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TNO report

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SORIANT VUM - final report

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Samenvatting

Om de risico's van offshore-projecten voor het mariene milieu te kunnen inschatten en om de noodzaak van eventueel te nemen maatregelen te bepalen, is het noodzakelijk om alle kennis over onderwatergeluid en de effecten bij elkaar te brengen. Hiertoe is een beoordelingsinstrument opgesteld voor onderwatergeluid, onder de noemer SORIANT (SOund RIsk Analysis Tool). In het kader van het project 'VUM SORIANT', dat is uitgevoerd in opdracht van Rijkswaterstaat, is een volledige risico-inschattingsketen geïmplementeerd. Hierbij is in eerste instantie de focus gelegd op het bepalen van effecten van heigeluid op de bruinvispopulatie.
Bij de inschatting kan nu de cumulatie van de effecten van het heien bij de aanleg van meerdere windparken over meerdere jaren worden meegenomen.
Daarbij wordt in de huidige versie van SORIANT vooralsnog gebruik gemaakt van een in Engeland ontwikkeld model, het Interim PCOD (Population Consequences of Disturbance), om de verwachte verstoring van bruinvissen bij de aanleg van meerdere parken door te kunnen vertalen naar effecten op de bruinvispopulatie in de Noordzee.

De volledige risico-inschattingsketen bestaat uit:

- Een module om gegevens over de aanleg (bv. locaties, tijdsduur van heiactiviteiten, type palen bv. monopiles, tripods) te definiëren.
- Een module voor het maken van geluidskaarten. Hierbij is het binnen het VUM traject ontwikkelde bronmodel voor heien, met de daaraan gekoppelde geluidspropagatiemodule geïntegreerd binnen SORIANT.
- Een module om effectafstanden en aantal verstoorde dieren in te schatten.
- Een module voor het accumuleren van verstoringseffecten bij de constructie van meerdere windparken (nationaal en internationaal)
- Integratie met een module (Interim PCOD, ontwikkeld door SMRU Marine en de Universiteit van St. Andrews) om effecten op de bruinvispopulatie te bepalen.

Dit beoordelingsinstrument is inmiddels toegepast tijdens de ontwikkeling van nieuwe richtlijnen voor het vergunningverleningsproces voor nieuwe offshore windparken in Nederland (Kader Ecologie en Cumulatie). Daarin is gekeken naar de effecten van zowel Nederlandse als ook omringende geplande windparken op de bruinvispopulatie in de Noordzee.

Het beoordelingsinstrument SORIANT is modulair en flexibel opgezet, zodat het eenvoudig uit te breiden is naar alternatieve methodes om effecten van verstoring door te vertalen naar populatie-effecten of naar andere type bronnen (bv. seismische survey, scheepvaart, zandwinningsactiviteiten, explosies en sonar) of diersoorten (bijvoorbeeld zeehonden en vissoorten). Op basis van het risico-inschattingsraamwerk dat in SORIANT gehanteerd wordt zijn in het rapport ook kennisleemtes geïdentificeerd.

Summary

To estimate the environmental risk of offshore projects and determine the potential need for mitigation measures, it is necessary to bring together the knowledge on underwater sound and its effects on the environment. To this aim, a prototype sound risk analysis framework (SORIANT), has been developed, which is aimed at assessing the impact of underwater sound on marine life. A complete risk assessment tool has been implemented in the 'VUM SORIANT' project, a project commissioned by Rijkswaterstaat. The tool initially focusses on determining the effects of pile driving sound during construction of offshore wind-farms on the harbour porpoise population. In the assessment process, the effects of accumulation of effects due to multiple windfarms can be accounted for over a period spanning multiple years. The current version makes use of the Interim PCOD model (Population Consequences of Disturbance), developed in the UK, which has been integrated to translate the predicted level of disturbance of construction of multiple farms to the effect on the North Sea harbour porpoise population.

The full risk-assessment chain consists of:
- A module for defining the construction process (e.g. location, duration of piling activities, type of piles).
- A sound mapping module. A source model that has been developed within VUM for pile driving sound has now been integrated into SORIANT.
- A module for determining effect distances and number of disturbed animals.
- A module for accumulating the disturbance effects due to the construction activities of multiple windfarms (national and international projects).
- Integration with a module for determining the population level consequences for the harbour porpoise, using the Interim PCOD model (developed by SMRU Marine and the University of St. Andrews).

The risk assessment tool has recently been applied during the development of new guidelines for the licensing process for new offshore windfarm developments in the Netherlands (Kader Ecologie en Cumulatie). The effects of planned Dutch as well as surrounding developments have been assessed on the North Sea harbour porpoise population.

The SORIANT risk assessment tool has been set up to be modular and flexible, enabling an easy extension to alternative assessment methodologies for estimating population level consequences, or to different type of sources (e.g. seismic surveys, shipping, dredging, explosions and sonar), or other species (e.g. seals or fishes). Based on the risk assessment framework adopted in SORIANT, key knowledge gaps that have been identified are reported.

Contents

1 Introduction

The Dutch government has set an ambition for sustainable energy by constructing offshore wind farms. In the 'SER-akkoord' (September 2013), a goal has been set to achieve a total of 4450 MW energy operational by offshore wind in 2023.
This could potentially be increased up to 6000 MW in the following years.
The Dutch government is developing mitigation and monitoring requirements in order to reduce the impact on marine life.

Rijkswaterstaat (RWS) has asked TNO to further develop SORIANT (**SO**und **RI**sk **AN**alysis **T**ool) to facilitate the assessment of impact of pile driving activities on marine mammals and to investigate effectiveness of possible mitigation measures. By describing the entire chain from source up to population level impact, SORIANT also serves as a framework to for identifying knowledge gaps as input for the research agenda.

The SORIANT tool is aimed at computing and visualizing impact of pile driving activities on marine mammals. It has been developed to support RWS in the formulation of assessment criteria and the development of legislation by allowing for the evaluation and analysis of different wind farm construction scenarios. The tool can also be used for environmental impact assessment (EIA or MER) studies.

This report describes the implementation of the prototype SORIANT developed during the project "VUM SORIANT", which couples physical aspects of the sound source and propagation with ecological effects. This report provides an overview of the framework used, implemented modules, and examples of applications. A final section is dedicated to knowledge gaps identified in the process of developing and implementing the framework.

The development of the SORIANT tool has been carried out in parallel with several related projects:

- Werkgroep onderwatergeluid – An expert working group has been tasked by RWS from 2013 to early 2015 to develop an assessment framework ecology and accumulation of effects to develop guidelines for new permits (Heinis and de Jong, 2015). The resulting framework, which estimates the impact of multi-year wind farm construction activities on the North Sea harbour porpoise population has been implemented in SORIANT.
- VUM Pile drive source model project (Nijhof et al. 2014): The project "Integratie: bronmodel en propagatiemodel" a high resolution Finite Element Model (FEM) has been further developed to estimate the source properties for different pile configurations (size, strike energy, water depth). Alongside a new propagation model (AQUARIUS 2.0) has been developed that allows for coupling the output of the FEM model to sound maps at large distances from the pile. This model has been integrated into the SORIANT tool.

Currently, SORIANT is focused on pile driving sound occurring during the construction phase of offshore wind-farms. New in the current SORIANT implementation is:

- Integration of the high resolution FEM source model for pile driving.

- Modular approach for sound propagation (different types of sources require different implementations of propagation models).
- Estimation of number of affected animals and duration of effect on animals.
- Accumulation of pile driving activities over multiple wind farms and multiple years.
- Coupling to a population level consequence model (Interim PCOD), which allows for an estimation of the population level effects on marine mammals.

To retain flexibility, the SORIANT risk assessment framework has been implemented in MATLAB, using a text-based user-interface. A wide range of input parameters can be modified, and a suite of propagation models can be selected, depending on the sources and environments that need to be modelled.
This flexibility allows for a better understanding of the sensitivities of the estimated risk to input parameters, and easy adaptation to new insights in legislation.
Due to the large number of parameters that have to be specified, the tool is currently aimed at expert usage. Once input parameters, assumptions and uncertainties in risk assessment models are better understood, simplified versions of the SORIANT tool could be developed for specific applications that would allow for a wider spread usage..SORIANT follows a modular approach, which can easily be extended to other types of sources (e.g. support vessels, deterrent devices during construction, sound during operation/ maintenance and decommission phase), or other offshore activities, such as dredging, seismic surveys, explosions, etc.

