REPORT

Inventory and assessment of models and methods used for describing, quantifying and assessing cumulative effects of offshore wind farms

Applicable for a selection of representative species

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Author's note:

The preparation of this report was assigned by Rijkswaterstaat Zee & Delta, on behalf of the Environment Subgroup related to the Political Declaration on energy cooperation between the North Seas Countries.

The report has been prepared within the scope of this assignment. An agreed upon set of publicly available literature has been reviewed, resulting in the suite of models and methods included in this report. Accordingly, the authors would like to emphasise that the suite of models and methods included is non-exhaustive, but is the best available based on the agreed upon literature used.

1 Introduction

1.1 Background

In 2016 the North Seas energy ministers signed the "Political Declaration on energy cooperation between the North Seas Countries". The objective of this declaration is to facilitate cost-effective implementation of offshore renewable energy, in particular offshore wind energy, through voluntary cooperation to ensure a sustainable, secure and affordable energy supply in the North Seas countries. The countries will jointly work on the development of a common environmental assessment framework (CEAF) for cumulative impacts of offshore renewable energy. Under the Political Declaration an Environmental Subgroup has been formed, led by the Netherlands. The Subgroup has the task to develop the CEAF. A framework for an approach has been defined by the Subgroup.

1.2 Objectives of this report

The objective of this report is to provide an inventory and assessment of models and methods used for describing, quantifying and assessing cumulative impacts of offshore wind farms on (populations of) a number of selected receptor species. The outcome of this inventory and assessment will be used to determine a series of best performing methods and models as input to the CEAF.

At the moment of writing there is still ongoing work in many of the North Sea countries on both development of new models and methods as well as on updating existing models and methods. The focus of this report is, however, on readily available and applicable models and methods, as the Environmental Subgroup has the objective to deliver a working 'prototype' of the CEAF by the end of 2019.

1.3 Receptor species

The Environmental Subgroup has selected and approved six representative receptor species related to the key cumulative impacts of offshore wind farms:

- **Harbour porpoise** (*Phocoena phocoena*), impacts of underwater sound generated by pile driving during construction.
- **Black-legged kittiwake** (*Rissa tridactyla*), impacts of collisions with rotating rotor blades of offshore turbines, of particular interest from the perspective of the UK and Norway.
- **Lesser black-backed gull** (*Larus fuscus*), impacts of collisions with rotating rotor blades of offshore turbines, of particular interest from the perspective of continental NW Europe.
- **Red-throated diver** (*Gavia stellata*) impacts of habitat loss among seabirds due to the presence of operational offshore wind farms.
- **Common guillemot** (*Uria aalge*), impacts of habitat loss among seabirds due to the presence of operational offshore wind farms.
- **Nathusius' pipistrelle** (*Pipistrellus nathusii*), impact of collisions of bats with rotating rotor blades.

1.4 Approach

A first inventory of the present available models and methods is prepared, based on a literature review. A set of literature was provided by the Environmental Subgroup at the start of the assignment, this was augmented by the authors with a number of references. The full list of literature is included in Appendix A1. The inventory of models and methods can be found in Appendix A2 (separate excel file), a short description of each model is included.

To assess the different cumulative impacts of offshore windfarms on the receptor species four possible frameworks have been developed to predict the cumulative impact on the receptor species' populations, integrating models and methods, and indicating necessary input and possible output :

- framework of models and methods to assess the impact of piling sound on the harbour porpoise population (Chapter 2)
- framework of models and methods to assess the impact of collision-linked mortality on populations of the black-legged kittiwake and the lesser black-backed gull (Chapter 3)
- framework of models and methods to assess the impact of habitat loss on populations of the red-throated diver and the common guillemot (Chapter 4)
- framework of models and methods to assess the impact of collision-linked mortality on populations of the nathusius' pipistrelle (Chapter 5)

The performance and reliability of the different models and methods as part of the four frameworks are assessed in Chapter 2 to 5 respectively. This assessment is based on a set of general criteria:

Table 1 – General assessment criteria

Criteria	Description
Direct applicability	The model or method is applicable for the entire North Sea area and publicly available
Direct availability of input data	The input for the model or method is directly available for the whole North Sea area
Reliability of the models or methods	The outcome of the method or model provides reliable results in describing and assessing the extent of the (cumulative) impacts
Ability to quantify	The model or method is able to quantify or reliably estimate the amount of (cumulative) impacts on each of the final receptor species
Scientific acceptance	The model or method has been scientifically reviewed or it has been validated with field measurements
Previous use	The model or method has been applied for impact assessment of offshore wind farms

2 Underwater sound marine mammals: methods and models

For the assessment of impacts of underwater sound the receptor species harbour porpoise is selected (see paragraph 1.3). Many investigations and much monitoring have been ongoing for this species. This chapter describes the performance and reliability of applicable methods and models.

The direct applicability of the methods and models below for other marine mammals is limited as there is a lack of input data (e.g. spatial and temporal shifts in displacement). However, it is expected that with more research, combined with expert judgement, impacts on seals could be added to (some of) these models.

2.1 Introduction to the impact of underwater sound

In this paragraph a possible framework of models and methods to assess the impact of piling sound on the harbour porpoise population is presented. In the draft minutes of the TG Sound Workshop of November 2017 several other possible frameworks are mentioned. The framework presented in Figure 1 requires a combination of various models and methods to predict the impact of impulsive sound on the population of the receptor species (harbour porpoise). The framework consists of four model or calculation steps (blue) combined with several data or analysis stages and results (white). First the sound level produced by the specific piling activities needs to be determined. With this information, the propagation of sound through water can be calculated. With the behavioural threshold, established for the receptor species harbour porpoise (this might need some consensus as different thresholds are used in different countries), the area influenced by the piling activities can be visualized. This information combined with information about the spatial distribution of the harbour porpoise throughout the North Sea (calculated with a distribution model) will give the potentially affected harbour porpoise population. Subsequently an indication of the impact on the population size can be calculated with an impact model.

In the following paragraphs the four calculation steps will be analysed and possible models associated with the steps will be presented.

