a function of the harbour porpoise disturbance days for the Dutch scenarios. Scenarios 5 and 6, in which the vulnerable sub-population is varied, have been omitted here. When the number of harbour porpoise disturbance days is less than 10^6, the 5th percentile value for population reduction increases linearly in line with disturbance days. A least-square fit in this area shows an increase in reduction of 11.03 individuals per 1000 harbour porpoise disturbance days. That increase drops off at larger numbers of disturbance days. The calculation results suggest that the maximum population reduction as disturbance increases is limited to approximately 80% of the vulnerable sub-population. The fitted trend line complies with the following formula:

$10{-}3$ follows from a least-square fit to the points for which $\mathrm{hpdd}<1$; the factor 0.8 were fitted by eye.

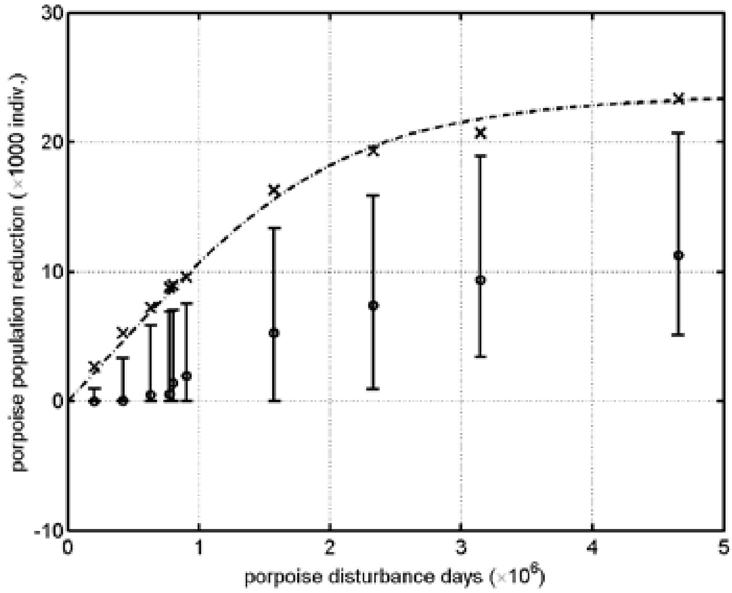


Figure 3-9 Calculated additional population reduction as a function of the number of harbour porpoise disturbance days for the Dutch scenarios with the same vulnerable sub-population of 30,000 animals (scenarios 1-4, 7-10 and 16-17. See Section 3.7.1 and Table 3-4). Circles indicate the median values and the vertical lines show the bandwidth between the 10% and 90% percentiles. The '×' symbols indicate the 5th percentiles. The line follows the formula fitted to the 5th percentiles (see text above this figure).

Figure 3-10 shows that the number of harbour porpoise disturbance days is also a good indicator in the international wind farm and seismic scenarios of population reduction and that the same formula is a good description of the calculated 5th would not appear to depend on the size of the vulnerable sub-population.

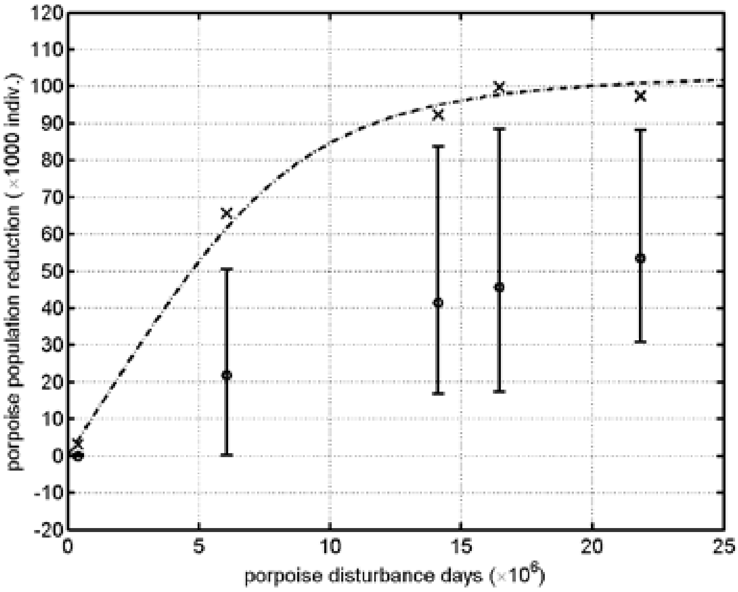


Figure 3-10 Calculated additional population reduction as a function of the number of harbour porpoise disturbance days for the international scenarios with a total 'vulnerable sub-population' of 99,329+30,000 animals (scenarios 11-15. See Section 3.7.1 and Table 3-4). Circles indicate the median values and the vertical lines show the bandwidth between the 10% and 90% percentiles. The '×' symbols indicate the 5th percentiles. The line follows the formula fitted to the 5th percentiles (see text above this figure).

3.4 Conclusions from the Interim PCoD results

The estimated number of harbour porpoise disturbance days resulting from the impulsive sound from offshore piling or seismic surveying is, according to this model, a sound initial measure for the effect on the population.

On the basis of the parameters selected in the present study for the harbour porpoise population in the North Sea, an initial estimate can be made without any extra Interim PCoD calculations of a maximum population reduction with a 95% confidence interval for non-exceedance using the following approximation formula:

is the number of individuals in the vulnerable sub-population.

Further findings are:

- The calculated number of harbour porpoise disturbance days is sensitive to the selection of the threshold value for disturbance: at a threshold SEL_1 of 144 dB re 1 μPa^2s (scenario 10), the disturbance areas for the various locations (and therefore the estimated number of harbour porpoise disturbance days) are a factor of 0.32 (± 0.08) smaller than at a threshold SEL_1 of 136 dB re 1 μPa^2s (scenario 1). Additional acoustic calculations have shown that this factor, at a threshold SEL_1 of 140 dB re 1 μPa^2s is equal to 0.58 (± 0.08);

- The calculated number of harbour porpoise disturbance days increases linearly in the selected scenarios (with one rest day between two piling days) in line with the selected duration of the disturbance (scenarios 3-6-7);
- The application of the German sound standard (SEL_1(750m) = 160 dB re 1 $\mu Pa^2 s$) has a major effect. In the Dutch scenario (2), the number of harbour porpoise disturbance days falls (by comparison with scenario 1) by a factor of 11. This results in a minor increase in the population in the median estimate (this is within the margins of the linear trend). In the international scenario (14), with the sound standard for all farms, the number of harbour porpoise disturbance days is a factor of 3.5 smaller than in the scenario 13, in which that standard is used in Germany only;
- Given the piling strike energy of 2000 kJ assumed in this study, and without mitigation measures, SEL_1(750m) ≈174 dB re 1 $\mu Pa^2 s$ (depending on the local conditions). In this way, a reduction of 14 dB or more is required to comply with the German sound standard. The calculation results for the construction of the Dutch farms with a less stringent sound standard (scenarios 16 and 17) show that, in these cases also, the calculated population reduction is considerably smaller than in the scenario (1) without a sound standard;
- The total calculated effect of the seismic scenario (15) is of the same order of magnitude as the total effect calculated for the construction of the wind farms (scenario 11);
- Figure 3-11 shows that it is only the number of 'impulse days' – days on which piling or seismic surveying takes place – that is a less reliable indicator of the effect on the population because it does not take the local size of the disturbance area and the harbour porpoise population density into account.

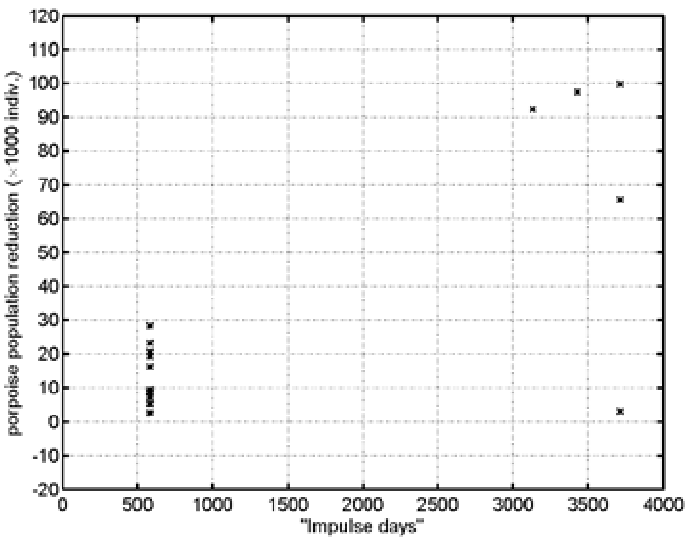


Figure 3-11 Calculated additional population reduction (5th percentiles) as a function of the number of impulse days for all scenarios (see Section 3.7.1 and Table 3-4).