Accumulation of pile driving with other activities, such as seismic surveys, is relevant in the context of the Marine Strategy Framework Directive (MSFD).
A noise register of ‘impulsive sound’ (pile driving, seismic surveys, sonar, explosions) has been proposed as Indicator 11.1 for Good Environmental Status (GES), which Europe aims to achieve by 2020 (Dekeling et al. 2013). Examples of initial attempts of accumulating pile driving and seismic survey activities in the North Sea are provided in this report. An outlook on how SORIANT can be extended to accumulate the effects of different types of sources is provided in the section describing knowledge gaps.

2 SORIANT Implementation

2.1 SORIANT Framework

SORIANT is based on a risk assessment and mitigation scheme which was advised by the Marine Board of the European Science Foundation (ESF) (Marine Board - ESF, 2008). This risk-assessment scheme is schematically depicted in Figure 1, which distinguishes between assessing onset of individual responses (e.g. TTS, disturbance) and ecological significance of these responses (e.g. population consequences).

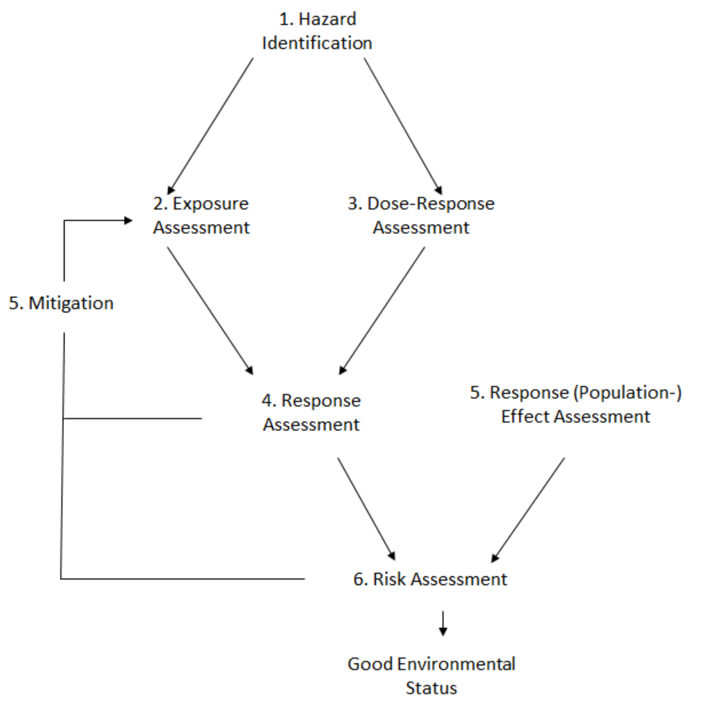

Figure 1 : Risk management approach, adapted from the approach proposed by the Marine Board of the European Science Foundation (ESF. 2008). This extended approach distinguishes between response assessment (e.g. area or number of animals with TTS or behaviourally disturbed) and population level effect (significance of disturbance) (see TNO memo to RWS, dd. 04-06-2013).

The SORIANT tool now is able to cover the entire range from describing the pile driving activity (source properties, duration of construction), sound mapping, computing the effect of distances and duration, and estimating the resulting population level impact due to accumulation of activities (see Figure 2).
The following steps are carried out by SORIANT for harbour porpoises specifically:

1. Computation of sound propagation per driven pile using the AQUARIUS sound propagation model.
2. The area within which animals are disturbed or are at risk of receiving a hearing threshold shift by a pile driving impulse, based on relevant risk thresholds.
3. Computation of the number of disturbed animals, by multiplying the disturbed area by the estimated animal density during the season of the activity.

4. Computation of the number of 'animal disturbance days' for the entire project, while accounting for the seasonal dependence of the animal density and the duration of the disturbance.
5. Computation of the statistic of the development of the population over several years, using the Interim PCOD model, developed by SMRU Marine (see www.smru.co.uk/pcod).

In the current prototype version of SORIANT the capability to process this whole chain (1) – (5) depends on the species considered. The main focus has been on the impact of pile driving on harbour porpoises, because this species was considered an 'indicator species', which was assumed to be most sensitive to pile driving sound (Heinis and de Jong, 2015). For this species, all steps (1) – (5) are implemented in SORIANT. For other marine mammal species, such as harbour and grey seals, steps (1) – (4) are implemented (see Knowledge Gaps section for more details).

Mitigation measures, such as the frequency dependent absorption of different types of bubble screens, are not explicitly modelled in the current version of SORIANT. Instead, generic noise limits can be introduced, and their effect on a population of porpoises can be evaluated. By comparing different scenarios including a normal source, and a source that has been reduced to a specified noise threshold, requirements for mitigation measures (in terms of how much reduction is required) can be established using SORIANT.

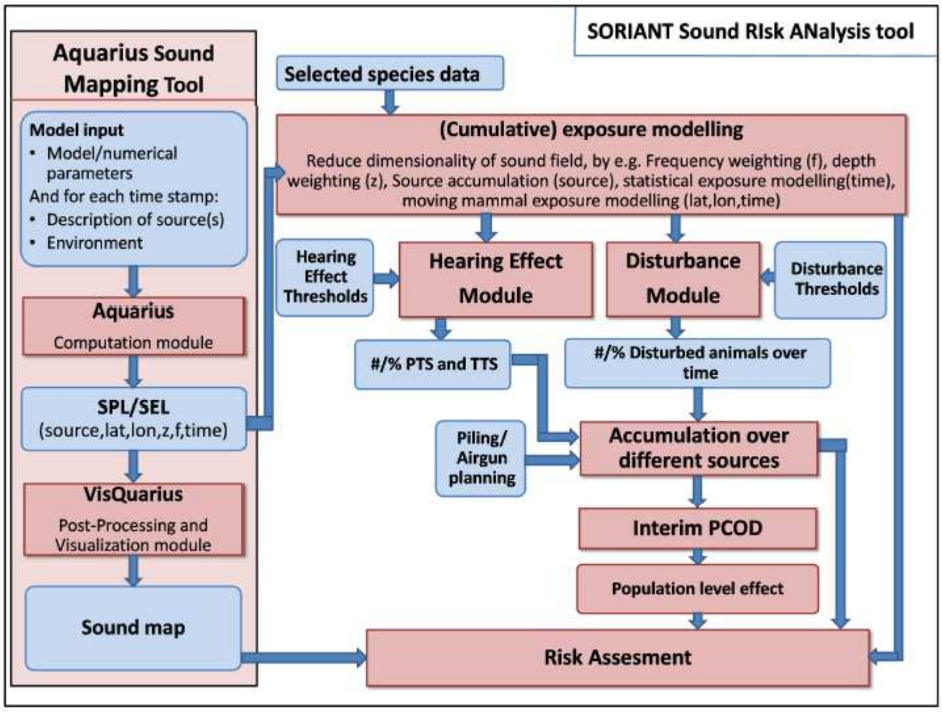

Figure 2 : Implementation of SORIANT framework – modules (red) and interaction between modules. Blue boxes indicate output generated by modules. For a more detailed description of the modules see in Binnerts et al. (2014): source and propagation models (chapter 2) and exposure and assessment modules (chapter 3). Mitigation measures are not yet explicitly modelled (see text for detail).

2.2 Source model and propagation model

Different source models use different 'flavours' of the AQUARIUS sound propagation module. For pile driving sound, the user can choose between two types of source models:

1) An empirically determined effective monopole source level, which can be scaled by a strike energy, which serves as proxy for pile size (Heinis & de Jong, 2015).
   This option provides a very quick estimate for the sound map. However the extrapolation to other piles, is likely resulting in uncertainty in the estimated source properties.
2) A modelled source level using the FEM model (Zampolli et al. 2013, Nijhof et al. 2014), in which the pile geometry, hammer force function, material and sediment properties and water depth need to be specified.
   Currently, only a limited number of pile types have been implemented, and still requires further validation.

A variety of propagation models are implemented in SORIANT (Binnerts et al. 2014), which are listed in Table 1. Some of the models are dedicated to a particular kind of source model, others are more generic and publically available models used to compare/validate faster implementations, or can be used to model other types of sources than pile driving, which allows for future accumulation of sound sources (see Chapter 4 for an outlook on accumulation).

Table 1 : Overview of implemented sound propagation models (from Binnerts et al. 2014).