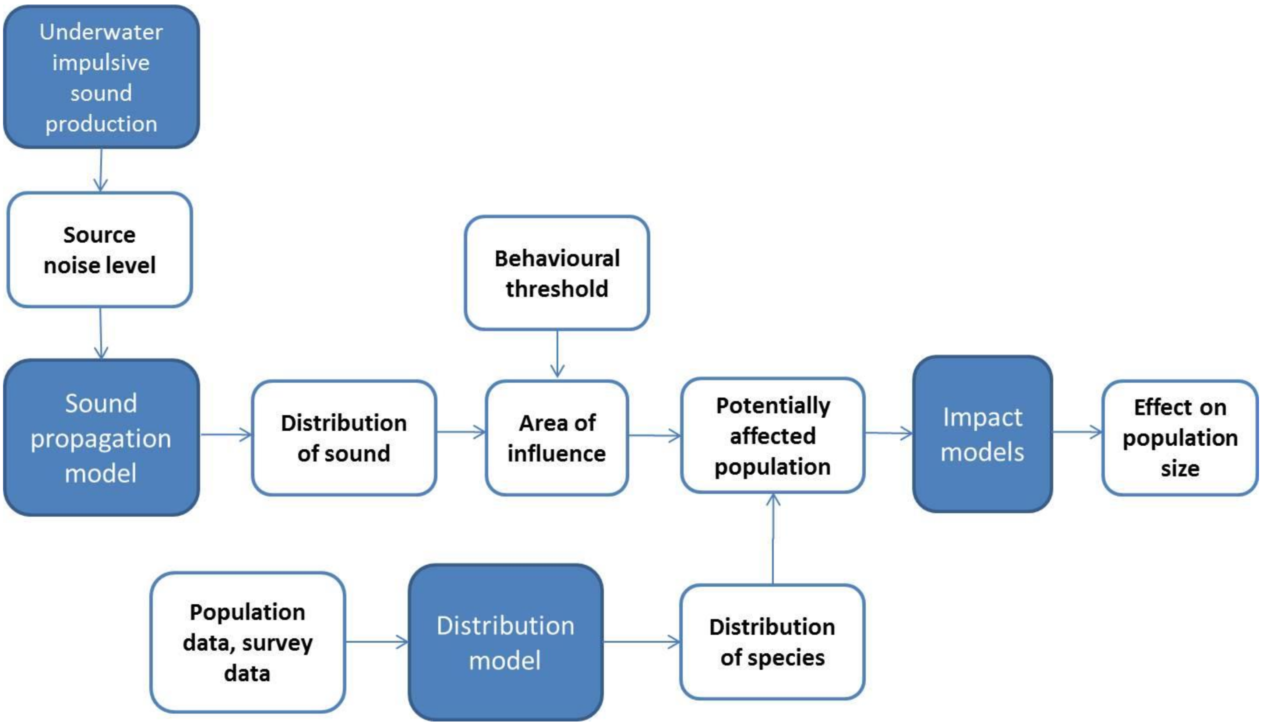

Figure 1 – Framework underwater sound to population impact

2.2 Underwater impulsive sound production (piling)

Before the transmission of the sound levels through the water can be calculated, the sound level of the source (piling) needs to be quantified. This can either be done by using field measurements of previous piling activities, literature review (in combination with expert judgement), or by means of a model. The outcome of this step generates the input for the sound propagation models. Table 2 contrasts the models and methods that are available at the moment against the general assessment criteria as mentioned in paragraph 1.4. In Table 3 the pros and cons of the models and methods are described. Appendix A2 provides a detailed description of the models and methods per criterion.

Table 2 – Overview of criteria per model and method related to impulsive sound

Model/method	**Direct applicability**	**Direct availability of input data**	**Reliability of the performance**	**Ability to quantify**	**Scientific acceptance**	**Previous use**
AQUARIUS 2.1 (Hybrid model)	b	a	c	a	c	…
Data from Literature/field measurements	c	c	n.a.	n.a.	c	c

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
b	With a few adjustments the model or method is applicable/available/reliable/able to quantify/scientifically accepted/ used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
n.a.	Not applicable
…	Not enough information

Table 3 – Pros and cons per methods to determine impulsive sound

Name model/method	**Pros**	**Cons**
AQUARIUS 2.1 (Hybrid model)	• Detailed calculation of piling sound • Can also calculate sound propagation (step 2)	• Needs detailed information about wind farms to be built in future which is available at a late development stage • Model only accessible by TNO (Dutch research institute)
Data from literature/field measurements	• Can be used by anyone if available • Closest to the truth	• Should be used in combination with expert judgement • Data is rare for specific piling activities

Discussion and summary underwater impulsive sound production

The model AQUARIUS 2.1, also referred to as the hybrid model, is the most detailed method to calculate piling sound level for future offshore wind farms. The model uses detailed information of the construction of a wind farm: data about the pile, the piling hammer and the location (e.g. soil composition) (REF4). As this type of data is not always available for future offshore wind farms, assumptions are needed to determine the cumulative impacts of future wind farms. The amount and quality of the assumptions used reduce the performance and reliability of the model. As part of a Rijkswaterstaat project (Follow-up Implementation Masterplan (VUM)) this model was recently validated with field measurements taken during the construction of two offshore windfarms in the Dutch North Sea (Luchterduinen and Gemini) (personal comment from TNO). This assessment only includes the hybrid model, however it is likely that there are other similar models being developed.

Currently data from measurements and/or literature combined with expert judgement are the most readily available source of information that can be used to predict/estimate the sound level during piling of offshore wind foundations.

2.3 Underwater sound distribution

After the specifics of the impulsive sound levels are determined, the propagation of the sound through the water can be calculated. There are numerous sound propagation models available. However, not all models are suitable for either the North Sea (relatively shallow water) or piling sound in particular. Models such as Nucleus+ or Gundalf are developed to calculate the distribution of sound by airguns (used for seismic surveys) and are therefore not applicable for calculating the sound distribution of the construction of wind farms. The table below provides a selection of models which can be used for piling in the North Sea. The models are selected because they are frequently mentioned in literature and because they can be applied in shallow water conditions and are able to assess high as well as low sound frequencies (REF44). It is also best to use a range dependent model, because sound propagation is very dependent on the variety of the underwater landscape.

Table 4 – Overview criteria per underwater sound propagation model

Model/method	Direct applicability	Direct availability of input data	Reliability of the performance	Ability to quantify	Scientific acceptance	Previous use
AQUARIUS 2.1 (Hybrid model)	b	a	c	a	c	…
AQUARIUS 1	b	c	c	c	c	c
Kraken	c	c	c	c	b	c
Scooter	c	c	b	c	b	c
Oases	c	c	c	c	b	c
Inspire	b	c	c	c	c	c

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
b	With a few adjustments the model or method is applicable/available/reliable/able to quantify/scientifically accepted/ used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
…	Not enough information

Table 5 – Pros and cons underwater sound propagation models

Name model/method	Pros	Cons
AQUARIUS 2.1 (Hybrid)	• Detailed calculation of piling sound • Can also model the specific sound level propagation (step 2)	• Needs detailed information about wind farms to be built in the future which is not yet available • Model only accessible by TNO
AQUARIUS 1	• Directly applicable • Rather accurate results as many (a)biotic	• Model only accessible by TNO • Detailed input information necessary

Name model/method	Pros	Cons
	parameters are taken into account	- Limitation with calculating sound level over larger distance (>6 km)
Kraken	- Different versions available with different complexities - Publicly available software - Directly applicable	- Has limitations within the higher frequencies
Scooter	- Publicly available software Internationally well known	- Not range dependent
Oases	- Internationally well known - Directly applicable	- Only range independent version is publicly available
Inspire	- Directly applicable - Validated with field measurements	- Not publicly available

Discussion and summary underwater sound distribution

All the models mentioned in Table 5 can be used to calculate the sound distribution of piling activities. The models can however only be used by experienced staff, some models are not publicly available, and all models are quite complex to use. The models are based on different equation methods. A review of underwater sound propagation models (REF44) shows that the accuracy of the modelled output will be critically dependent upon not just the model used, but logically also upon the input parameters used for the model.