4 Possible approach for seals

4.1 Introduction

PCoD calculations were not made for seals. It was decided to work with the Interim PCoD model on the basis of expert opinion as described in Chapter 2 because there was a lack of data about the movement and behaviour of individuals in space and time. Data of this kind are available for seals and the energetic consequences of an interruption in foraging options based on the location and diving data can, in principle, be calculated (see, for example, [New et al., 2014]; [Costa, 2012]). A model using the data and focusing on the calculation of the cumulative effects of impulsive sound on seal populations will, however, not be available in the short term (see also Chapter 6 Knowledge gaps).

The cumulative effects of impulsive sound on seal populations cannot therefore be calculated in this way as yet. However, an impression of the possible extent of the effects can be obtained by running through the staged procedure presented in Chapter 2:

1 Calculate sound propagation per piling strike or seismic airgun pulse;
2 Calculate the area of sea where seals are disturbed by piling strikes or seismic airgun pulses on the basis of the relevant acoustic threshold value[22];
3 Calculate the number of animals that may suffer disturbance by multiplying the disturbance area by an estimate of the local animal population density, where possible specifically for the season during which the activity takes place;
4 Calculate the number of animal disturbance days per offshore project by multiplying the calculated number of disturbed animals a day by the number of disturbance days, taking the seasons into account;
5 Calculate the statistics for the possible development of the seal population over the years using the SMRU Interim PCoD model.

The sections that follow here contain an overview of the available information for each stage, including uncertainties and choices that still have to be made.

4.2 Sound propagation and disturbance area

As with the harbour porpoise, a calculation is needed for seals of the expected level of underwater sound propagation (SEL_1 in the lower half of the water column) around the source of the sound. For the time being, when determining the area in which seals are disturbed, the sound is weighted using the M_{pw} weighting for 'pinnipeds in water' from [Southall et al., 2007] (see the discussion of 'frequency weighting' in the Intermezzo in Section 2.3.2.) The effect assessments for the Round 2 wind farms assume a threshold value (based on limited information) for avoidance/disturbance of $SEL_{1,w}$ = 145 dB re 1 $\mu Pa^2 s$ (see Intermezzo in Section 2.3.2). In the absence of specific data for the grey seal, the effect calculations so far have assumed that the threshold value for avoidance/disturbance for grey seals is comparable with the value for the harbour seal.

[22] Using a procedure comparable to that applied to the harbour porpoise, it has been assumed that effects on hearing did not determine population effects (TTS) or will not occur because mitigation measures are taken (PTS). See Section 2.3.3.2.

The calculated distribution for seals of the sound during piling for the construction of a wind farm off the Dutch coast is shown in Figure 4-1 (after [Arends et al., 2013]). The distribution at 1 m below the water surface can be found on the left of the figure, with the distribution at 1 m above the seabed being on the right. The black lines are the contour within which the threshold value for avoidance by seals (Table 2-1) of $SEL_{1,W}$ = 145 dB re 1 $\mu Pa^2 s$ is exceeded. The figure shows that, in local average wind conditions (= 6.5 m/s) and given a piling energy of 1,200 kJ, the piling location could be avoided by seals near the seabed in an area of 653 km^2. At 1 m below the surface of the water, this area is 67 km^2. In this example, the distances in which avoidance occurs are 15 km (near the seabed) and 5 km (1 m below the surface). The distances and areas estimated in this way are much smaller than those that apply to the harbour porpoise (cp. Figure 4-1 with Figure 2-2) because the assumed threshold value for avoidance for seals is higher than for harbour porpoises. The figure also shows that there is a broad zone between the coast and the outer edge of the avoidance/disturbance area where seals can migrate between the different core areas (the Wadden Sea and the Delta Area) without being disturbed.

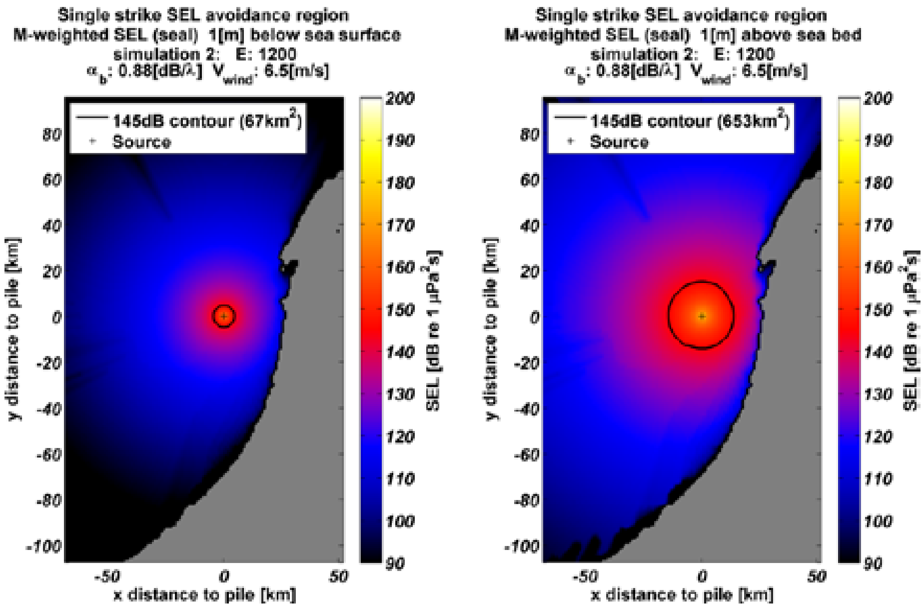


Figure 4-1 Calculated distribution of $SEL_{1,W}$ at a depth of 1 m below the surface (left) and 1 m above the seabed (right). Wind speed 6.5 m/s. The piling location is shown by the '+' symbol. The black lines show the contour within which the threshold value for avoidance (see Table 2-1) is exceeded for seals. The grey area shows the Dutch coast.

4.3 Seal populations and distribution

The North Sea is home to two species of seal: the harbour seal *Phoca vitulina* and the grey seal *Halichoerus grypus*. Both species use resting places (sand banks, beaches or rocks) as bases for foraging. The animals forage in the immediate offshore area but they can also make trips of some hundreds of kilometres.

Because they are ‘central-place foragers’[23], densities are generally higher at and near the places where the animals rest. An analysis of tagging data for grey and harbour seals on the North Sea coast of North and South Holland, where there are almost no resting places [Aarts et al., 2013], showed that both species use the coastal zone for foraging. It also emerged from that study that harbour seals move further offshore on average than grey seals (see figure 7 in [Aarts et al., 2013]). Recent tagging data collected during the monitoring of the construction of the Luchterduinen wind farm does not paint as clear a picture: in both species, the highest densities were seen in the first 20 km off the coast [Kirkwood et al., 2014]. This study also found that 5 of the 15 tagged grey seals, and 2 of the 12 harbour seals, use the coastal zone to swim from the Delta Area to the Wadden area or in the other direction.

Figure 4-2 provides a picture of the predicted relative densities for harbour seals using a model based on data relating to tagged animals in combination with area characteristics [Brasseur et al., 2012]. In recent years, large amounts of new tagging data have become available for both harbour and grey seals. The use of GPS transmitters has also led to a dramatic increase in the quality (in other words, the accuracy) of the data. With these data, in combination with data from more recent counts (which show that the Dutch seal populations have increased sharply), it should be possible to produce a new, improved, chart for both species. However, that chart is not yet available.