Name/ References	*Short description*	*Range dependent*	*Bottom loss/ surface loss*	*SSP*
Aquarius 1	A very fast flux based propagation model applicable in shallow iso-velocity water for medium to high frequencies. [Ainslie, 2009b]	Approximates bathymetry with wedges between depth at source, minimum depth and depth at receiver.	Yes/ Yes	No
Aquarius 2	Mode propagation code using a mode lookup table instead of computing the mode shapes for each water depth over and over. Modes are currently computed using [KRAKEN, 2014]. The Aquarius 2 propagation routine is coupled to the FEM pile model through the mode contribution factors.	Staircase approximation, adiabatic assumption	Yes/ Yes	Yes
Aquarius 3	A fast hybrid propagation model based on mode and flux theory. [Sertlek & Ainslie, 2014a] [Sertlek & Ainslie, 2014b]	Staircase approximation, adiabatic assumption	Yes/ Yes	No
Aquarius 4	**Not yet implemented.** As Aquarius 3, but including a correction term for the array directivity, resulting in both a horizontal and a vertical directivity.	Staircase approximation, adiabatic assumption	Yes/ Yes	No
RAM	Parabolic equation model [Jensen, 2011]. Current implementation based on RAM [Collins, 1993]; edited by Mathieu Colin such that it allows parallel computing on multiple CPU cores and inclusion of a bubble layer.	Staircase approximation	Yes/ No	Yes

The empirical pile driving source model (option 1) is used in combination with Aquarius 1 or 3. The high resolution source model (option 2) developed in the “Integratie: bronmodel en propagatiemodel” project has been integrated into SORIANT (Nijhof et al. 2014). Figure 3 shows a schematic view of how the FEM model is used to create sound maps. It was found that the sound field was better predicted when modes were computed with the FEM model, instead of a point source assumption made in option 1 (Nijhof et al. 2014). For this reason a modal decomposition of the predicted FEM sound field is performed , which then allows for computing the sound maps at large distances from the pile driving source using the Aquarius 2. The full methods of the FEM pile source model and the interface with Aquarius 2 are described in detail in Nijhof et al. (2014).

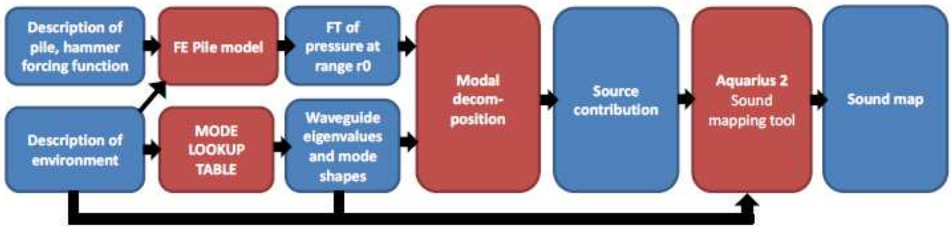

Figure 3 : Schematic picture of coupling FEM source model to the propagation model, used to create sound maps (Nijhof et al. 2014).

2.3 Description of source activities:

The duration of the pile driving activity is required to estimate accumulation and resulting population level impact of the impact. To estimate the duration, the following parameters of a construction site are specified. Because often only generic information is available on future wind farms, it was chosen to specify parameters based on available information (Heinis and de Jong, 2015).

- Location (longitude, latitude).
- Planned wind farm capacity (in MW).
- Capacity per turbine.
- Pile type (monopile, tripod or jacket).
- Number of piles per day (may be < 1, i.e. 1 pile per 2 days to account for replacement of piling platform, etc.).

Using the piling schedule, an estimate can be obtained for the number of days each location (on a longitude-latitude grid) is disturbed per specified period (typically per year, or season).

2.4 Effects of sounds on marine mammals

The SORIANT framework considers two potential effects (see Heinis and de Jong, 2015 for more detail) of sounds on marine mammals:

1) Risk of a hearing threshold shift, which may be temporary (TTS) or permanent (PTS).
   The onset of this effect is assumed to be caused by the (unweighted) sound exposure level, SEL_{cum}, accumulated over all pulses during piling of 1 pile. A species-specific movement model is adopted to account for avoidance, that may reduce the risk of hearing threshold shifts.

2) Risk of significant behavioural disturbance
   The disturbance is assumed to be determined when the single strike, SEL_1, at the location of an animal exceeds a threshold. The SEL_1 may be weighted or un-weighted for frequency, depending on the species considered.

Risk threshold values are specified by the user, which results in depth-dependent effect areas as a function of distance from the pile location. These depth-dependent effect areas can be depth weighted (i.e. mean, or by time spent at different depth) to estimate an depth-weighted effect area.

2.5 Number of affected animals and distribution of disturbance days

The number of animals to be affected per day is computed by taking the product of the depth-weighted effect area with the estimated animal density. Due to limited availability of animal density data, SORIANT currently relies on estimated densities per species per season to be specified by the user for each piling location.

Long-term movement patterns of animals are currently ignored due to the lack of adequate movement models. Such models are currently being developed for harbour porpoises in the North Sea (e.g. Nabe-Nielsen et al. 2014, 2015) or information from tagged animals (seals) could be used to estimate the duration of disturbance for individuals (e.g. Gordon et al. 2015). This however is not yet implemented.

2.6 Estimating population level consequence

Recently, different approaches for estimating population level consequences on marine mammals are being developed (Harwood et al. 2013; Thompson et al. 2013; Nabe-Nielsen et al. 2014, 2015). In consultation with RWS, SORIANT has been interfaced with the Interim PCOD model (Heinis and de Jong, 2015). This model was developed to assess the population level impact of renewable energy activities on different marine mammals species: the harbour porpoise, the harbour seal, gray seal and the minke whale. The interim PCOD model consists of a population dynamics model that is characterized by demographic variables of the population (Harwood et al. 2013). To relate the duration of disturbance to vital rates of animals in the model, the Interim PCoD model used the process of expert elicitation, where experts where asked to judge the probability (and associated uncertainty in their estimate) of a reduction in vital rates for different species and life categories.

The SORIANT model is used to predict the daily number of animals affected for each day of piling for all wind farms in a specified period (e.g. 2016 – 2023), which is then used as input for the Interim PCOD model. This produces a probability distribution of the population size for each modelled year, from which the total cumulative effect can be estimated after the construction activities.

The demographic parameters describing the population dynamics in the Interim PCOD model, are species and location specific. They also implicitly include any potential effects of activities producing loud impulsive sound (e.g. seismic exploration, underwater explosions) that have occurred during past years, so it is mainly suited for assessing the population level consequence of activities that introduce new pressures, such as pile driving activities. It can therefore not be directly applied to seismic surveying or underwater explosions, as these activities have been carried out in past years as well.

2.7 Software implementation

The SORIANT framework has been implemented in Matlab © 2012a software. For running the Interim PCOD module (v 2.1), it is also required to install the R-studio environment (v3.1). Due to the rapid evolution of the SORIANT risk assessment framework, the implementation is text-based, and aimed at expert users. Computational requirements depend on the complexity of the problem. Effect distances for a single pile can be computed on a standard desktop (Windows 7, Intel Core i5 CPU, 4 GB RAM) within approximately 1 hour. However, an international scenario with multiple windfarms operation requires approximately a day on a relatively high performance desktop (Windows 7, Intel Core i7 CPU, 32 GB RAM).

2.8 Data requirements

The environmental and ecological databases given in the table below define the Bathymetry, sound speed profile, wind speed (surface properties), and sediment (bottom characteristics) on a global scale, and animal distribution and sensitivity data.

Database source	***Short description***
Geophysical/meteorological database	
Etopo1	Bathymetry database [Etopo1, 2014]
Gebco08	Bathymetry database [Gebco_08, 2014]
SRTM 30+	Bathymetry database [SRTM30+, 2014]. Bathymetry used in google maps and google earth.
EMODNET-SRTM30	Bathymetry database. As SRTM 30+; but merged with a high resolution bathymetry of various seas around Europe available from [Emodnet, 2014].
KNMI Wind speed database	Monthly, seasonal or yearly averaged wind speed at 10m in m/s. [KNMI, 2014]
World ocean atlas (WOA) [World Ocean Atlas, 2013]. Data currently implemented in sound mapping tool dates from 2009.	Sound speed profile of water at world ocean atlas depths.
	Temperature in Celcius of water at world ocean atlas depths.
	Salinity in parts per million of water at world ocean atlas depths.
Sediment properties	**Sediment properties database not yet included. Possible sources are:** **http://www.ngdc.noaa.gov** **http://www.emodnet.eu/geology**
Ecological databases	
Animal sensitivity database	Animal sensitivity thresholds for risk of hearing effects (TTS, PTS) and behavioural disturbance due to pile driving sound are currently set in parameter-file.