When comparing the models to the criteria they vary when it comes to the applicability. AQUARIUS and INSPIRE are not directly applicable because these two models are not publicly available. Whereas Kraken, Scooter and Oases are publicly available but have their own limitations either in their suitable frequency range or in not being range dependent. At close range the predicted sound levels vary, at larger ranges the sound levels calculated by different models are more comparable.

2.4 Distribution of harbour porpoise

To assess the spatial density of harbour porpoise in the proximity of the areas affected by piling sound different methods have been developed by several countries surrounding the North Sea. These models predict the presence of harbour porpoise in different areas of the North Sea. Table 6 contrasts the models and methods against the general assessment criteria as mentioned in paragraph 1.4. In Table 7 the pros and cons of the models and methods are described. Appendix A2 provides a detailed description of the models and methods.

Table 6 - Overview criteria per distribution model

Model/method	Direct applicability	Direct availability of input data	Reliability of the performance	Ability to quantify	Scientific acceptance	Previous use
Gilles	c	c	c	n.a.	c	…
Heinänen	b	b	c	n.a.	c	…
Joint Cetacean Protocol	c	c	b	n.a.	…	…

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
b	With a few adjustments the model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
n.a.	Not applicable
…	Not enough information

Table 7 – Pros and cons species distribution models

Name model/method	Pros	Cons
Gilles	• Covers a large area of the North Sea • Based on survey data	• Only habitat (abiotic) parameters included • Winter season not included • Based on SCANS II
Heinänen	• Underwater sound as parameter included • Also winter season included • Biotic data included • Based on survey data	• Covers only the German EEZ area • Less season details
Joint Cetacean Protocol	• Covers 17 years of survey data • Covers a large area of the North Sea • Data is easily accessible (uses open source program R)	• Only useable on assessment covering a larger area >1000 km^2 • Doesn't include biotic parameters and hardly any abiotic parameters

Discussion and summary harbour porpoise distribution

The Heinänen model is country specific and is therefore not directly applicable to the entire North Sea. All three models use actual survey data. Of the assessed models the Heinänen model is the most sophisticated because of the wide range of data used, but consequently it will be a lot of work to expand this to the whole North Sea. The population densities developed by Gilles and Joint Cetacean Protocol are the most straightforward to use even though these are based on older SCANS II data. Gilles is suitable for seasonally migrating populations and can predict distribution densities at a more detailed scale than JCP as it uses more detailed abiotic and biotic parameters to determine the distribution.

2.5 Population impact

After determining the number of affected harbour porpoise, the next step is to calculate the impact on the population. To assess the population level impacts two main approaches can be identified for marine mammals: (i) a rule based method which results in a threshold for the number of deaths that should not be exceeded, or (ii) a predictive modelling approach which is used to predict and explore the future impact of sub-lethal impacts (REF46). The potential biological removal (PBR) is a popular method to assess population level impacts. The PBR is a measure of the maximum number of individuals of a species that may be removed from the population in addition to natural mortality, expressed as a virtual annual additional mortality, without the population undergoing a structural decline. The iPCoD framework and the DEPONS model are two main examples of predictive modelling approaches.

Table 8 compares these three models and methods against the general assessment criteria as mentioned in paragraph 1.4. In Table 9 the pros and cons of the models and methods are described. Appendix A2 provides a detailed description of the models and methods.

Table 8 - Overview of criteria per population model related to impact of underwater sound

Model/method	**Direct applicability**	**Direct availability of input data**	**Reliability of the performance**	**Ability to quantify**	**Scientific acceptance**	**Previous use**
PBR	c	c	n.a.	a	b	c
iPCoD	c	c	b	b	c	c
DEPONS	b	b	c	c	c	b

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
b	With a few adjustments the model or method is applicable/available/reliable/able to quantify/scientifically accepted/ used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
n.a.	Not applicable

Table 9 – Pros and cons per population model related to impact of underwater sound

Name model/method	**Pros**	**Cons**
PBR (rule-based method)	• The method does not require the user to make any decisions about what is or is not acceptable in relation to population change • Simple estimate of annual allowable mortality for discrete populations	• Not useful for assessment of sub-lethal impacts (e.g. disturbance) • Most marine mammal populations are wide-ranging and not effectively closed at the scale at which PBR may be applied • The single PBR value must incorporate all sources of man-made mortality that the population might be subject to – good estimates of bycatch etc. are often lacking.
iPCoD (predictive modelling)	• Useful for cumulative assessment for harbour porpoise, grey seal, harbour seal, bottlenose dolphin and minke whale • Commonly agreed and used method • Publicly available software • Runs very fast (5–15 mins for 500 replicate simulations of one scenario)	• Effects of disturbance not fully based on research data, but expert judgement. • Does currently not include density dependent population regulation (but this will be in the updated version)
DEPONS (predictive modelling)	• Useful for cumulative assessment for harbour porpoise • Can potentially be developed for other species of marine mammals • Based on real habitat use data • Publicly available software	• Requires a large amount of data: only sufficient data to parameterise for Inner Danish Waters harbour porpoise population - currently being extended to the rest of the North Sea. • Runs are a time consuming process (5–8 days for 10 replicate simulations of one scenario)

Discussion and summary population impact

The JNCC guide to Population Models used in Marine Mammal Impact Assessment (REF10) provides a good overview and description of the models and methods above. It also points out the advantages and disadvantages when applying these models.

The PBR method is a popular method as it is relatively simple to use and does not require any specific knowledge of the carrying capacity of the environment or direct estimates of population vital rates other than an estimate of unconstrained growth rate (known as Rmax) and requires only one recent/current population estimate. However, PBR is not meant to be used to assess the population impact of offshore wind turbine construction on harbour porpoise populations. It is a method to determine the population threshold level. In addition it only takes into account mortality rate and not the implication of sub-lethal impacts which is important for determining the effect of offshore wind developments.

Unlike PBR, iPCoD and DEPONS are population models that can be used to determine the cumulative impact of offshore wind turbine construction on harbour porpoise populations. Nielson and Harwood (REF7) provide a comparison of the two models and give an overview of the consequences on the population dynamics. In general the models differ in level of complexity. iPCoD is less complex and requires less input data compared to DEPONS. Hence, results will be obtained more rapidly when using iPCoD. Both models are publicly available, however iPCoD can be used to predict population consequences for the entire North Sea, whereas DEPONS only uses sufficient data to parameterise for harbour porpoise populations in Danish waters. The DEPONS model will be updated to be able to also parameterise the harbour porpoise population for the rest of the North Sea[1], an updated version of DEPONS is expected to be available in the summer of 2018.

2.6 Cascade of models and methods

Based on the assessments above a cascade of models and methods can be made for the framework related to the impact of underwater sound on the population of harbour porpoise. Different combinations of models and methods are possible; Table 10 gives an overview of the total assessment of all models and methods. It provides insight into which models are more or less ready to use and thus could be combined in a cascade to define the impact of underwater sound on the population of harbour porpoise.