[23] After foraging, ‘central place foragers’ return to their starting location. In the case of seals, these are the places where they gather to rest.

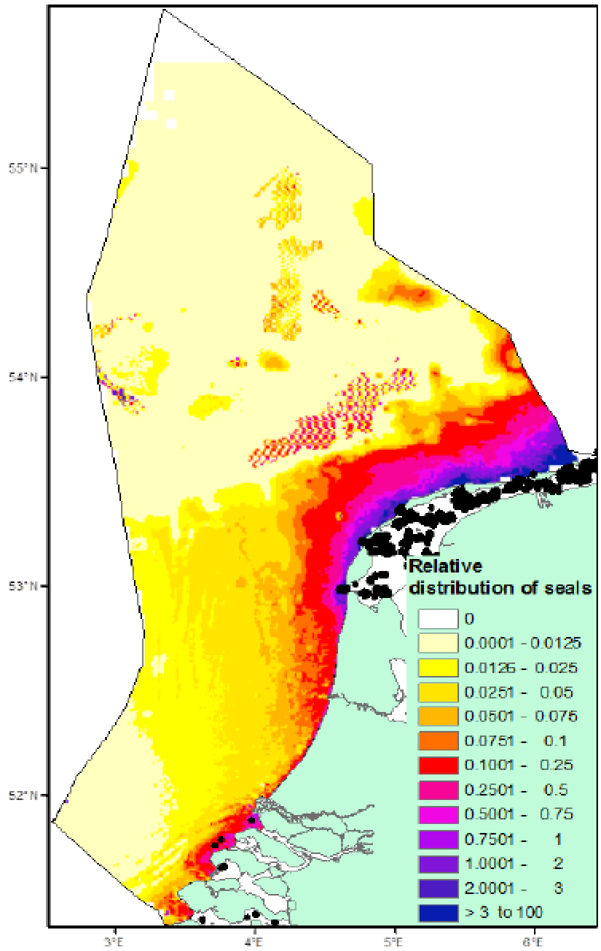


Figure 4-2 Modelled relative population density of harbour seals on the DCS [Brasseur et al., 2012]. Black dots show resting places.

4.4 Number of disturbed animals and animal disturbance days

To make an estimate of the number of seals on the DCS disturbed at the start of piling, the chart in Figure 4-2 with the modelled relative density of Dutch harbour seals by Brasseur et al. (2012) can be used. The colours in the chart state the population density per km^2 (see Intermezzo 'Estimate of the number of disturbed seals' for the procedure). As in the approach for harbour porpoises, the total number of animal disturbance days is then estimated by multiplying the number of disturbed animals a day by the number of disturbance days.

Intermezzo *Estimate of the number of disturbed seals*

After the projection of the calculated disturbance contour on the chart shown in Figure 4-2, the area (km^2) is determined for each density category (colour-coded) with the avoidance contour line. The density categories are defined on the basis of a lower value and an upper value. Because the various density categories were subdivided in a more or less logarithmic way by Brasseur et al., it is probably better to use a 'logarithmically transformed average value' for the calculation (rather than an arithmetical average of the upper limit and the lower limit). The sum of those areas multiplied by the associated average density per colour category is the relative measure for the number of seals inside the avoidance contour line. This number is then standardised at the total number of seals on the entire DCS determined using the same relative measure. The quotient of these two figures gives the estimate of the percentage of all seals on the DCS that may be located within the avoidance contour line at any given moment. Multiplication by the total number of Dutch seals results in an estimate of the number of disturbed seals.

4.5 Extrapolation of disturbance to population effects

In recent years, calculations have been conducted for a range of environmental impact assessments using the procedure described in Section 2.3.3.2 for the determination of the surface area where TTS or PTS may occur in both harbour porpoises and seals. It emerged from these calculations that the number of seals that may be disturbed by piling sound is small (< 1% of the Dutch population) and that the possibility of PTS in seals is negligible.

Until now, it has been argued on the following grounds that effects on harbour seals at the population level can be excluded:

- Given the fact that the planned locations are a relatively large distance offshore, where the seal population density is low, the number of seals that may be affected is small;
- The size of the affected area is small by comparison with the total habitat and so there will be no question of ‘density effects’ (competition for food and so on);
- Migration routes between the two Dutch core areas (the Wadden Sea and the Delta Area) are not blocked;
- The effect is temporary (1 day per foundation, with piling lasting approximately 2 hours a day) if only one wind farm is to be built annually.

It is not certain that this argument will remain valid given the Dutch plans for offshore wind energy for 2017 and after. In those plans, wind farms will no longer be built exclusively outside the 12-mile zone, but also inside it (albeit no closer than 10 miles to the coast). It can also be assumed that several wind farms will be built a year.

Thompson et al. (2013) and Harwood et al. (2014) arrived, on the basis of different modelling approaches for the effects of piling sound, at similar conclusions for the seal population in the Moray Firth: that the possibility of substantial effects on a local population of seals as a result of piling sound from a wind farm built relatively close to the shore cannot be excluded. However, in that case, many more animals were disturbed than has been found to be the case so far in the Dutch situation: it was thought that every day of piling could disturb more than 20% of the local population and that PTS could not be excluded for approximately 5% of the population.

By contrast with harbour porpoises, the relevant 'management unit' for seals is much smaller because both the harbour seal and the grey seal are bound to specific resting places. Although it is known that there are exchanges between the various populations living on the edges of the North Sea and that the increase in the Dutch population of grey seals is in part the result of immigration from the

United Kingdom [Brasseur et al., 2014], the size of the population that may be affected by underwater sound is determined primarily by the animals' radius of action with respect to the resting places. In the Netherlands, that means that it would be possible to assume a single total population of two, more or less distinct populations. It also implies that the accumulation of effects caused by Dutch farms planned off the coasts of Holland and Zeeland in combination with foreign farms is probably less relevant.

5 Guideline for writers of environmental impact assessments

As a guideline for environmental impact assessments and appropriate assessments for future Dutch Offshore Wing Energy projects, the following staged approach has been recommended:

1. Calculation of sound propagation per piling strike (source level, local parameters, propagation model);
2. Calculation of disturbance areas for harbour porpoises and seals (sound propagation, frequency weighting and threshold value);
3. Calculation of number of possibly disturbed harbour porpoises and seals (disturbance areas multiplied by local animal population density in the relevant season);
4. Calculation of the number of animal disturbance days (disturbed animals a day multiplied by the number of disturbance days);
5. Estimation of the possible effect on the population on the basis of the number of animal disturbance days;
6. Calculation of the cumulative exposure of harbour porpoises and seals in the vicinity of the pile and the determination of the distance within which animals are at risk of PTS; investigation and description of how this risk can be mitigated (using acoustic deterrents and/or soft start piling).

The relevant procedures are described in the following sections.

5.1 Calculation of sound propagation per piling strike

Using the available information about the planned piling work, the expected underwater sound propagation (SEL_1 in the lower half of the water column) around the pile should be calculated. The accuracy of this calculation will depend on the availability of detailed information and of the acoustic model used. If there are major variations in the foundations used in a farm, for example because the water depth or soil composition varies, these should be taken into account by making several calculations.

At present, there is still no fully validated model for underwater sound generated by offshore piling. This study used TNO's AQUARIUS model, in which the underwater sound levels measured during the construction of the Prinses Amalia wind farm (Q7) were extrapolated to other project locations. The piling sound model used should cover at least the following elements:

- The sound emanating from the pile depending on the piling strike energy;
- The water depth in all the routes between the locations of the source and the recipient;
- Reflection and dissipation of sound and absorption in the seabed;
- Reflection and dissipation of sound on the surface of the sea as affected by the wind;
- The depth dependence of the sound at the recipient locations;
- The frequency dependence of the source and propagation (in one-third-octave bands).

5.2 Calculation of the disturbance area per piling strike

The estimate of the disturbance area follows from the calculated sound propagation (SEL_1) and the applicable threshold for disturbance. The area is determined by the contour around the pile within which the calculated SEL_1 exceeds that threshold value.