Animal distribution data	**Seasonal mammal and fish distribution not yet available/ Require to be specified by user per operation site**
Demographic database	Variables (for modelling the population dynamics e.g. vital rates, population size, effect of disturbance on vital rates) of different North Sea marine mammal species with the Interim PCOD model are specified in the statistical tool R© modules for each species.

3 Example applications of SORIANT

This chapter provides a brief overview of different applications, and types of outputs that can be achieved with the new version of SORIANT.

3.1 Estimating risk of permanent threshold shifts

The risk of hearing threshold shifts (and related risk of injury) due to the accumulated sound exposure of pile driving is estimated using an animal response model. This model is used to explore the influence of parameter choices (responsiveness, type of soft-start) on effect distances predicted for harbour porpoises (Figure 4). Figure 4 shows how the cumulative sound exposure level SEL_{cum} for the complete period of pile driving varies with distance, including the effect of a soft start. The estimated cumulative SEL can then be compared to effect distances of acoustic deterrent devices to assess the reduction in risk of PTS (red horizontal line).

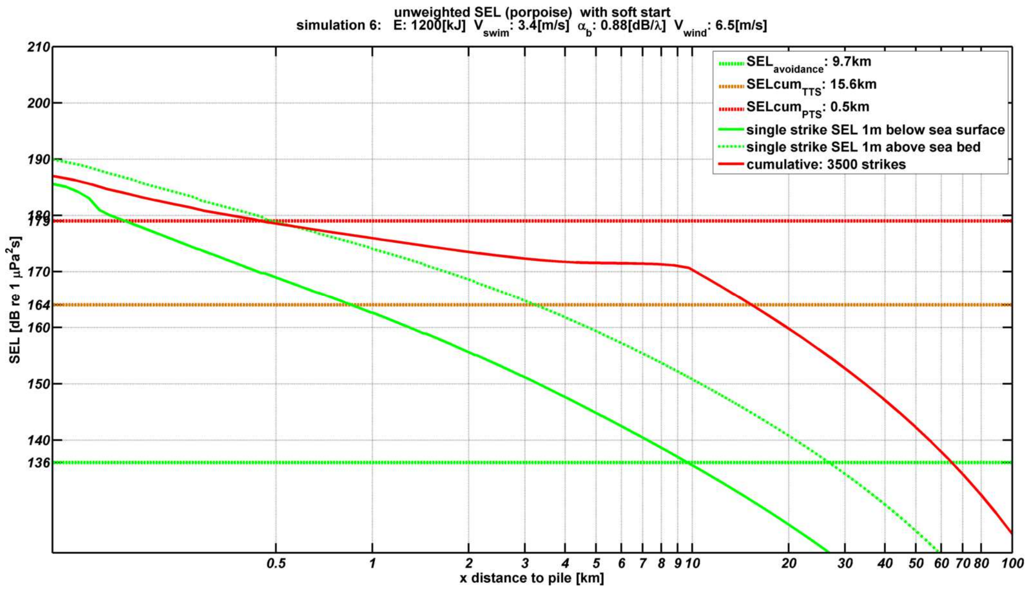

Figure 4 : Modelled effect distances for harbour porpoises resulting from a single pile driving event, including the effect of animal response, and soft-start (de Jong, unpubl.). The green lines indicate the single strike SEL_1 for an animal close to the sea surface (solid) and bottom (dashed). These can be compared to the threshold for avoidance response (solid horizontal green line). The red curve shows the cumulative SEL_{cum} over the total number of strikes for a single pile. These are compared to SEL thresholds for TTS and PTS (orange and red horizontal lines) to determine effect distances for hearing effects.

3.2 Sound maps using a high resolution source model

The FEM model for the pile source developed in the “Integratie: bronmodel en propagatiemodel” project has been integrated into SORIANT and can be used to generate sound maps, in a similar fashion to maps generated with the empirical source model (see Figure 5). Once the FEM source model has been fully validated, this allows for a realistic modelling of piles of various characteristics (e.g. size, effect of bottom depth/properties) on computed effect distances.

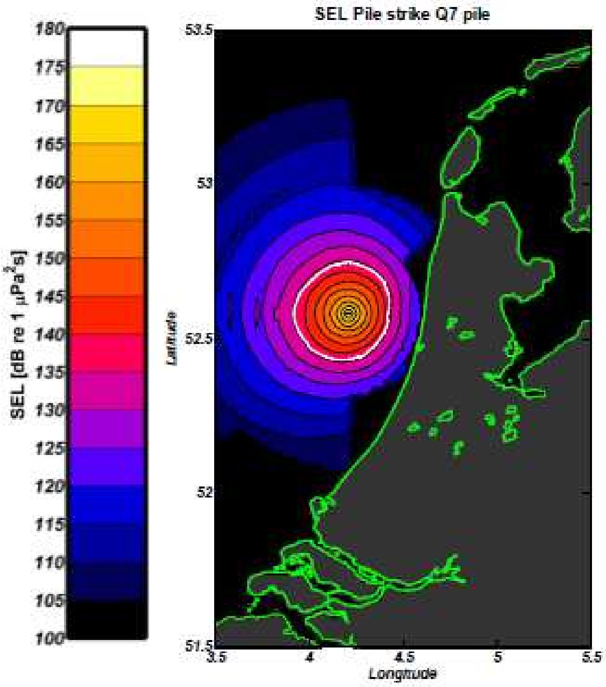

Figure 5 : Unweighted SEL at 1m above the bottom due to a typical hammer strike on a pile in the North sea. A contour of SEL_1 = 136 dB re 1 μPa^{2}s contour is plotted in white, to illustrate the area in which, for example, harbour porpoises may be disturbed by the underwater sound (Nijhof et al. 2014).

3.3 Sound maps for multiple wind farm construction activities in the North Sea

Effect distances can now be computed for a large range of scenarios, allowing for an assessment of the cumulative impact of multi-year construction activities. Figure 6 shows an example of the pile driving effect distances computed for all wind farm construction sites in a one-year period from the international scenario considered in the “Werkgroep Onderwatergeluid” (Heinis and de Jong, 2015). Overlapping effect distances of different wind farm locations illustrate the potential of cumulative disturbance in some areas due to different wind farm construction sites throughout a year.

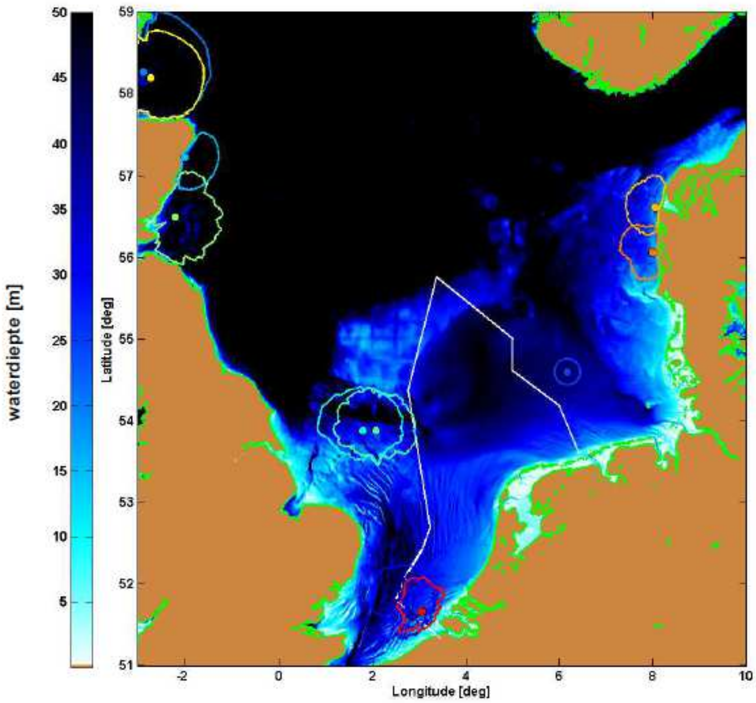

Figure 6 : Example of computed disturbance areas for the one year period due to wind farm construction activities in the North Sea (Heinis and de Jong, 2015).

3.4 Population level consequences of disturbance using the Interim PCOD model

An international multi-year scenario was constructed by the 'Werkgroep onderwatergeluid' which is illustrated in Figure 7. By combining the duration of construction with the effect distances (e.g. Figure 6), the number of behaviourally disturbed animals per day was estimated, which was then used as an input to the Interim Population Consequences of Disturbance (PCOD) model, which has recently been developed by SMRU Marine and University of St. Andrews (Harwood et al. 2013). This then predicted the evolution of the harbour porpoise population in the North Sea, thereby quantifying the effect of behavioural disturbance on a population level (Figure 8). Figure 8 shows the probabilities of reduction in population size of the North Sea harbour porpoise predicted by the stochastic population dynamic model in Interim PCOD. The reduction is expressed as the number of animals at any time relative to the an undisturbed population that has been evolved under the same assumptions. This allows for assessing the additional effect of the pile driving activities on the population (Harwood et al. 2013).
By comparing the population level effect of different scenarios, the effectiveness of different mitigation measures (timing and duration of construction, norm in radiated sound exposure) can be investigated.