There are several cascades of models possible. One possible cascade of models and methods is the one used in the Netherlands as part of the Framework for Assessing Ecological and Cumulative Effects (KEC, in Dutch) (REF1). KEC uses a combination of data from literature and AQUARIUS to detail the first two steps of the framework. For the final steps iPCoD is used to model the population density and the impact on the population. For easy reference KEC provides an estimation formula based on the results from iPCoD, which can be used instead of the full iPCoD. Taking into account the direct applicability of models and methods, it is also possible to construct a different cascade. For the first step, available literature and measurements from previous piling activities are the most straightforward to use.

Table 10 – Total assessment of models and methods related to impact of underwater sound.

Sound production	Sound distribution	Harbour porpoise distribution	Population impact
AQUARIUS 2.1 (Hybrid model)	AQUARIUS 2.1 (Hybrid model)	Gilles	PBR
Data from Literature/field measurements	AQUARIUS 1	Heinänen	iPCoD
	Kraken	Joint Cetacean Protocol	DEPONS*
	Scooter		
	Oases		
	Inspire		

*in the case that DEPONS is available for the whole North Sea this summer

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[1] *For more information reference is made to the DEPONS website: http://depons.au.dk/currently/subprojects-sp-timeline/*

🟥	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
🟧	With a few adjustments the model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
🟩	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously

There is a lot of information available and together with expert judgement reliable input for a propagation model can be provided. There are multiple options for the sound propagation model to use. AQUARIUS and INSPIRE will probably provide the most reliable results as they are frequently validated, but those models are not publicly available. Other models also give good results, but their limitations need to be taken into account. However, it is advised to use a range dependent model, because sound propagation is very dependent on the variety of the underwater landscape. Heinänen provides good results but only contains data on Germany, Gilles and JCP are directly applicable. JCP can only be used for larger areas. Either iPCoD or DEPONS can be used to calculate the impact on the population. DEPONS is the most sophisticated model because it gives insight into how the population develops over time, but takes a long time to run. iPCoD is faster and easier to use but, for the time being, it not include density dependent population regulation.

2.7 Future developments underwater sound

Based on the literature review conducted for this inventory and assessment, there are some future developments which could be of relevance. These are included in short bullet points below:

- Alignment of iPCoD and DEPONS models, in order to compare outcomes, most importantly population level predictions. Reference is made to REF7 for some examples of possible alignment.
- Models to calculate the propagation of underwater sound associated with offshore piling are still under development. Currently TNO is working on an AQUARIUS model version 3.0. This AQUARIUS model is in principle a combination of the hybrid model and Aquarius 2.0 and it is less complex. Also this new version will include improvements in uncertainties of underwater sound at larger distances >6 km from the source (personal comment TNO).
- A study conducted by CSA Ocean Sciences Inc. and funded by Bureau of Offshore Energy Management (BOEM) works on standardizing modeling for sound propagation from activities associated with offshore renewable energy development with a focus on pile driving (https://www.boem.gov/AT-16-05/).
- The second version of DEPONS is planned to be available in the summer of 2018. This version of the model will be re-parameterized including new information from the research on mechanism that control porpoise dispersal in the North Sea and variations in the size and spatial distribution of prey patches.

3 Collision risk birds: methods and models

For assessing the cumulative impacts of bird collisions with rotating rotor blades of offshore turbines, the receptor species black-legged kittiwake and lesser black-backed gull are selected (see paragraph 1.3). Collision risk models (CRM) have been developed and are used to estimate the number of fatal collisions of flying birds at offshore wind farms. Different models and methods are used to determine the population impact.

3.1 Introduction to the impact of collision risk

In this paragraph a possible framework of models and methods to assess the impact of collision-linked mortality on bird populations is presented. This framework (presented in Figure 2) requires a combination of various models and methods to predict the impact of collision risk on the population of the receptor species (black-legged kittiwake and lesser black-backed gull). The framework consists of two model or calculation steps (blue): (i) Collision Risk Model, and (ii) Method to assess impacts on population level. These steps are combined with several input (blue) or output data (white), including bird survey data, turbine details, bird details and avoidance rate.

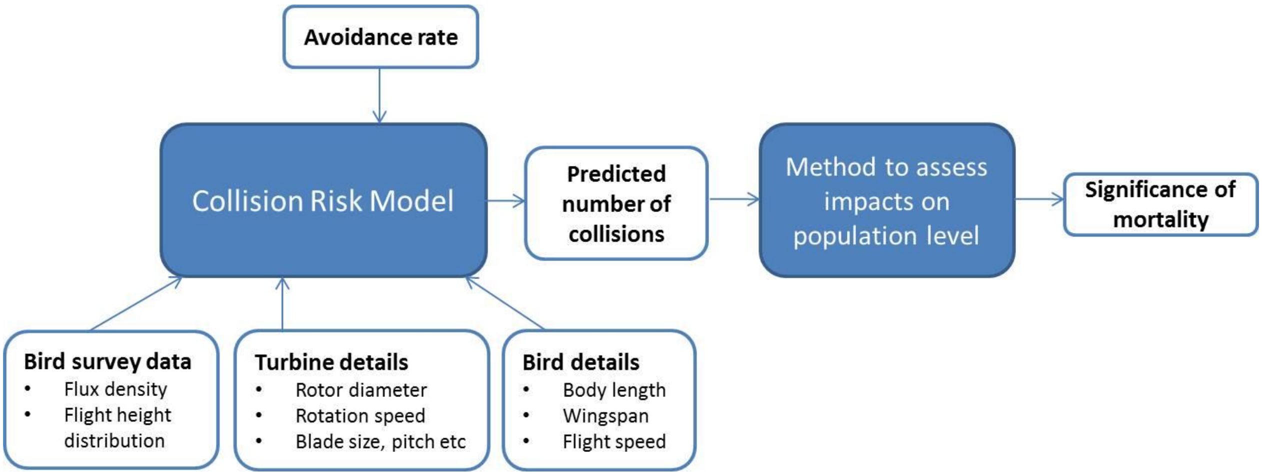

Figure 2 – Framework collision-linked mortality to population impact

In the following paragraphs the two model steps will be analysed and possible models and methods associated with the steps will be presented; starting with a review of available collision risk models and followed by a description of methods used to assess impact on population level.

3.2 Collision risk models

Before the impact of collision-linked mortality on populations can be assessed, the number of collisions needs to be predicted. This is done using Collision Risk Models (CRMs), combined with a variety of input data. The outcome of this step generates a predicted mortality, which can be used to adjust the survival input parameter for population models.

The Band model (2012) (REF14) is at present the most frequently used CRM in the UK and Northwest Europe. However, this is not the only CRM that is available. Masden and Cook (REF29) identified ten distinct CRMs. The models described vary in suitability for different situations and circumstances, but with the exception of the Band model have all been developed for onshore wind farms and are not (yet) adapted to offshore wind farms. In Table 11 the models and methods are assessed against the general assessment criteria. In Table 12 the pros and cons of the models and methods are described. In Table A-

2 in Appendix 4 an overview is given of the advantages of other models compared to the Band model, based on Masden and Cook.