At present, the recommendation for harbour porpoises is to assume a threshold value for the unweighted sound exposure level: SEL_1 = 140 dB re 1 $\mu Pa^2 s$.
This threshold value was selected as a compromise between the effects observed in the laboratory starting at an SEL_1 of 136 dB re 1 $\mu Pa^2 s$ [Kastelein et al., 2014] and the field observations in which harbour porpoise activity declined starting at an SEL_1 of approximately 144 dB re 1 $\mu Pa^2 s$ [Diederichs et al., 2014]. See also the Intermezzo in Section 2.3.1.

At present, the recommendation for seals is to assume a threshold value for the weighted sound exposure level: $SEL_{1,W}$ = 145 dB re 1 $\mu Pa^2 s$, in which the spectrum is weighted in line with the M_{pw} weighting for 'pinnipeds in water' from Southall et al. (2007).

It is advisable to calculate the disturbance area for two situations: one with, and one without, wind. The selected wind speed should be representative for the maximum wind speed at which piling can take place. The average of the two calculation results can then be used as the estimated effective disturbance area (~±50%).

5.3 Calculation of the potential number of disturbed harbour porpoises and seals per piling strike

The potential number of disturbed animals is calculated by multiplying the calculated disturbance area by an estimate of the density of the undisturbed population around the calculated disturbance area (Section 5.2)

The latest available information, for example from IMARES observations and models, should be used to estimate the population densities of harbour porpoises and seals on the DCS: [Geelhoed et al., 2011 & 2014] for the harbour porpoises and [Brasseur et al., 2012] for the seals.

5.4 Calculation of the number of animal disturbance days per project

This staged procedure assumes that piling for turbine foundations disturbs harbour porpoises and seals for a day. In practice, driving a single pile takes between 1 and 4 hours at most and no more than one monopile is driven a day with the same piling platform.

That means that the number of animal disturbance days resulting from piling for an offshore wind project can be estimated by multiplying the number of 'impulse days' (= number of turbine foundations) by the estimate of the number of disturbed animals per pile. The Underwater Sound Working Group agreed that calculations using a single disturbance day per 'impulse day' on the basis of the limited data available about the duration of disturbance was a feasible compromise. If there are major variations in the foundations used in a farm, for example because of differences in water depth or soil composition, the differences should be factored in by calculating the disturbance area and the animal disturbance days for each type of foundation.

Where there are spatial overlaps of disturbance areas around piling locations, steps should be taken when necessary to take those overlaps into account when piling takes place on the same day. In the current approach, multiple disturbances of animals on the same day do not result in additional animal disturbance days.

5.5 Estimation of the possible effect on the population on the basis of the number of animal disturbance days

The present study used SMRU's Interim PCoD model to extrapolate disturbance by underwater sound to an effect on the population as a whole. This approach could be adopted in future studies. The results for the limited set of scenarios adopted in this study (see Section 3.3) suggest that there is an approximately linear relationship between the total number of harbour porpoise disturbance days (over the course of six years and several projects) and the reduction in the harbour porpoise population after those six project years.

Using the parameters selected in the present study for the harbour porpoise population in the North Sea, an initial estimate can be made without any extra Interim PCoD calculations of a maximum population reduction with a 95% confidence interval for non-exceedance using the following approximation formula:

is the number of individuals in the vulnerable sub-population.

In addition, a picture is required of the cumulative effects. The scenarios described in Section 3.3 are based on assumptions. New information may become available about planned wind farms during environmental impact assessments. The number of animal disturbance days should also be taken into consideration in those plans and projects (in so far as they have been calculated).

Test criterion
The development of a test criterion for the assessment of the effects of impulsive sound on marine mammal populations was not included in the instructions for this report. In a parallel process, the government is working with the Underwater Sound Working Group to establish a standard for the maximum permissible annual reduction in the number of animals in a given population. The interim objective of ASCOBANS (Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas) will guide the derivation of the standard for harbour porpoises in the Dutch sector of the North Sea (in other words, the DCS):

to restore or maintain the population at 80% of the carrying capacity or more.
In addition, it must be highly probable (95%) that this level can be achieved or maintained. The standard for the maximum permissible annual reduction in the number of harbour porpoises in the Dutch population will be set out in the 'Ecology and Accumulation Assessment Framework'.

A statistical estimate of the effect of sound disturbance on the ultimate size of the population follows from the Interim PCoD calculations. This means that the objective underlying the standard, as in the case of ASCOBANS (at least 80% of the carrying capacity) can, in principle, be directly compared with a maximum limit for the population reduction calculated with PCoD. The requirement that there should be a high probability (of at least 95%) that the population reduction calculated with the Interim PCoD model will not be larger over a given number of years means that the 5th percentile values must be adopted.

5.6 Calculation of the distance within which there is a risk of PTS in animals

The emphasis during the development of the staged procedure was on disturbance. However, in addition, the risk of PTS in animals that are too close to the piling location when piling starts must be limited. A procedure for estimating the cumulative exposure of animals to underwater sound during piling taking any avoidance behaviour into account has been described in Section 2.3.3.2. The total exposure depends on how far away the animal is located when piling begins. Comparing the calculated SEL_{cum} with the threshold values for the cumulative exposure at which PTS can occur from Table 2-1 makes it possible to determine the maximum distance from the pile within which there is a risk. This effect can probably be mitigated by warning the animals present using acoustic deterrents and/or a soft start for piling.

6 Knowledge gaps

6.1 Introduction

Chapter 2 describes the actual or possible choices involved in the quantification of the steps in the effect change from the primary abiotic effect – the production of impulsive sound by human activities in the North Sea – up to and including a possible effect on populations of marine mammals: the staged procedure (or 'line of reasoning') for determining the cumulative effects of impulsive sound on marine mammals. There is a level of uncertainty *or* a bandwidth in the quantification of each of these steps with the associated selected parameter. That level of uncertainty can be determined by a more or less known variation in the selected value but also (and usually) by the fact that little, and sometimes almost nothing, is known about the parameter in question (this is a 'knowledge gap').

This chapter provides an overview of the knowledge gaps identified by the members of the Underwater Sound Working Group. An overview is provided in the following sections and the knowledge gaps have been structured as follows:

- Quantification of sound propagation (Section 6.2)
- Threshold values for disturbance/changes in behaviour (Section 6.3)
- Threshold value for PTS (Section 6.4)
- Quantification of the number of disturbed animals and animal disturbance days (Section 6.5)
- The size of the vulnerable sub-population (Section 6.6)
- Extrapolation of animal disturbance to effects on vital rates (Section 6.7)
- Assumptions in Interim PCoD model about population development and demographic parameters (Section 6.8)

6.2 Quantification of sound propagation

- The source level of the piling sound has, until now, been estimated using f observational data relating to Q7 as the upper limit of a range of estimates with a bandwidth of 6 dB. In addition, a scaling approach has been adopted for the estimate of the applied hammer energy. There has only been limited experimental validation of this estimate. Comparable levels have been found at distances of approximately 1 km from the pile in OWEZ and German farms.
- The hybrid model developed by TNO [Zampolli et al., 2013], which calculates piling sound using detailed data about the pile, the piling hammer and the locality, could, in principle, provide a more accurate description of sound propagation but this model still requires further validation and it also requires more detailed information about the projects for the construction of wind farms than is available at present.
- Sound propagation has been calculated using the AQUARIUS model. This model has not yet been validated experimentally for distances in excess of 6 km. It is expected that this knowledge gap will be remedied (to some extent at least) in the next few years. During the construction of the ENECO Luchterduinen (2014) and GEMINI farms (2015), measurements have, and will be, made at larger distances for the purposes of validating source and propagation models.

- Calculations with realistic variations in piling hammer energy, seabed composition and disturbance of the water surface by wind show a spread of approximately ± 50% in the calculated affected area.
- The modelling of the source levels from seismic airgun arrays in AQUARIUS, and in particular sound emanation in the directions that are important for propagation over larger distances, require further development and experimental validation.