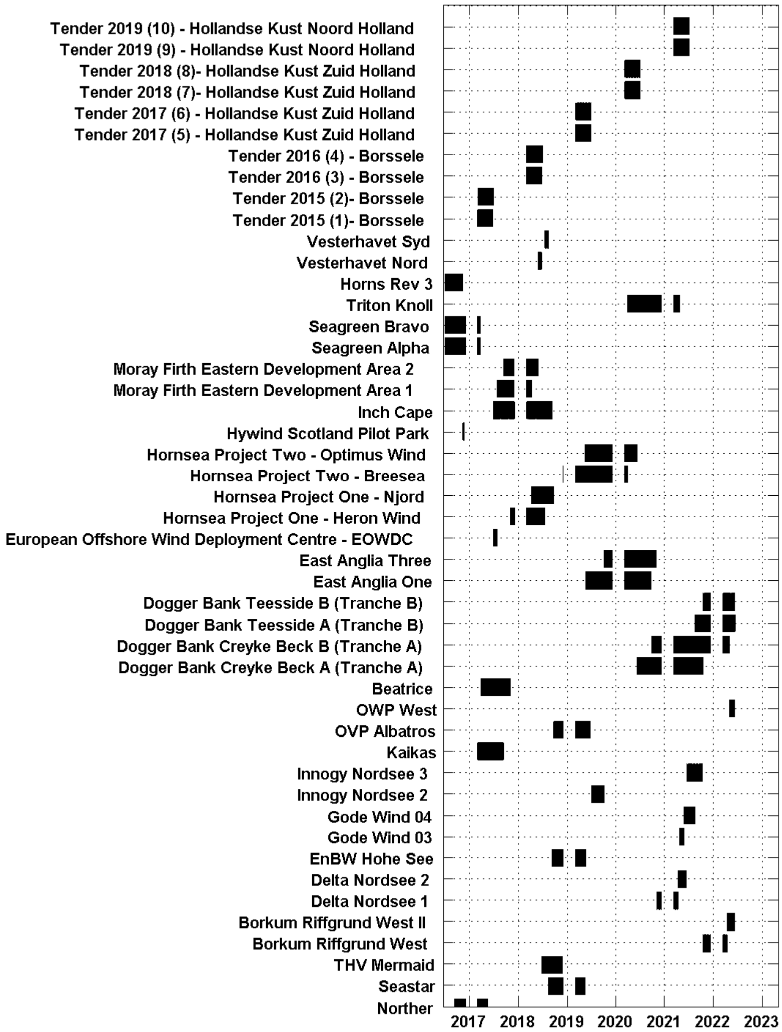

Figure 7 : Example time schedule generated by SORIANT for an international scenario of wind farm constructions in the North Sea. The black bars indicate days of piling. Piling was assumed to be halted during the winter.

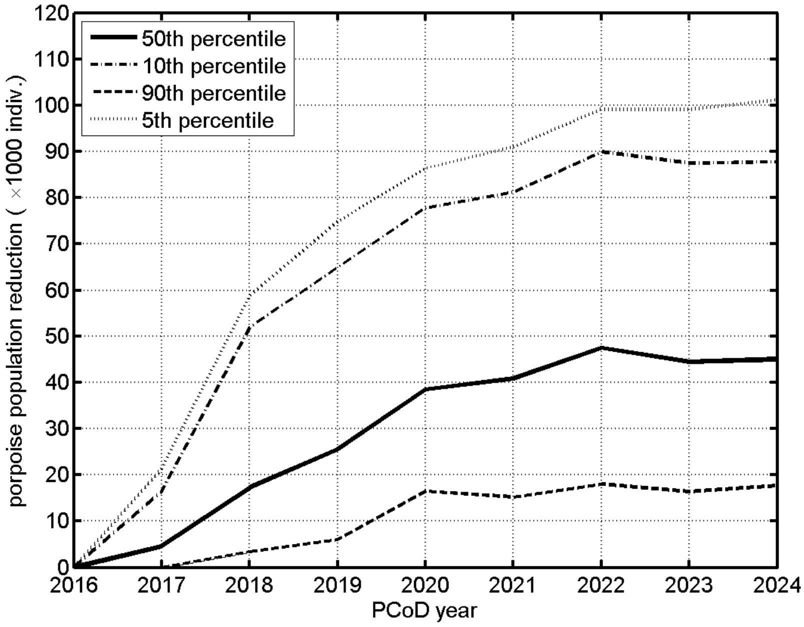

Figure 8 : Illustration of output generated by the Interim PCOD model, which has been interfaced with SORIANT. Shown is the modelled reduction population resulting from the international scenario considered by the 'Werkgroep onderwatergeluid' (Heinis and de Jong, 2015).

3.5 Disturbance maps for noise register to support MSFD

To enable an assessment whether EU Member States have achieved Good Environmental Status, it has been proposed to set up a register of the occurrence and intensity of sound sources producing impulsive sounds (van der Graaf et al. 2012). The density of activities producing loud underwater sound has been proposed to visualize trends in sound producing activities and allow for assessing cumulative effects of multiple impulsive sound sources.

To support the interpretation of the noise register, SORIANT could be used to generate maps of the spatial distribution and intensity of behavioural disturbance (instead of the intensity of the activity that produces the underwater sound). Here the effect, in this case disturbance, is accumulated, rather than the sound produced by the activities. The advantage of using these maps over a map of the intensity of the activity itself, is that the size of the disturbance areas is accounted for, which allows for a more straightforward link to impact on marine life.