Table 11 – Overview of criteria per collision risk model

Model/method	**Direct applicability**	**Direct availability of input data**	**Reliability of the performance**	**Ability to quantify**	**Scientific acceptance**	**Previous use**
Band model	c	c	c	c	c	c
Updated Band model (Masden)	c	c	…	c	…	a
Bradbury model	c	c	b	c	a	…
Other onshore CRMs (REF29)	a	…	…	…	…	…

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/used previously
b	With a few adjustments the model or method is applicable/available/reliable/able to quantify/scientifically accepted/used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/used previously
….	Not enough information

Table 12 – Pros and Cons collision risk models

Name method/model	**Pros**	**Cons**
Band model	• Can be used for all bird species • Specifically adapted for use related to offshore wind farms • Depends on the availability of location-specific data on wind turbines and bird presence	• Includes only the moving rotor in the collision estimate, as it is assumed that birds will avoid non- or slow-moving objects. Might not be the case for species turning their head downwards • Assumes all flights to be perpendicular, and that oblique angles of approach will cancel out
Update Band model (Masden)	• Can be used for all birds species both onshore and offshore • Uncertainty is incorporated using the method as proposed by McAdam (2005) • Uses R, a free software for statistical computing, to perform calculations in a standardised way	• Includes only the moving rotor in the collision estimate, as it is assumed that birds will avoid non- or slow-moving objects. Might not be the case for species turning their head downwards • Assumes all flights to be perpendicular, and that oblique angles of approach will cancel out
Bradbury model	• Maps the relative sensitivity of a certain area to offshore wind farms • Calculates what the increase in mortality would be for the same species of seabirds and coastal birds as a result of collisions with wind turbines	• Less detailed than Band model • Assumptions based on one reference and expert judgement
McAdam (2005)	• Incorporates uncertainty in model	• Not (yet) adapted to offshore wind farms
Smales et al. (2013)	• Includes collisions with stationary components	• Not (yet) adapted to offshore wind farms
Bolker et al. (2014) and Desholm (2006)	• Uses a constant probability of collision, this removes the theoretical calculation of the probability of collision and the associated uncertainty of factors such as avoidance	• Not (yet) adapted to offshore wind farms
Holmstrom et al. (2011)	• Incorporates angle of approach, which can have	• Not (yet) adapted to offshore wind farms

	a significant impact on the probability of collision and thus the estimates of mortality	

Discussion and summary Collision Risk Models

The Band model is the most frequently used and highly developed model to determine collision risks of offshore wind farms to flying (sea)birds. It is considered generally fit for purpose and it is directly applicable. As long as the other models require further development and are not directly applicable offshore, the Band model will be, for the time being, the most appropriate model.

In 2015 Masden (REF15) conducted a wide range of interviews among stakeholders to review the existing use of the Band model and possible need for a new or updated model. Masden concluded that a new collision risk model that was fundamentally different was not required by the industry and the Band model was considered generally fit for purpose. But it required an update especially with regard to incorporation of uncertainty in the modelling process and the choice of input parameters. The Masden version of the Band model was a proof of concept and the published version was not produced with the intention to be used in assessments. However, this next step is in progress, with the freely available online app and associated R code due to be published by Marine Scotland in spring 2018.

The Bradbury model (REF54) has been developed to calculate the combined impacts of habitat loss and collision mortality. The Bradbury model uses data on the presence of seabird species and their species-specific sensitivity indices to wind farms to map the relative sensitivity of a certain area to offshore wind farms. This makes it a suitable tool for marine spatial planning. In 2015 an extension to the Bradbury model was prepared to estimate absolute numbers of collision victims.

When comparing the Band model and the Bradbury model, the Dutch Framework for Assessing Ecological and Cumulative Effects (KEC) (REF1) concluded that the Band model is more suitable for use in project EIAs, since it is more detailed than the Bradbury model. In contrast to the Bradbury model, the applicability of the Band model depends on the availability of location-specific data on wind turbines and bird presence. KEC also concluded that as long as it is not known empirically how many actual victims there are among various species of birds, the Band model would seem to provide the most realistic estimates of the numbers of collision victims. Especially given the fact that this model contains the best descriptions of the features of wind turbines.

The majority of the data that are needed as input parameters for the Band model are available. The reliability of the outcomes of CRMs greatly depends on the choice and quality of the input data that are used in the model. Important input parameters are location-specific data of wind turbines, bird presence[2], flight speed, flight height and avoidance rate (REF15). Empirical data are collected to provide realistic estimates of bird fluxes, species-specific data on flight speed and avoidance rates[3].

Avoidance has proven to be difficult to quantify and is likely to vary in response to a wide range of environmental and ecological factors, as well as the configuration of the wind farm. In 2014 Cook et al (REF32) wrote a review on the use of avoidance rates in CRMs. This study resulted in recommended avoidance rates for use in the Band model focussing on five priority species, including black-legged

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[2] *The Band model has been primarily developed for using density data from ship-based or aerial survey data and aims to address seabird species that are well recorded by these types of surveys. For this purpose the European Seabirds at Sea (ESAS) database can be used. This is a collaborative partnership between the Joint Nature Conservation Committee (JNCC) and seabird researchers in Northwest Europe. Also data collected in national monitoring programs are used, for example in the Netherlands data is used from the North Sea Monitoring program of Rijkswaterstaat (MWTL).*

[3] *Recent studies, like the ORJIP Bird Collision Avoidance Study (REF13), were designed to improve the evidence base for seabird flight, avoidance behaviour, and collisions in offshore wind farms. Also in other monitoring programs, like WOZEP in the Netherlands, empirical data is collected in existing wind farms to improve and validate input that is needed for CRMs.*

kittiwake and lesser black-backed gull. Furthermore, the ORJIP[4] Bird Collision Avoidance Study (REF13) focussed on the development of an appropriate methodology for data analysis to quantify empirical avoidance rates (EARs), based on existing research and equipment/data limitations. This study indicates that bird avoidance behaviour is likely to lead to a greater reduction in collision rates than current avoidance rates applied in CRMs assume.

The output of CRMs is an estimation of the number of birds colliding, with 100 per cent collision mortality assumed. In the case of the Band model the collision rate is expressed in number of birds colliding per month (output). Actual measurements of collision rates to validate the models are still in their infancy, because it has proven to be extremely difficult to conduct reliable monitoring of the numbers of actual collisions between rotating turbine blades and flying birds. This is difficult primarily because it is impossible to recover carcasses to estimate collision rates (which is possible at onshore wind farms), which in turn also makes it extremely difficult to identify the species of birds concerned. Techniques that make use of cameras or thermal imaging technology to identify the species just before the moment of impact are under development and some are in use, but no firm results have yet been published[5]. For the time being the Band model seems to provide the most realistic estimates of the numbers of collision victims, but it has to be taken into account that validated data on collision and avoidance rates are still scarce lacking for offshore locations and species. The ORJIP study which was recently published (April 2018), presents the latest recommendations on avoidance rates to be used in CRMs. In this study avoidance rates have been obtained for both receptor species.