6.3 Threshold values for disturbance/changes in behaviour

- The calculated effect distances are highly dependent on the discrete threshold value selected[24]. Information about the dose-effect relationship for harbour porpoises is limited to a laboratory study (SEAMARCO) and a number of German field studies. More detailed information about the dose-effect relationship (with the level of the behavioural response depending on the exposure level and the background sound level) could make the estimates of the number of potentially disturbed animals more robust. It is possible that more information will become available from the monitoring of the GEMINI wind farms about the effect of piling sound on harbour porpoise activity. However, it may be wondered whether these results will lead to a significant advance in our understanding of the dose-effect relationship with respect to what we have already learnt on the basis of the results for the Borkum II-West project (but not yet applied in the Interim PCoD model). This is information about the proportion of the harbour porpoises located inside the disturbance contour that are found to respond, and about the duration of the disturbance (until the recovery of harbour porpoise activity).
- The threshold value for avoidance/disturbance in seals is based on a single study from SEAMARCO (see Intermezzo ‘Threshold values for the effects of underwater sound on marine mammals’ in Section 2.3). In order to make a more reliable estimate of the disturbance area, more laboratory and field observations will be required to determine the threshold value for disturbance (or the dose-effect relationship) more precisely.
- For the time being, the calculations for harbour porpoises do not take hearing sensitivity as a function of the frequency into account. The unweighted threshold values used at present are based on studies of piling sound and airguns, and therefore apply to the relevant low-frequency impulsive signals. In the case of seals, a species-dependent (M_{pw}) frequency weighting is being used for the time being on the basis of [Southall et al., 2007]. The effect of the form of the signal and the frequency content (this depends on things such as the distance to the piling location) on the dose-effect relationship needs to be investigated further. Linking threshold values for avoidance and TTS/PTS to the hearing threshold in the way proposed by Tougaard et al. (2014) may have an effect on the estimate of the number of affected animals.

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[24] The term 'discrete threshold value' is used because it indicates the boundary between 'no disturbance at all' and any other form of disturbance defined as **all** responses with a score of 5 or more on the scale of Southall et al. (2007). By contrast with a dose-effect relationship in which the probability of the occurrence, or the level, of an effect gradually increases in line with the exposure level (in other words, the dose).

6.4 Threshold values for hearing threshold shifts

- Because it is not ethical to conduct experiments to determine threshold values for PTS onset, these values are currently estimated using the limited data available about threshold shift rises in line with increasing exposure levels. On the basis of data about land animals, it is cautiously assumed that, at a auditory threshold shift of 40 dB, the risk of permanent damage is such that this can be adopted as an approximate value for PTS onset. Data about threshold shift rises in the presence of exposure to piling sound are lacking for the time being (see also Annex B).
- It is assumed that the onset of a threshold shift depends on the total exposure dose SEL_{CUM}. In the meantime, a range of studies have found that the 'duty cycle' for exposure (continuous sound as opposed to a single pulse or a series of pulses) is an important factor here (see Annex B). In addition, it will probably also be necessary to take an 'effective quiet' threshold value into account, below which sound levels do not contribute to the SEL_{CUM} that results in a auditory threshold shift.
- For the time being, the calculations for harbour porpoises, like those for disturbance (Section 6.3), do not take hearing sensitivity as a function of the frequency into account. The effect of the signal form and frequency content on the dose-effect relationship needs to be investigated further. Linking threshold values for avoidance and TTS/PTS to the hearing threshold in the way proposed by Tougaard et al. (2014) may have an effect on the estimate of the number of affected animals.
- On the basis of various arguments (Section 2.3.4), this study assumes that the possible occurrence of TTS can be ignored when estimating population effects. However, no research as yet been conducted looking at the possible ecological consequences of a temporary threshold shift. In Germany [BMU, 2013], TTS onset qualifies as an 'injury'.

6.5 Quantification of the number of disturbed animals and animal disturbance days

The number of disturbed animals is calculated by multiplying the estimated disturbance area (area within the contour line inside which the threshold value for disturbance is exceeded in the sound charts generated using AQUARIUS) by the estimated population density of animals (that are not disturbed by underwater sound) in that area for the time of the year in which the disturbance takes place.

- In the case of harbour porpoises, the estimated densities are highly uncertain (the 95% confidence interval for the average estimates used here is between approximately -50% and +100% [Geelhoed et al., 2011]). Furthermore, almost nothing is known about any possible season-dependent migration patterns, site fidelity, and possible sex- and age-specific variations in these factors. Although tagging studies are taking place in Danish waters that are generating more information about individual animals, particularly in the Kattegat/Skagerrak region (for example, [Sveegaard, 2011]), this gap will not be remedied for the North Sea in the short term. This makes it difficult to provide a more precise estimate of the number of animals affected at different times of the year.
- IMARES has made a chart showing the spatial variation in the relative density of the harbour seal population on the DCS [Brasseur et al., 2012]. A similar chart has also been made for grey seals [Brasseur et al., 2010] but based a

limited number of animals, making it less reliable. In recent years, large amounts of new tagging data have become available for both harbour and grey seals. In addition, the quality of the data has improved dramatically due to the use of GPS transmitters. The development of charts including these new data, if possible for different seasons, would make it possible to produce a better estimate of the number of harbour and grey seals disturbed by sound.
- The total number of animal disturbance days is calculated by multiplying the number of animals that may be disturbed on one day by the duration of the disturbance. No unequivocal picture has yet emerged from the information available at present about the duration of the disturbance (see Section 2.4.2). However, the model results have proven to be relatively sensitive to the selected values (8, 24 and 48 hours).
- The accuracy of the number of estimated animal disturbance days also depends on the accuracy of the available information about the timetable for the future construction of wind farms. At present, that timetable is highly uncertain with respect to the numerous international projects in the North Sea.
- The accuracy of the number of estimated animal disturbance days also depends on the accuracy of the available information about developments in seismic surveying in the North Sea, which is equally uncertain, if not more so.

6.6 The size of the vulnerable sub-population

For calculations with the Interim PCoD model, the user must define a ‘vulnerable sub-population’. This is the proportion of the total population – in the case of the harbour porpoise, the animals living in the North Sea – that may be affected by the activity producing the sound. The size of the population is highly dependent on the extent to which the animals are bound to a particular area (this may depend on age and sex, and the time of the year). Information in this area is lacking (see also Section 6.5).

6.7 Extrapolation of animal disturbance to vital rates

An important assumption is that the response level described as 'disturbance' corresponds to the interpretation of disturbance by the experts consulted for the Interim PCoD model. The model assumes a statistical relationship between the number of days on which an animal demonstrates a ‘significant behavioural response’ and the ‘vital rates’ of that animal. This relationship was estimated by means of expert elicitation. In addition, it was suggested to the experts that a ‘significant behavioural response’ corresponds to level 5 on the scale used in Southall et al. (2007). It was concluded in the ecologists workshop – with the approval of John Harwood, one of the authors of the Interim PCoD model – that the interpretation of avoidance/disturbance used in the staged procedure resides on basic principles that are comparable with the definition of ‘significant behavioural response’ supplied to the experts by SMRU.

The main knowledge gaps are to be found in the field of the extrapolation of the disturbance of individuals by sound to the effects on the health/condition of those individual animals, and the consequences for survival and reproduction. In the Interim PCoD model, this knowledge gap is filled in by using expert estimates of the relationship between disturbance and vital rates in a formal expert elicitation process (see Intermezzo in Section 2.5.1). Although, at present, the Interim PCoD model is effectively the only operational instrument available for determining population effects, there are still many reservations. Some of them could be resolved if more quantitative information were to be available about the relationship between disturbance and the health/condition of individual animals (of various ages). This would make possible the application of a ‘full PCoD model’ (see Figure 2-7).

The members of the Underwater Sound Working Group identified a large number of knowledge gaps relating to this step in the effect calculations for **harbour porpoises**. Those gaps were sometimes highly detailed (and stated in the form of concrete research proposals) but also formulated in more general terms. In the discussion points listed here, we have tried to do justice to the different contributions, but some of them have inevitably been grouped together.

- Effect of disturbance on feeding and energy expenditure (‘time-budget’ analysis) This issue is more important for harbour porpoises than for other marine mammals because they are smaller and have to eat regularly to maintain their weight. That makes them relatively sensitive to disturbance because of the implications for feeding. This involves questions such as: at what level of disturbance will a disturbed animal use more energy than an undisturbed animal, at what level of disturbance does an animal stop foraging, does the animal become used to the source of disturbance, how long can an animal manage without food, in what conditions (including the amount of time spent without feeding, available food supplies) can a food shortage be remedied without there being a substantial effect on survival chances, and how is that related to the time of the year?