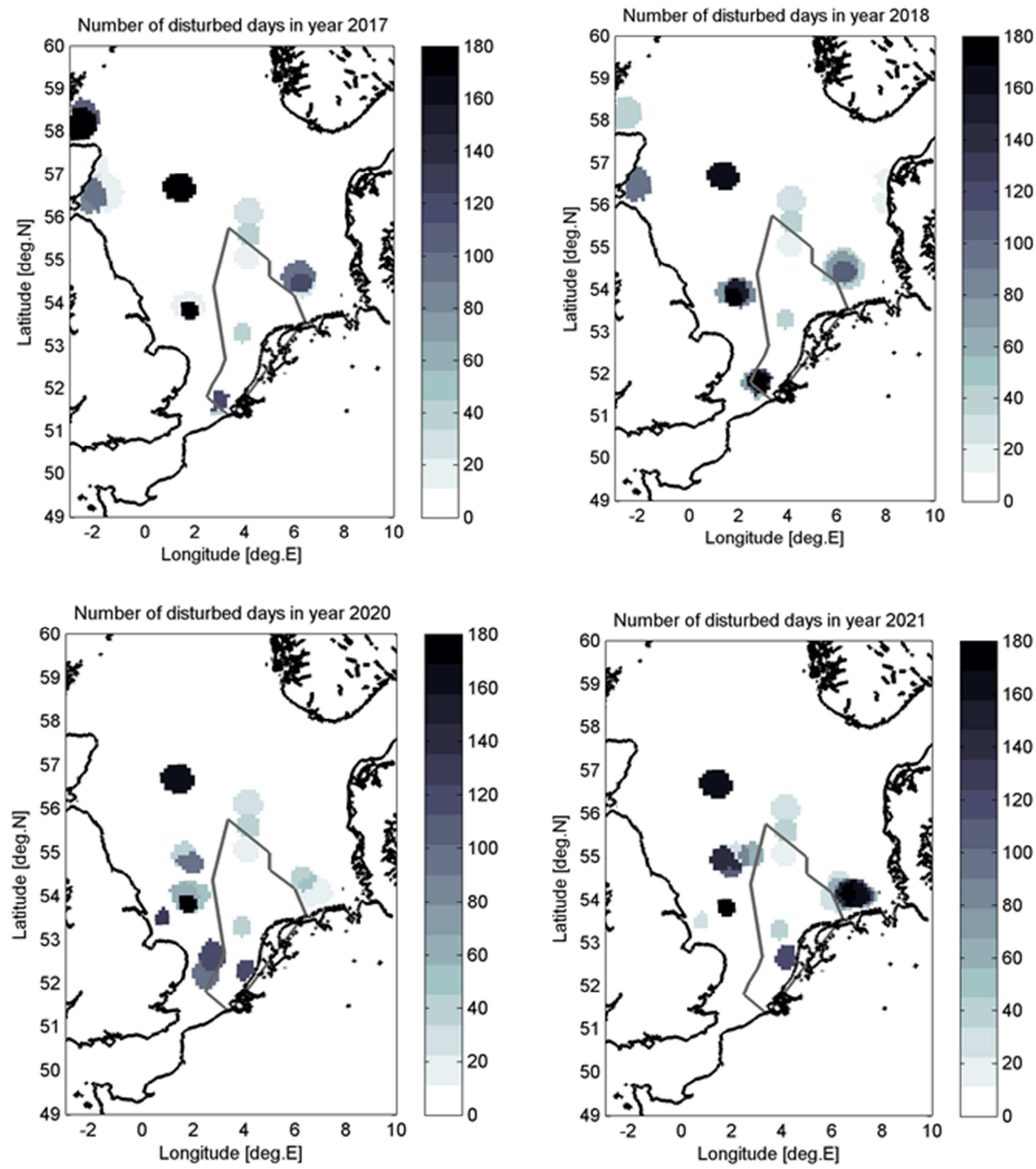

Figure 9 : Example of disturbance maps of pile driving and seismic survey activities generated by SORIANT, which is based on an international multi-year pile driving scenario considered by the 'Werkgroep onderwatergeluid' (Heinis and de Jong, 2015). The gray scales indicate the number of days per year that each location the single strike SEL_1 due to pile driving or seismic surveys exceeds 140 dB re 1 $\mu Pa^2 s$, which is adopted as a threshold for behavioural disturbance in Heinis and de Jong, 2015.

An example of such maps is shown in Figure 9, which is based on the international scenario considered by the 'Werkgroep onderwatergeluid' (Heinis and de Jong, 2015). Here the intensity of the disturbance is measured by the number of disturbance days per year, where each location is considered to be disturbed when it is within the effect distance to at least one activity involving impulsive sound. Disturbance was assumed to occur when the SEL_1 > 140 dB re 1 $\mu Pa^2 s$, which is appropriate for harbour porpoises (Heinis and de Jong, 2015), and also proposed as a limit for adopting sources in the EU noise registry (Dekeling et al. 2013). These maps account for potential spatial-temporal overlap of different activities, thus avoiding double-counting of individual effects during the accumulation. By overlaying these maps with animal density maps, or individual-based modelled animal tracks, these maps can be converted into number of animal disturbance days, which appear to be well correlated with the population level effect predicted with the Interim PCOD model (Heinis and de Jong, 2015).

Examples as shown in Figure 9 are useful to visualize the accumulated effect of different sources, and could provide a practical interim management tool for planning noise producing activities when information to assess population level effects is absent. For instance, using maps such as shown in Figure 9 hotspots with long-term disturbance could be identified, as well as potential blocking of migration routes, or overlap with protected/sensitive areas.

4 Knowledge gaps

The understanding of impact of pile driving noise on marine life is a dynamic and quickly developing field. For this reason a modular approach was adopted for SORIANT, that is flexible and generic enough to allow it to evolve with new knowledge becoming available. Recently, a set of knowledge gaps were identified for the effects of wind farm construction marine life (Masterplan 2.0, 2015).

The knowledge gaps identified in Masterplan 2.0 that relate to SORIANT were:
- Are there new models or data that are relevant for implementation in the SORIANT tool?
- Validation of the propagation of sound due to pile driving, by the use of data collected in recent and already planned measurements.
- How can we extend the current implementation of SORIANT for other species (seals and fish)?
- How can we harmonize the SORIANT implementations for various sources of impulsive sound (piling, seismic exploration, explosions) to support the MSFD implementation?

The following sections briefly address these issues in more detail.

4.1 New data and models relevant for implementation in the SORIANT tool

4.1.1 Validation of pile driving source model and sound propagation

The high resolution FEM source model requires further validation. Benchmarking of different model approaches and comparison to a measured pile has been performed during the COMPILE workshop (Nijhof et al. 2014). However, there is a need to compare to different types of piles in different environments and a need to compare model predictions to measurements obtained out to larger distances (>> 5 km). Once validated, the FEM source model can then be used to model different types of piles in different environments. Source characteristics derived from these models could be stored in a database, to allow for a quick computation using a long-range propagation model (Aquarius 4). This would enable an exploration of the range of pile parameters that fit in the required boundary conditions set by the regulating authority (Heinis and de Jong, 2015).

4.1.2 Harbour porpoise density data

The current SORIANT version requires manual input of site-specific density information, because of limited availability of up-to-data animal density databases. For harbour porpoises, seasonal dependent density information is collected from aerial surveys (e.g. Geelhoed et al. 2012; Aarts et al. in prep) which could be incorporated into the model. Methods to statistically overlay density information with sound exposure maps are being developed that may be used to estimate the number of animals affected by hearing effects (e.g. Aarts et al. in prep; von Benda-Beckmann et al., 2015, submitted).

4.1.3 Effect of pile driving sound on harbour porpoise hearing sensitivity

Current estimates of risk of PTS due to pile driving (Heinis and de Jong, 2015) are based on TTS-onset measurements due to a single air-gun exposure (Lucke et al. 2009). Recent measurements by Kastelein et al. (2015) show higher SEL threshold levels for TTS-onset due to intermittent playback of pile driving sound than those measured by Lucke et al. (2009). In addition, recent work by Tougaard et al. (2015) suggests that the frequency content of the sound needs to be accounted for when estimating the risk of TTS. These recent studies need to be evaluated to assess the consequence for PTS thresholds adopted for predicting hearing effects of pile driving sound on the hearing of harbour porpoises.

4.1.4 Population consequence models for behavioural disturbance

Assessing population level effects of underwater sound on marine life is currently at its infancy. Models are being developed for marine mammals (Harwood et al. 2013; Thompson et al. 2013; Nabe-Nielsen et al. 2014), however these still rely on a wide range of assumptions and expert judgments. Also, these models contain uncertainty in density estimation, movement behavior and vital rates, and exist only for a limited number of species.

Thus, a wide range of scenarios need to be considered to understand the sensitivity of such models to input parameters and assumptions. Input parameters to which the Interim PCOD model seemed sensitive in the context of harbour porpoises, and which are still not well quantified, are (Heinis and de Jong, 2015):

- Size of vulnerable subpopulation
- Habitat usage
- Duration of disturbance for individual animals
- Effect of disturbance of vital rates
- Effect of distance to source on level of disturbance (vs fixed SEL threshold)

The assessment of population level effects is an international challenge. Therefore, international collaboration between nations and research institutes is seen as a key factor to move this field forward, for instance to compare, develop and refine risk assessment models such as SORIANT, and to develop effective monitoring strategies to reduce uncertainties on these parameters.

The DEPONS model, an agent-based population consequence model, has been developed by the University of Aarhus (Nabe-Nielsen et al. 2014; van Beest et al. 2015) to assess the effect of wind farm construction, and operational noise on the population of wind farms. The model relies on knowledge of movement behaviour of harbour porpoises, prey availability, and response to pile driving noise, which have been based on observations where possible. However, the model does not yet contain acoustic modeling of individual wind farms, but currently relies on a generic effect distance which has been applied to all wind farm construction sites considered.

It would be useful to compare the Interim PCOD and DEPONS approaches, and to update the expert judgments used in the Interim PCOD approach, to better understand the influence of underlying assumptions on the estimated population level effect, and to harmonize international efforts of estimating cumulative effects of wind farm construction activities on the North Sea harbour porpoise.

4.2 Extend framework to seals and fish

The SORIANT risk assessment module is set up generically to easily adapt different thresholds for species other than harbour porpoises, which are mainly gray and harbour seals, as well as fish species.

A proposal for estimating the population level effect of pile driving sound on harbour and gray seals, in line with the approach adopted here for harbour porpoises, is described in detail in Heinis and de Jong (2015).

Sound effects on fish are qualified as an overall knowledge gap, and open research questions regarding effects of sound on fish, as well as potential population level consequences, are summarized in the Masterplan 2.0 (Masterplan 2.0, 2015).