3.3 Population impact

CRMs are used to estimate numbers of casualties. To assess the impact of collisions on populations of birds, other models or methods are required. In this paragraph the models and methods that can be used to assess the population impact are described. After estimating the number of collisions, the next step is to calculate the potential impact on the population. The potential biological removal (PBR) is a measure of the maximum number of individuals of a species that may be removed from the population in addition to natural mortality, expressed as a virtual annual additional mortality, without the population undergoing a structural decline. The State-space model and the Leslie matrix model are examples of predictive modelling approaches.

Different population models have been developed for different species and different breeding colonies. In the UK, for example, population models were produced on behalf of Marine Scotland for several species, amongst others a State-space based model for the receptor species black-legged kittiwake using colony counts from 1985 to 2012, along with productivity and survival data (REF31, REF47). Another example is the 0-model that was developed in the Netherlands for the lesser black-backed gull (based on the Leslie matrix model) by Bureau Waardenburg (2012) (REF38) to estimate the impacts of offshore wind farms.

In Table 13 the models and methods are assessed against the general assessment criteria as described in paragraph 1.4. In Table 14 the pros and cons of the models and methods are described. Appendix A2 provides a detailed description of the models and methods.

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[4] *Offshore Renewables Joint Industry Programme (ORJIP).ORJIP is a UK-wide collaborative programme of environmental research with the aim of reducing consenting risks for offshore wind and marine energy projects. https://www.carbontrust.com/offshore-wind/orjip/*

[5] *Dirksen (REF18) wrote a review of methods and techniques for field validation of collision rates and avoidance amongst birds and bats at offshore wind turbines. The inventory shows that, to date, few systems have been able to systematically detect and record bird collisions at offshore wind turbines.*

Table 13 - Overview criteria per population model related to impact of collision risk

Model/method	**Direct applicability**	**Direct availability of input data**	**Reliability of the performance**	**Ability to quantify**	**Scientific acceptance**	**Previous use**
PBR method	c	c	b	a	a	c
State-space Model *Black-legged kittiwake*	c	c	c	b	c	c
0-model (Leslie matrix) *Lesser black-backed gull*	c	c	c	c	c	c

a	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/used previously
b	With a few adjustments the model or method is applicable/available/reliable/able to quantify/scientifically accepted/used previously
c	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/used previously
….	Not enough information

Table 14 – Pros and cons per population model related to impact of collision risk

Name model/method	**Pros**	**Cons**
PBR	• Requires very little input data • Relatively simple to calculate • Can be used in an initial screening process to determine which projects will clearly have a significant impact on populations	• Considers only whether a pre-determined level of mortality is exceeded • Not suitable for use in quantifying the impact of additional mortality on population size
State-space model *Black-legged kittiwake*	• Useful with very limited data • Provides a flexible approach for several species • Powerful in forecasting population sizes • Predictions of future population levels can be made even in the absence of accurate demographic information, under the (restrictive) assumption that demographic variables, though unknown, are constant	• Colony specific data are needed • In cases of limited data, the model can be used, but only when this limited data relates to rates of survival and productivity, in other cases of limited data availability the model cannot be used.
0-model (Leslie matrix) *Lesser black-backed gull*	• Relatively simple, robust model • Based on field measurements • Can be used for a range of species if input data are available • Validated with data from France and the UK • Calculates additional mortality due to collisions an if the threshold for acceptable additional mortality is exceeded	• The most important parameters reproduction and survival rate can be measured in a lot of ways • Survival rate data must be available and reliable

Discussion and summary population impact

A key advantage of PBR is that it requires very little input data, only the minimum current population size, mean age at first breeding and mean adult survival. In addition, it is relatively simple to calculate. This simplicity could make PBR an attractive approach to assess the potential population level impacts of offshore wind farms on seabirds, although there are also arguments against it (see Table 14). PBR generally cannot be used to assess whether the population-level impacts of offshore wind farms results in not meeting the conservation objectives of protected sites (REF55). This is because PBR considers only whether a pre-determined level of mortality exceeds, rather than the biological impact of any additional mortality at population level. In REF34 it was suggested that the most appropriate approach is to use PBR in an initial screening process to determine which projects will clearly have a significant impact on populations. For the remaining projects, REF34 and REF 55 suggest that a density-independent Leslie matrix model should be used to estimate the population size at the end of the lifetime of the project with and without the demographic impacts of the wind farm using matched simulations.

There are different models that can be used as a base to estimate changes in populations for specific species. The State-space model uses a Bayesian approach[6] and proved to be extremely powerful in forecasting population sizes (REF31). It was tested with actual data of several species in the UK, including the black-legged kittiwake. The Leslie matrix is an age-structured population growth model. This model is used to model the changes in populations over a period of time. It is a proven simple and robust way of modelling animal populations (REF38). This model is based on data from kittiwakes along the Dutch coast and validated with data from France and the UK. Both models are relatively simple, have been used before, are validated and can be used for a range of species, as long as data are available.

To determine whether or not a particular level of predicted collision level is acceptable or not a so called metric is needed. The metrics help with forming a judgement on whether protected populations will decline to unacceptably low levels in the presence of the predicted mortality. In the UK a variety of metrics have been used to assess the population level impacts associated with proposed offshore wind farms (see REF56). An overview of these metrics can be found in Appendix A4 (table A4). The use of these metrics in the UK was reviewed in REF33, REF47 and REF56.

3.4 Cascade of models and methods

Based on the assessments above a cascade of models and methods can be made for the framework related to the impact of collision linked mortality on the population of black-legged kittiwake and lesser black-backed gull. Different combinations of models and methods are possible; **Error! Reference source not found.** gives an overview of the total assessment of all models and methods and insight into which models are more or less ready to use and thus could be combined in a cascade to define the impact of collision risk on the populations of birds.

One possible cascade of models and methods is the one used in the Netherlands as part of KEC (REF1). KEC uses a combination of the Band model and PBR to assess the impact of offshore wind.

Table 15 – Cascade of models and methods related to impact of collision risk

Collision risk	Population impact
Band model	PBR
Updated Band model (Masden)	Other metrics
Bradbury model	Space-state model *Black-legged kittiwake*
Other onshore CRMs (REF29)	0-model *Lesser black-backed gull*

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[6] *A method of statistical inference*

🟥	The model is not directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
🟨	With a few adjustments the model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously
🟩	Model or method is directly applicable/available/reliable/able to quantify/scientifically accepted/ used previously

Taking into account the direct applicability of models and methods it is also possible to construct another cascade. For the first step the Band model is directly applicable for predicting the number of collisions. These figures can be used to estimate the population risk with the 0-model (REF48). This is probably also the case for the State-space model, but this was not confirmed in literature.