- Habitat suitability It is not yet entirely clear in the case of harbour porpoises whether or, if so, why the areas where the highest population densities are seen (at specific moments) are the most suitable habitats. Are the survival chances of harbour porpoises that are driven out of an area of this kind actually adversely affected (see previous point)? To what extent are seasonal variations in population levels linked to variations in the availability of food supplies?

- Mother-calf combination Can the sensitivity of pairings of mothers and calves to disturbance by comparison with solitary animals be affected by the masking of communications by piling sound?

Much more data are available for harbour and grey seals than for harbour porpoises. That includes both population estimates and knowledge about the movements of individual animals. In combination with experimental data about the energetic costs of changes in behaviour (see, for example, [Rosen et al., 2007]; [Sparling & Fedak, 2004]; [Sparling et al., 2007]), it is thought that the effect on the population could be estimated by combining an agent-based model (see, for example, [Nabe-Nielsen et al., 2014]) with a Dynamic Energy Budget.

6.8 Assumptions in Interim PCoD model about population development and demographic parameters

The Interim PCoD model assumes that the harbour porpoise population is stable and that demographic development does not depend on the population density. This means that, after the one-off inclusion of an effect on the population, in other words a fall in numbers as a result of the activities, the population in the model outcomes will not recover after the activities cease. This is probably not realistic. We need to know more about the population-density-dependent effects on demographic developments in order to arrive at a more realistic estimate of changes in the population in the years when there is disturbance, but above all after the disturbance ceases:

- Has the carrying capacity been reached and, if so, what are the factors limiting population growth?
- Does competition for food play a role if animal population density increases when the animals are driven out of a particular area by underwater sound?

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A Members of the Underwater Sound Working Group + participants at the workshop on 10-10-2014

The members of the RWS Underwater Sound Working Group in 2014 were:

- Aylin Erkman, RWS Sea and Delta
- Christ de Jong, TNO
- Floor Heinis, HWE
- Geert Aarts, IMARES
- Lianke te Raa, TNO (project manager)
- Martine Graafland, RWS Space and Water
- Martine van Oostveen, Royal HaskoningDHV
- Meike Scheidat, IMARES
- Michael Ainslie, TNO
- Niels Kinneging, RWS Sea and Delta
- René Dekeling, Ministry of Defence & Infrastructure and the Environment
- Roelant Snoek, Arcadis
- Ron Kastelein, SEAMARCO
- Sander von Benda-Beckmann, TNO
- Steve Geelhoed, IMARES
- Suzanne Lubbe, RWS Sea and Delta

The following attended the ecologists workshop on 10 October 2014:

- Aylin Erkman, RWS Sea and Delta
- Christ de Jong, TNO
- Floor Heinis, HWE
- Geert Aarts, IMARES
- John Harwood, University of Saint Andrews (Scotland)
- Meike Scheidat, IMARES
- Roelant Snoek, Arcadis
- Ron Kastelein, SEAMARCO
- Sander von Benda-Beckmann, TNO
- Steve Geelhoed, IMARES

B Background to TTS/PTS in harbour porpoises and seals

Memorandum dated 10 March 2013 (with additional material from 2014)
To: underwater sound working group
From: Christ de Jong (TNO)

B.1 Introduction

The Underwater Sound Working Group (2013) coordinated by RWS North Sea is attempting to clarify and harmonise the situation with respect to the modelling of the possible effects of underwater sound during piling for offshore wind farms on harbour porpoises and seals for the purposes of Appropriate Assessments.

The aim of this memorandum was to contribute to that effort, particularly with respect to the threshold values for PTS and TTS in harbour porpoises and seals.

B.2 Conclusions

- The threshold values used until now for the sound dose that can result in TTS and PTS onset in harbour porpoises and seals are, because of a major shortage of relevant data, uncertain and therefore highly conservative.
- The specification of the frequency and the timing of the exposure at which the threshold shift is observed could make the threshold values more meaningful. Recovery from the 6 dB TTS_4 used now as the threshold value ('TTS onset') will generally occur after approximately 16 minutes.

B.3 Approach

TNO is drawing on the available data from previous projects (in other words, the construction of Q7) to calculate, with the AQUARIUS model for underwater sound propagation in the North Sea, how piling sound propagates in the vicinity of a piling location. In consultation with biologists, an estimate has been made of the possible numbers of harbour porpoises and seals, and the possible behavioural response of these animals to piling sound. These data are being combined to estimate the sound dose to which the animals will be exposed during the driving of a wind turbine foundation.

The calculated sound dose is then compared with threshold values for the dose above which relevant effects may occur. These are derived from dose-effect relationships and threshold values for relevant effects.

The discussion in the working group about the calculation of the exposure levels has been more or less completed. The approach and the input parameters for the model calculations have been determined and accepted. The threshold values to be used are still being discussed.

The current approach assesses three effects:

a *Behavioural changes*
b *Temporary increase in the hearing threshold (TTS)*
c *Permanent increase in the hearing threshold (PTS)*

This memorandum discusses possible hearing threshold shifts (TTS and PTS).

B.4 Increase in the hearing threshold

To clarify the subject of the discussion, we must first determine what we mean by TTS and PTS.

<u>Hearing threshold</u>
When underwater, harbour porpoises and seals depend on sound to establish a picture of their surroundings and what is happening there. The lowest sound pressure level that these animals can still just perceive (in 50% of exposure events) in surroundings where background sound is negligible is known as the 'hearing threshold'. This depends on the form of the signal, in other words on the frequency content and the duration of the signal. In the case of signals that last long enough, the hearing threshold is dependent upon the duration of the signal and it can be expressed as the level of the average square of the pressure level during the duration of the signal (in other words, the Sound Pressure Level, or SPL). Ron Kastelein (SEAMARCO) conducted the most recent measurements of the frequency-dependent hearing thresholds ('audiograms') in harbour porpoises and seals. See Figure B-1.

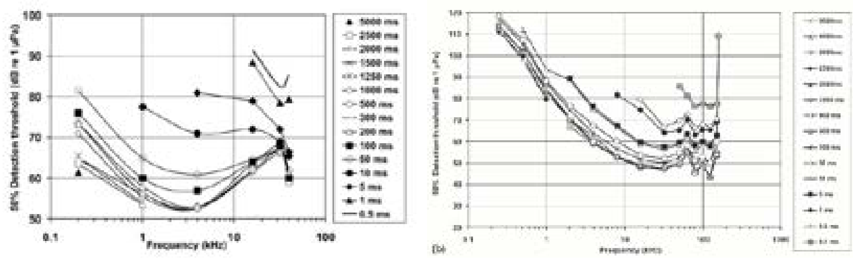

Figure B-1 Audiograms of seals (on the left, from [Kastelein et al., 2010a]) and harbour porpoises (on the right, from [Kastelein et al., 2010b]) for tonal signals of various durations.

<u>Threshold shifts</u>
A threshold shift, in other words a higher threshold value for the SPL above which the signal is still just audible in surroundings without any background sound, can, in principle, be found at all frequencies in the audiogram. A shift of this kind can occur as a result of exposure to sound but also of, for example, taking medicines.