4.3 Harmonization of implementations for various sources of impulsive sound

4.3.1 Modeling different sound sources

Different projects have been carried out, or are in progress, that can eventually lead to the incorporation of different sound sources into SORIANT:

- Seismic sources – an internal TNO project aimed at the development and implementation of a seismic source and propagation model (Binnerts et al. 2014) has been carried out in 2014. Here the source characteristics, computed by models used in the seismic industry, are converted into an effective point-source model so that they can be used in shallow water propagation models.
- Seismic sources – a new seismic array source model has been developed by Sertlek and Ainslie (submitted) that allows for modelling various array configurations.
- Underwater explosions – an impact assessment of underwater explosions on the North Sea harbour porpoise was carried out for the Netherlands Ministry of Defence (von Benda-Beckmann et al. 2015, submitted, Aarts et al. in prep).
- Shipping – The SONIC project funded by the EU aims to develop tools to investigate and mitigate the effects of underwater sound generated by shipping (http://www.sonic-project.eu/).

This work has made it possible to produce sound maps for different types of sources, such as pile driving, shipping, dredging, seismic surveying, underwater explosions. The source models, and the appropriate propagation models, are summarized in Figure 10.

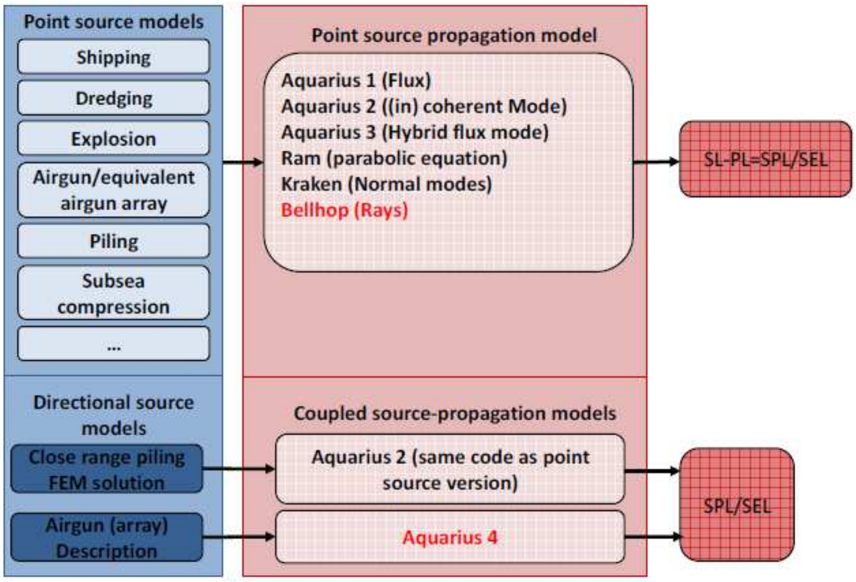

Figure 10 : Overview of connection between source and propagation models producing sound maps.

The main challenges of modeling these sound sources are as follows:

Seismic surveys:

- Validate airgun source and array model, and interface with propagation model and propagation of airgun. The main uncertainties in the airgun source model are caused by modeling of the bubble-bubble interactions and variability in high frequency output in horizontal direction, which is caused by movements of the airguns (e.g. Sertlek and Ainslie, 2015).
- The long range propagation (distances >> several km) of impulsive sound still requires experimental validation. Due to differences in source characteristics of pile driving (vertical line sources, direct contact with bottom) and seismic sources (multiple interacting bubbles, close to surface), seismic sources likely require a separate validation approach.
- Sound and disturbance maps are currently generated assume single shot location for determining disturbed area (Heinis and de Jong, 2015). The realism of the models should be extended to realistic track-lines (2D, 3D, coil, etc.) and different shooting methods (paired shots, pop-corn, etc.), and marine vibrator sources.
- Model animal response to moving seismic source and its effect on predicted cumulative SEL and resulting risk of TTS and PTS. Little is known on when (what levels) and how animals respond to an approaching seismic source. The responsiveness and movement pattern can have a big influence on the predicted risk of TTS and PTS (e.g. von Benda-Beckmann et al. 2014, Wensveen et al. 2015).
- Dose-response relationships for airgun sound for hearing effects (TTS, PTS) as well as behavioural disturbance. Current estimates of hearing effects due to pile driving rely on sensitivity to a single air-gun exposure (Lucke et al. 2009, Heinis and de Jong, 2015). However, recent studies by Kastelein et al. (2014) show that duty cycle of multiple pulses affects the risk thresholds for TTS in harbour porpoises. Therefore, exposures studies of multiple airguns with realistic duty

cycles are required to better estimate the risk of hearing effects in harbour porpoises and seals.
- Analogous to pile driving sound, the relation between degree of disturbance, and SEL and other contextual variables (such as distance to the source) are poorly understood.

Explosions:
- Validation of long-range (>> 2 km) propagation of explosion sound.
- Potential of behavioural responses due to single explosion events.
- Risk thresholds for injury and hearing effects for seals/fish/other species.

For ship-/dredging noise:
- Dose-response relationships for behavioural disturbance for continuous, low frequency sound.
- Relationships between continuous sound (e.g. due to continuous sound sources, or due to elevated noise levels due to distant impulsive sound sources) and potential chronic effects (e.g. masking, stress). Very little is known about the masking potential for marine mammals and fish, which makes it hard to interpret the ecological consequence of shipping and dredging sound at larger distances from the source.
- Fish are likely to be more sensitive to particle velocity than sound pressure level at lower frequencies. If sound maps are to be used to estimate effects on fish, there is a need to model the particle motion as well as sound pressure levels generated by these sound sources.
- Improved ship source level models (speed-, and ship class-dependence).

4.3.2 *Accumulation of effects*

The main challenges of accumulating effects of different sound sources depend on the effect that is considered. The focus of the EU is at assessing the cumulative effect of larger scale behavioural disturbance due to impulsive sound sources (seismic surveys, pile driving, explosions, sonar). A natural quantity for accumulating the effect over periods longer than a day, is the total duration of the disturbance rather than the sound level itself.

Figure 9 shows an attempt to accumulate effects of seismic and pile driving sound, by showing the geographical distribution of the number of disturbance days per year. However, a somewhat arbitrary choice was made on how short disturbances are accumulated. In this case, any disturbance lasting less than one day (i.e. a pile driving event of 2 hours) was counted as one day of disturbance. This method does not consider the possibility of multiple exposures of moving animals during the same day. It remains unclear how long individual animals are being disturbed by sound producing activities. This will depend on the movement behaviour of the animal, its responsiveness to the sound source, the possibility of habituation to the sound. More field studies are required that address the duration of disturbance for individual animals to different types of sources.

The duration of the disturbance is also used as basis for PCOD models to estimate the population level consequences. One of the challenges encountered when applying this model to seismic surveys was that the Interim PCOD model relied on a choice of demographic parameters (i.e. mortality rate), which had been based on harbour porpoise density information prior to the start of relatively new activities

such as pile driving for wind farm construction (Heinis and de Jong, 2015).
Other activities, such as seismic surveying and underwater explosions, have been going on for the past decade. Any potential effect these may have, is already implicitly accounted for in assumed mortality rate in the Interim PCOD model.
It is therefore not straightforward to interpret the outcome when these effects are explicitly used as an extra stressor in the Interim PCOD model. It could be explored, whether the contribution of the seismic and explosion activities could be estimated during the baseline period (the past decade during the first two SCANS surveys (Hammond et al. 2013), which were used to determine the demographic parameters), and re-estimate the demographic variables by explicitly modeling the contributions of seismic surveys and explosions in the Interim PCOD model.

5 Conclusion

A sound risk analysis tool (SORIANT) has been developed with the aim of assessing the environmental impact of underwater sound generated by offshore wind farm construction involving pile driving. New elements that were implemented in SORIANT during the course of the VUM-SORIANT project funded by RWS are:

- Integration of the high resolution FEM source model.
- Implementation of a modular approach for sound propagation (different types of sources require different implementations of propagation models), so that SORIANT can be easily extended to include other sound sources.
- Estimation of the number of affected animals and duration of effect.
- Accumulation of pile driving activities over multiple wind farms and multiple years.
- Coupling to population level consequence model (Interim PCOD), which allows for an estimation of the population level effect of pile driving activities on harbour porpoises.
- Mapping of disturbance, enabling the accumulation of effects due multiple impulsive sound sources such as pile driving and seismic surveying.

The prototype SORIANT framework is now able to model the whole chain of events from the source to the population level effects for harbour porpoises. Scenarios for wind farm development plans over multiple years in the North Sea can be defined and evaluated. By comparing the cumulative effect of disturbance under different scenarios (seasonal restriction, or under different noise thresholds at pre-described distance from the source), different guidelines can be compared and their effectiveness can be evaluated. This has been applied in the development of new guidelines for licensing of wind farm construction (Heinis and de Jong, 2015).