3.5 Future developments collision risk birds

Based on the literature review conducted for this inventory and assessment, there are some future developments which could be of relevance. These are included in short bullet points below:

- Other collision risk models are available, there are opportunities for further detailing (see paragraph 3.1) ;
- Empirical data is collected to validate estimated collision risks and to improve the input parameters that are used in collision risk models, e.g. in programs like WOZEP and ORJIP.
- Marine Scotland commissioned update to a stochastic version of Band (2012) and online tool that should be published in June 2018.
- JNCC commissioned work to assess the outputs of the ORJIP collision avoidance work and how to make best use of within collision risk modelling. Expected to be published within 2018.

4 Habitat loss birds: methods and models

For assessing the cumulative impacts of habitat loss among seabirds due to the presence of operational offshore wind farms, the receptor species red-throated diver and common guillemot are selected (see paragraph 1.3).

Information about displacement of seabirds is scarce. Studies on the displacement of seabirds at wind farms are often based on a comparison of distribution patterns before and after the construction of a wind farm. The outcomes of these studies often do not take into account possible impacts of large-scale temporal trends or stochastic variability (REF25).

4.1 Methods to estimate the impact of habitat loss

In this paragraph a possible framework to assess the impact of habitat loss on populations of the red-throated diver and the common guillemot is presented. This framework (presented in Figure 3) requires a combination of various models and methods to predict the impact of habitat loss on the population of the receptor species. The agreed upon set of literature is limited in extent as regards to habitat loss, therefore the framework and possible models and methods are discussed on a higher level as compared to the previous chapters on underwater sound and collision risk.

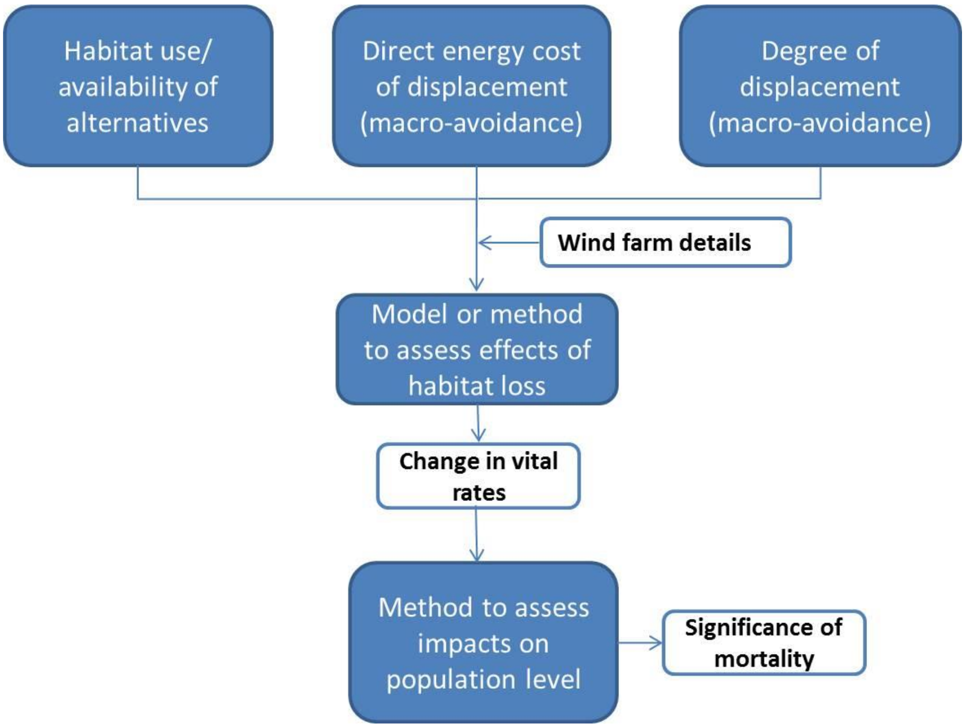

Figure 3 – Framework habitat loss to population impact

There is a link between macro-avoidance and avoidance for collision risk. When birds avoid wind farms the collision risk will decrease, but they may be susceptible to impacts via habitat loss.

Habitat use

In relation to assessing the impacts of wind farms, habitat models are used to estimate (i) the number of a certain bird species in the total relevant area, based on observational data; and (ii) the relative importance of smaller areas, which are potentially designated for locations of offshore wind farms. Depending on the foraging strategy of the bird species different variables are important. Habitat models for abundances around breeding colonies typically include the distance to the breeding colony and the maximum feeding range of the species.

Energy budget models

Detailed energy budget models require an understanding of the energetics of the species involved, including the division of energy to for example gonads and soma, dynamics of stored energy, (weight-specific) basic metabolic rate, costs of flight, foraging behaviour and food processing, reproductive investment. Such detailed knowledge is generally not available for seabirds. That is why Van Kooten et al (2017) (REF12) suggest an approach which does include the energy budget mechanism (using energetic state as a measure of individual fitness, which is reduced by expenses and increased by feeding), but which avoids the need for species-specific parameterization of the energetic model. In the UK Searle et al. (2014) (REF39) developed a model which predicts the energetic costs of displacement and barrier effects to breeding seabirds (as well as the subsequent impacts on survival rates and breeding productivity). This work was commissioned by Marine Scotland Science (MSS) (Scottish Government) for the purposes of informing the assessment of four large wind farms in the Forth and Tay region of eastern Scotland.

Degree of displacement

Recent studies focussed on determining the impacts of displacement on seabirds based on an extensive survey program and on monitoring methods and techniques (e.g. REF18, 25, 30, 35, 36, 37). For both receptor species a number derived using a degree of displacement model can be found in the literature (REF36). However, for guillemots a more detailed study is under way by Leopold et al. (in prep.). This work develops a relationship for this species between displacement, location, time of year, and certain technical specifications of offshore wind farms, such as turbine size (in: REF12).

In the UK some papers on studies of extent of displacement of seabirds at offshore wind farms have recently been published (REF35, 37, 41)).

Habitat loss

The assessment of habitat loss in KEC (REF1) was based on Bradbury et al. (2014). The Bradbury model (2014) was developed to calculate the combined impacts of habitat loss and collision mortality. This model can be used for seabirds and coastal birds. The Bradbury model uses data on the presence of seabird species and their species-specific sensitivity indices to wind farms to map the relative sensitivity of marine waters to offshore wind farms. The Bradbury model assumes that loss of habitat for seabirds and coastal birds will lead to a 10% increase in mortality (or definite emigration) among the birds experiencing this habitat loss. This assumption is based on just one reference (Bradbury et al. 2014) and no further clarification is given. The assumption must therefore be considered to be a highly arbitrary choice. The part played by density-dependent effects on populations has hardly been investigated at all and is largely unknown. At the time KEC was drawn up no other estimates were available.

Marine Scotland Science has commissioned the development of specific spatial analytical approaches for estimating the extent of displacement at marine renewable developments. This is based on sophisticated spatial analyses which are used to compare the densities and distribution of species in the development areas and surrounding waters over different time periods (e.g. usually pre-construction and operation). The analyses aim at estimating the extent of change in density and whether there are distributional changes that correlate with the development location[7] (REF42, 43). There are some examples available of this analytical approach being used in studies of displacement (see REF40).