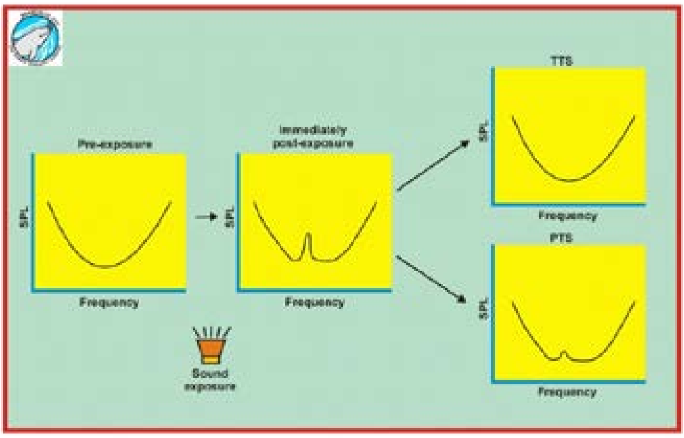

Figure B-2 Schematic representation of temporary (TTS) or permanent (PTS) threshold shifts caused by exposure to sound

A range of publications have now appeared showing that exposure to sound can result in threshold shifts in harbour porpoises and seals. See, for example, [Kastak et al., 2005 & 2008]; [Lucke et al., 2009] and [Kastelein et al., 2012/2013/2014]. In addition, there is a considerable amount of recent data, particularly for bottlenose dolphins, from studies by Finneran et al. showing that the effects are comparable with what we know about the effects of sound on humans and laboratory animals such as chinchillas.

Dose-effect relationship

The relationship between the exposure dose and threshold shifts depends on various parameters for sound and hearing. Like the audibility of signals, a threshold shift caused by exposure depends on the form of the signal, in other words on factors such as the frequency content and the duration of the signal. The frequency at which the threshold shift occurs depends upon the frequency of the exposure. In harbour porpoises and seals, the largest shift appears to occur at the exposure frequency [Kastelein et al., 2012 & 2013]. In the case of the bottlenose dolphin, this is 1.5 times the exposure frequency [Finneran et al., 2013]. Recent research looking at a harbour porpoise by SEAMARCO has shown that the hearing frequency affected depends on the exposure level [Kastelein et al., 2014]. The most recent data for the bottlenose dolphin [Finneran et al., 2013] show that the dose-effect relationship is probably frequency-dependent. The three TTS studies by SEAMARCO looking at the harbour porpoise show the same pattern between 1.5 and 7 kHz [Kastelein et al., 2012/2013/2014]. The threshold shift increases gradually during exposure and tails off after the exposure ceases. This means that the point in time at which the threshold shift is measured is an important factor in the assessment. Periodical exposure to sound is accompanied by a recovery in hearing between the periods of exposure. This means that the total effect will depend on the ‘duty cycle’ (the percentage of the total duration of exposure to the sound) [Kastelein et al., 2014].

Relevance of threshold shifts

An assessment of the relevance of a temporary or permanent threshold shift for individual harbour porpoises and seals and for the populations is outside the scope of this memorandum. However, such an assessment does determine the threshold values to be used for exposure. When determining the threshold values, it should be borne in mind that, in addition to the size of the threshold shift, the hearing frequency and the duration of the shift are relevant parameters. Until now, the limit values proposed by Southall et al. (2007) have been based on the avoidance of threshold shift that is measurable at any hearing frequency at any moment after exposure higher than or equal to 6 dB ('TTS onset') or 40 dB ('PTS onset'). It is thought that the specification of the frequency and the time after exposure at which the threshold shift is measured would make the threshold values more ecologically meaningful. However, this would require more data than is available at present.

B.5 Modelling

The most recent description of models for the rise in, and recovery from, a threshold shift can be found in the papers about the bottlenose dolphin from Finneran's group in the USA [Finneran et al., 2010 & 2013].

Increase

On the basis of data relating to humans, chinchillas and bottlenose dolphins, Finneran et al. (2010a) propose the following model for the increase in the threshold shift:

$$\mathrm{TTS}_4(D,\mathrm{SPL}) = a\log_{10}\left(1+10^{(D-b_1)/10}\right)\log_{10}\left(1+10^{(\mathrm{SPL}-b_2)/10}\right)$$

Here, TTS_4 is the threshold shift [in dB] as measured 4 minutes after the termination of exposure during a period of time *D* [in minutes] to a continuous sound of SPL [dB re 1 μPa]. *a*, b_1 and b_2 are fit parameters.

In this model, exposure duration *D* and level of exposure SPL are independent parameters. This model would appear to result in a better match with the observed data than a model using $\mathrm{SEL} = \mathrm{SPL} + 10\log_{10}(D/1\mathrm{s})$ as the parameter. In the case of both parameters, there is a threshold under which the parameter has no effect, and when $10^{(D-b_1)/10}$ and $10^{(\mathrm{SPL}-b_2)/10}$ are much smaller than 1[25]. Exposure to levels of less than b_2 do not affect the threshold shift and can therefore be described as 'effective quiet' [Ward et al., 1976]. Above this threshold value, TTS_4 increases, according to the model, in the case of a constant *D*, directly proportionally to the SPL and, in the case of a constant SPL, directly proportionally to *D*.

Recovery

A double exponential model has been proposed for recovery from a threshold shift after exposure [Finneran et al., 2010a]:

$$\mathrm{TTS}_t = \mathrm{TTS}_4\left[c_1\exp(-t/\tau_1) + c_2\exp(-t/\tau_2)\right]$$

[25] That would appear to be logical for SPL dependence because decibels are used, but not for duration *D* in minutes. This model would not appear to be based on a physical interpretation but primarily on a statistical fit with the observation data.

Here, TTS_t is the threshold shift at *t* [minutes][26] after exposure and c_1, c_2, τ_1, and τ_2 are fit parameters[27].

Periodical exposure

Finneran et al. (2010b) conclude that a 'modified power law' (MPL) model, as proposed by Humes & Jesteadt (1989 & 1991), results in the best description of the observations for the effects of the exposure of a bottlenose dolphin to tone pulses repeated at intervals. That model is stated as[28]:

$$TTS_{4,N} = 10\log_{10}\left\{\left[\left(10^{T_N/10}\right)^P + \left(10^{R/10}\right)^P - 1\right]^{1/P}\right\}$$

Here, T_N is the TTS_4 that would only be caused by the N^{th} exposure and *R* is the TTS already present at the time of the N^{th} exposure. The value of *R* depends on the increase in, and recovery from, the threshold shift caused by previous exposure. In humans and land mammals, the power *P* is approximately 0.1–0.4.

Because it is not yet possible to measure recovery in the initial seconds after the exposure, there are doubts relating to the practicality of this model for periodical piling sound.

B.6 Harbour porpoise

In 2013, the following series of measurements were available to us for harbour porpoises as a basis for the derivation of the increase in, and recovery from, threshold shifts.

- Threshold shift at 4 kHz after exposure to individual impulses from a seismic airgun [Lucke et al., 2009]
- Threshold shift at 4 kHz after exposure to wideband sound in the 4 kHz octave band [Kastelein et al., 2012b & 2013b]
- Threshold shift at 1.5 kHz after exposure to a tonal sound at 1.5 kHz [Kastelein et al., 2013a]
- Threshold shift at 1.5 kHz after exposure to sonar sweeps (2-1 kHz in 1 s, different duty cycles) [Kastelein et al., 2013d]

The numerical fitting of these data to the models for increases and recovery may be possible, but not within the scope of this short study. As a result, an attempt has been made below to give a qualitative assessment of the data.

Increase

Figure B-3 shows the increase in the threshold in response to exposure to sound in the 4 kHz octave band.

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[26] [Finneran et al., 2010a] use, probably erroneously, the unit 's' for the time constants τ_1, and τ_2. Nor is it clear whether the time is calculated from the point in time at which exposure ceases or starting 4 min after the exposure at which TTS_4 is observed. Here, we assume that *t* is calculated starting at the end of exposure, in minutes.

[27] This model would also not appear to be based on a physical interpretation but primarily on a statistical fit with the observation data.

[28] I could not find this equation in Humes & Jesteadt (1989). The Humes & Jesteadt (1991) paper suggests a model of this kind for the rise in TTS after previous exposure but without the '-1' term.