Due to the combined recent efforts sound maps can now be produced for a wide range of sources that produce impulsive sound (pile driving, seismic surveys, explosions) and continuous sound (e.g. shipping, dredging). However, the source and propagation models for these different types of sources still need various degrees of validation, and integration into the SORIANT tool. Key knowledge gaps to improve the realism for these sources have been summarized, and also challenges to assess impact on other species than the harbour porpoise, such as seals and fish. During the VUM-SORIANT project and the RWS funded activities for the ‘Werkgroep Onderwatergeluid’, first steps have been taken to accumulate effects due to different source types over longer periods.

The assessment of population level effects for many species is an international problem. Therefore, international collaboration between nations is seen as a key to move this field forward, for instance to compare, develop and refine risk assessment models such as SORIANT.

Due to the large number of parameters that have to be specified, the SORIANT tool is currently aimed at expert usage. Once input parameters, assumptions and uncertainties in risk assessment models are better understood, simplified versions of the SORIANT tool could be developed for specific applications that would allow for a wider spread usage.

6 References

Aarts, G., von Benda-Beckmann, A.M., Lucke, K., Sertlek, S.O., van Bemmelen, R., Verboom, W.C., Kastelein, R.A., Ketten, D.R., Lam, F.P.A., Geelhoed, S., and Ainslie, M.A., and Kirkwood, R., Movement behaviour influences population level exposure to underwater sound: impact of explosions on harbour porpoises. In preparation.

Benders, F. P. A., van der Zwan, T., Ainslie, M. A., Verboom, W. C. and te Raa, L. A. (2009). SAKAMATA: Concepts and algorithms. TNO report TNO-DNV 2009 A611.

Binnerts, B., Krom, P.P.J. de, Benda-Beckmann, A.M. von, Giodini, S., Nijhof, M.J.J., Jong, C.A.F. de, Ainslie, M.A., Raa, L.A. te (2014). Aquarius and SORIANT model description. TNO report TNO 2014 R11881, p. 27.

Dekeling, R.P.A., Tasker, M.L., Ainslie, M.A., Andersson, M., André, M., Castellote, M., Borsani, J.F., Dalen, J., Folegot, T., Leaper, R., Liebschner, A., Pajala, J., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Van der Graaf, A.J., Werner, S., Wittekind, D., Young, J.V.,(2013). Monitoring Guidance for Underwater Noise in European Seas - 2nd Report of the Technical Subgroup on Underwater noise (TSG Noise). Part II Monitoring Guidance Specifications. Interim Guidance Report. May, 2013.

de Jong, C.A.F. (2013). Berekeningen en advies onderwatergeluid voor heiwerkzaamheden Offshore Windpark Q4-West. TNO memo TNO-060-DHW-2013-00852.

Geelhoed, S., Scheidat, M., and van Bemmelen, R. (2013) Marine mammal surveys in Dutch waters in 2013," IMARES report C027/14 (2011).

Giodini, S., and Ainslie, M.A. (2013). Wintershall - SEL study for two small arrays and one low pressure array, 21 August 2013, TNO-060-DHW-2013-02097.

Hammond, P.S., Macleod, K., Berggren, P., Borchers, D.L., et al. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management, Biological Conservation, Volume 164, 107-122.

Harwood, J., S. King, R. Schick, C. Donovan and C. Booth (2013). "A protocol for implementing the interim population consequences of disturbance (PCOD) approach: quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations," report SMRUL-TCE-2013-014. Scottish Marine and Freshwater Science 5(2)

Heinis, F., and de Jong, C.A.F. & Rijkswaterstaat Underwater Sound Working Group (2015). Cumulative effects of impulsive underwater sound on marine mammals. TNO report TNO 2015 R10335-ENG.

Kastelein, R. A., Gransier, R., Marijt, M. A.T., and Hoek, L. Hearing frequencies of a harbor porpoise (Phocoena phocoena) temporarily affected by played back offshore pile driving sounds. J. Acoust. Soc. Am. 137 , 556-564.

Marine Board - ESF (2008). The effect of anthropogenic sound on marine mammals - A draft research strategy. Position paper.

Masterplan 2.0 (2015). Monitoring and researching ecological effects of Dutch offshore windfarms, Masterplan 2.0. Arcadis, Draft Report, dd 27-05-2015.

MSFD (2008). Establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), Official Journal of the European Union.

van der Graaf, A. J., Ainslie, M. A., Andre, M., Brensing, K., Dalen, J., Dekeling, R. P. A., Robinson, S., Tasker, M. L., Thomsen, F. and Werner, S. (2012). European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES. Report Technical Subgroup on Underwater noise and other forms of energy, 1-75.

Nabe-Nielsen, J. Sibly, R.M., Tougaard, J., Teilmann, J. and Sveegaard, S. (2014) Effects of noise and by-catch on a Danish harbour porpoise population. Ecol. Modell. 272, 242–251.

Nijhof, M.J.J., B. Binnerts, C.A.F. de Jong, and M.A. Ainslie. (2014a). An efficient model for prediction of underwater noise due to pile driving at large ranges, Proceedings of Internoise 2014, Melbourne, Australia, 2014.

Nijhof, M., Binnerts, B., Ainslie, M., and de Jong, C. (2014b). Integration source model and propagation model, TNO Report TNO 2015 R10186, 1- 59.

Sertlek, H.Ö., and Ainslie, M.A. (*2015*). AIRGUN SOURCE MODEL (AGORA): Its Application For Seismic Surveys Sound Maps In The Dutch North Sea, UAC 2015, conference proceedings of UAC 2015.

Snoek, R.C., Impulse register: visualization, Arcadis Memo to OSPAR ICG-Noise, 4 March 2015.

Thompson, P.M., G.D. Hastie, J. Nedwell, R. Barham, K.L. Brookes, L.S. Cordes, H. Bailey and N. McLean (2013). Framework for assessing impacts of pile-driving noise from offshore wind farm construction on a harbour seal population," Environ. Impact Assess. Rev. 43, 73–85.

Tougaard, J., Wright, A.W., Madsen, P.T. (2015). Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises, Marine Pollution Bulletin, 90, 1–2, 196–208.

van Beest, F.M, Nabe-Nielsen, J., Carstensen, J., Teilmann, J. & Tougaard, J. (2015). Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS): Status report on model development. Aarhus University, DCE – Danish Centre for Environment and Energy, 43 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 140

von Benda-Beckmann, S., and te Raa, L. (2013). SORIANT risk management framework & tool design considerations, memo to RWS, dd. 04-06-2013.

von Benda-Beckmann, A. M., Benders, F. P. A., te Raa, L. A., and Ainslie, M. A. (2012). SAKAMATA 3: Risk assessment model. TNO 2010 A428.

von Benda-Beckmann, A.M., Aarts, G., Sertlek, O., Lucke, K. Verboom, W.C., Kastelein, R.A., Ketten, D., Bemmelen, R. van, Lam, F.P.A., Kirkwood, R., and Ainslie, M.A. (2015). Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (Phocoena phocoena) in the Southern North Sea, *submitted to Aquatic Mammals*.

von Benda-Beckmann, A.M., Aarts, G., Lucke, K. Verboom, W.C., Kastelein, R.A., Sertlek, O.,Ketten, D..Bemmelen, R. van, Wees, R.M.M. van. Giodini, S., Geelhoed, S.C.V., Kirkwood, R., Lam, F.P.A., and Ainslie, M.A., Assessment of impact of underwater clearance of historical explosives by the Royal Netherlands Navy on harbour porpoises in the North Sea, TNO Report TNO 2014 R10916, 1- 139.

von Benda-Beckmann, A.M., Wensveen, P.J., Kvadsheim, P.H., Lam, F.-P.A., Miller, P.J.O., Tyack, P.L., Ainslie, M.A., 2014. Modeling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. Conserv. Biol. 28, 119-128.

Wensveen, P.J. von Benda-Beckmann, A.M., Ainslie, M.A., Lam, F.P.A, Kvadsheim, P.H., Tyack, P.L., Miller, P.J.O. (2015). How effectively do horizontal and vertical response strategies of long-finned pilot whales reduce sound exposure from naval sonar?, Marine Environmental Research, 106, 68-81.

Zampolli, M., Nijhof, M. J., de Jong, C. A., Ainslie, M. A., Jansen, E. H., Quesson, B. A. (2013). Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving. Journal of the Acoustical Society of America 133(1), 72-81.

7 Signature

Den Haag, June 2015

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