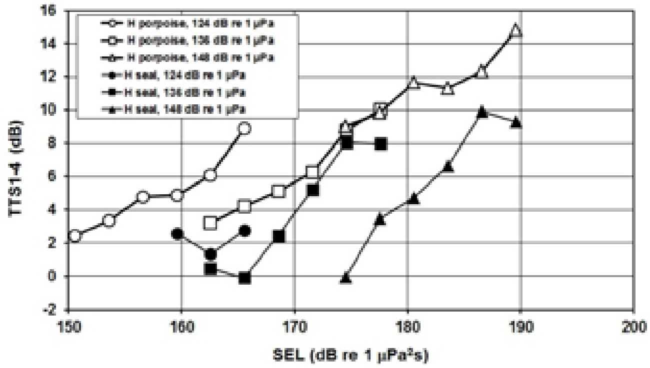

Figure B-3 Increase in the threshold shift (measured 1-4 minutes after exposure) at 4 kHz in harbour porpoises and seals after exposure to sound in the 4 kHz octave band as a function of SEL. The legend shows the associated SPL [Kastelein et al., 2013b].

The rise here would appear to be approximately 0.5 dB TTS / 1 dB SEL_{CUM}. The lines in Figure B-3 show this trend for a constant SPL. The TTS rise here is proportional to $10\log_{10}(D/1s)$ and not to *D*, as suggested by the increase model.

The $TTS_{16\text{-}18}$ measurements at 16 to 18 minutes after the exposure of a harbour porpoise to an airgun signal show a much sharper rise in line with increasing SEL. At SEL values of less than 164 dB re 1 μPa^2s, no significant $TTS_{16\text{-}18}$ was measured; at an SEL of 164.5 dB, the threshold shift was 7.8 dB and, in response to later exposures to an SEL of 165.5 dB, a TTS_{16} of 15.5 dB was measured; two days later, an SEL of 165.8 dB resulted in a 21 dB TTS_{18}.

Intermittent piling sound: The TTS increase is much smaller when there is a 10% duty cycle than in the case of a 100% duty cycle (1-2 kHz sweeps study; [Kastelein et al., 2013].

<u>Recovery</u>
The overall picture to emerge from the data are as follows.

- The data from Kastelein show an initial trend in recovery from a threshold shift of approximately $-10\log_{10}(t/1\ \text{min})$:
  - Recovery after 48 minutes: $TTS_{48} \approx TTS_4 - 11$ dB
  - Recovery after 24 hours: $TTS_{(24\cdot 60)} \approx TTS_4 - 26$ dB
  - If that trend were to be extrapolated, recovery after 1 week would be $TTS_{(7\cdot 24\cdot 60)} \approx TTS_4 - 34$ dB and after 1 month $TTS_{(30\cdot 7\cdot 24\cdot 60)} \approx TTS_4 - 49$ dB. However, these estimates are probably optimistic because the model for land mammals and bottlenose dolphins [Finneran et al., 2012a] indicates that long-term recovery is slower.
- A maximum TTS_4 of 27.5 dB measured by Kastelein et al. (2013d) in the harbour porpoise (at 1.5 kHz after exposure to sonar sweeps) fell within 24 hours to 2.5 dB and complete recovery was observed two days later.

- Lucke et al. (2009) suggest that recovery from the measured TTS_{18} of a maximum of 21 dB was also seen within three days (no exact data were available).
- Given the rough initial trend, a measured TTS_{16} of 21 dB would correspond to $TTS_4 = 21+10\log_{10}(16/4) \approx 27$ dB.
- It should be noted that we now use the exposure dose at which which Lucke et al. (2009) measured these $TTS_{16\text{-}18}$ values as the threshold value for TTS onset. The possibility cannot be excluded that Lucke et al. would have been able to find TTS onset (6 dB) at lower exposure doses if they had been able to make observations sooner after exposure (TTS_4).
- Given the data available, a value for the ‘effective quiet’ level of exposure cannot be determined.

A TTS that is still relevant one hour after exposure (TTS_{60} = 6 dB, for example) corresponds, given an estimated recovery of $10\log_{10}(60/4)\approx12$ dB, to TTS_4 = 18 dB. At the estimated TTS rise of 0.5 dB TTS / 1 dB SEL_{CUM}, the SEL_{CUM} at which this TTS_4 = 18 dB is found is approximately 24 dB higher than the threshold value for TTS onset (TTS_4 = 6 dB). It should be noted that it is unclear whether this assumed rise also applies to periodical piling sound.

Periodical exposure

The model used by Finneran et al. (2010b) would not appear, because of the time scale in minutes, to be applicable to piling sound (typical pulse duration of 100 ms and a pulse interval of 1-2 s, resulting in a duty cycle of 5-10%), or to the sonar sweeps (duration 1 s, duty cycle 5-100%, pulse interval 0-19 s) in the study of Kastelein et al. (2013b).

The results of the SEAMARCO studies, in which a harbour porpoise was exposed to sonar sweeps (2-1 kHz in 1 s) at a range of duty cycles, show that hearing recovery may result in an increase in the SEL_{CUM} threshold value for TTS onset (6 dB after 1-4 minutes) of 4 to 8 dB. We do not know whether this increase will also apply to periodical piling sound but we realise that neglecting this effect may result in the possible overestimation of the effect distances.

B.7 Seals

The following series of measurements were available to us for harbour and grey seals as a basis for the derivation of the increase in, and recovery from, threshold shifts.

- Threshold shift at 2.5 kHz after exposure to broadband sound in the 2.5 kHz octave band [Kastak et al., 2005]
- An incidental threshold shift of ~50 dB at 5.8 kHz after exposure to a tonal sound at 4.1 kHz (60 s, SPL 184 dB re 1 μPa^2, SEL 202 dB re 1 μPa^2s), resulting in a probable permanent threshold shift of 7-10 dB after three months [Kastak et al., 2008]
- Threshold shift at 4 kHz after exposure to wideband sound in the 4 kHz octave band [Kastelein et al., 2012a]
- An incidental threshold shift of 44 dB at 4 kHz after exposure to broadband sound in the 4 kHz octave band (60 min, SPL 163 dB re 1 μPa^2, SEL 199 dB re 1 μPa^2s). Recovery after 4-5 days [Kastelein et al., 2013b].

The trends for increase and recovery would appear to be comparable with those for the harbour porpoise.

The threshold value for TTS onset that is currently in use is an extremely conservative limit that was derived indirectly by Southall et al. (2007) from the data of Kastak et al. (2005). Kastak et al. (2005) found a 6 dB TTS onset after exposure to continuous sound at an SEL of 184 dB re 1 $\mu Pa^2 s$ (25 min, SPL 152 dB re 1 μPa^2). This threshold value is comparable with the value found by Kastelein et al. (2012a): SEL = 184 dB re 1 $\mu Pa^2 s$ (60 min, SPL = 148 dB re 1 μPa^2). Incidentally, Kastelein et al. also found TTS onset at SEL = ~172 dB re 1 $\mu Pa^2 s$ (60 min, SPL = 136 dB re 1 μPa^2). The SEL threshold value proposed by Southall et al. (2007) for TTS in seals as a result of impulsive sound follows from the measured threshold value for a bottlenose dolphin (not a pinniped) exposed to a single watergun impulse and suppositions about the relationship between the threshold values in bottlenose dolphins and seals, and it is probably very conservative (as is also stated by Southall et al., 2007). The application of this threshold value to periodical piling sound is particularly conservative because it does not take possible recovery between the pulses into account (see the relevant comments relating to the harbour porpoise).

When seals in a pool were exposed to recorded piling sound at an SEL_1 of 140 dB re 1 $\mu Pa^2 s$, Kastelein et al. (2011) found no significant TTS after 21,000 strikes (SEL_{CUM} = 183 dB re 1 $\mu Pa^2 s$). This could indicate an ‘effective quiet’ threshold value that is higher than SEL_1 = 140 dB re 1 $\mu Pa^2 s$, or a TTS onset threshold value for piling sound that is higher than SEL_{CUM} = 183 dB re 1 $\mu Pa^2 s$. In both cases, the weighting currently used for an SEL_{CUM} without taking recovery into account and with the threshold value currently used can be described as conservative.

SEAMARCO continued this study later and exposed the seals for 3 hours (180 min) of piling sound (SEL_{CUM} = 190 dB re 1 $\mu Pa^2 s$). The report has been completed and financing is being requested.

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Colophon

The Framework for Assessing Ecological and Cumulative Effects of offshore wind farms was drawn up for the Ministry of Economic Affairs by Rijkswaterstaat, under the guidance of an interdepartmental steering group of representatives from the relevant directorates of the Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs.

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