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[7] *Details of the software are at: https://www.creem.st-andrews.ac.uk/download/mrsea-guidance.*

In January 2017 the Statutory Nature Conservation Bodies (SNCB, theSNCBs, the statutory advisors on nature conservation to the UK and devolved governments) have drawn up the SNCB matrix approach (REF35). This advice is provided by the SNCBs to give an insight into the type of approaches that are currently used in most assessments of seabird displacement for UK wind farm applications. Essentially this describes the guidance the SNCBs provide for assessments of such impacts. The biological basis to the prediction of impacts is limited.

Population impact

There are models available on specific colonies of common guillemots in Scotland. Van Kooten et al, 2017 suggest a single model for the population of all birds that inhabit a study area, not individual models for individual colonies. This model has not yet been developed. A model for red-throated divers is not yet developed. It is unclear whether sufficiently reliable data for parameterization and validation of this model is available (REF12)). In REF57 a red-throated diver individual based model was developed to look at the impact of offshore wind farms, but they had limited success due to a paucity of data.

4.2 Future developments habitat loss birds

Based on the literature review conducted for this inventory and assessment, there are some future developments which could be of relevance. These are included in short bullet points below:

- Van Kooten et al (2017) (REF12) wrote a work plan for future research on the consequences of seabird habitat loss from offshore wind turbines. The aim of the work described in this plan is to develop and apply an assessment method for the (potential) influence of habitat loss for individual birds on their population development for five seabird species (among which are both receptor species assessed herein: common guillemot and red-throated diver).
- For guillemots a more detailed study is under way by Leopold et al. (in prep.). This work develops a relationship for this species between degree of displacement, location, time of year, and certain technical specifications of offshore wind farms, such as turbine size (mentioned in: Van Kooten et al, 2017) (REF12).
- JNCC UK is currently carrying out a more detailed study on displacement of red-throated divers. This project will tag breeding red-throated divers with geolocator and time-depth recorder tags to investigate where they go and the proportion of time they spend foraging in the non-breeding season. From this, we hope to infer whether red-throated divers have the potential to theoretically increase the proportion of time they spend foraging to mitigate the additional energetic requirements from displacement.
- There is currently a follow-on modelling project of the study by Searle et al. (2014) (REF39) (commissioned by Marine Scotland Science (Scottish Government)) which aims to develop more generic modelling approaches which could be applied to any offshore wind farms in UK waters, and which also uses GPS tracking data for the seabird species which are now available. Again, this new modelling approach will be relevant to predicting the impacts on breeding seabird populations. The model is referred to as SeabORD and the commissioned report is due to be published in the next few weeks.

5 Collision risk bats: methods and models

For assessing cumulative impacts of collisions of bats with rotating rotor blades the receptor species Nathusius' pipistrelle is selected (see paragraph 1.3). It should be noted that bat fatalities not only occur because of direct collisions with the rotor blades, but also through barotrauma as a result of the low pressure and dynamics in pressure in the air turbulence near the rotor blades (REF3).

5.1 Methods to estimate migration and collision risk bats

Basically the same framework of models and methods used to estimate the population impact of collision-linked mortality on birds can be used for bats. It should be noted that a specific collision risk model for bats is not yet developed. The agreed upon set of literature is limited in extent as regards to collision risk for bats, therefore the framework and possible models and methods are discussed on a higher level as compared to the previous chapters on underwater sound and collision risk.

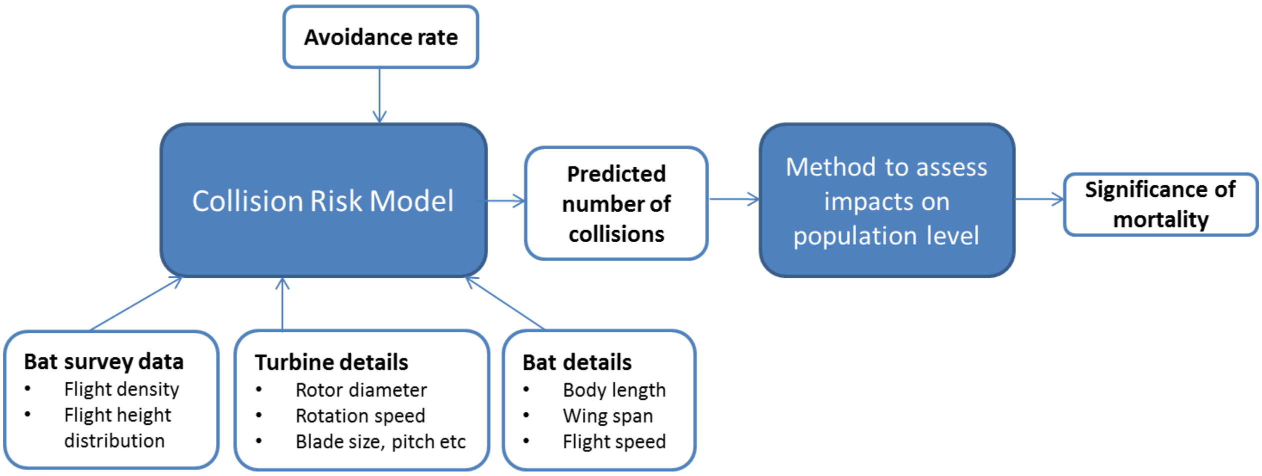

Figure 4 – Framework collision risk bats to population impact

REF1 states that for bats there is not enough information to determine whether or not bats are present offshore in large enough numbers to suffer from potentially significant impacts. There is not enough information about bats' behaviour at sea and in the presence of operational wind farms. In addition, there is no reliable model for estimating the number of offshore collision victims for this species group.

Quantitative assessment

In REF3 a quantitative assessment is carried out of the cumulative impacts of offshore wind farms in the Southern North Sea on the bats that are considered to be most vulnerable (including Nathusius' pipistrelle). Brinkmann et al. (2011) (in REF3) developed a method to predict the number of bat fatalities for wind farms based on the number of bat recordings from the nacelle of a wind turbine. In more than 30 onshore wind farms in Germany bat activity was registered and fatality searches were conducted. According to REF3 this method cannot be used for offshore wind farms because of the different circumstances. Therefore a preliminary estimate based on expert opinion on the number of fatalities was used for the quantitative assessment. It was assumed in REF3 that there will be one victim per turbine per year and based on the number of 8 000 turbines to be installed in the Southern North Sea in the near future, they assume that a maximum of 8 000 potential fatalities. A worst case scenario would be to use this number for each bat species, but based on the available information on recorded bat activity in the North Sea it is more realistic to divide this number based on the relative abundance of the respective species, thus arriving at estimates of 7700 (95.7%) fatalities on a yearly basis for Nathusius' Pipistrelle.

Prototype estimator for migrating populations

In an international study (REF16) a prototype estimator for migrating populations of bats was developed. This was based on data, or estimates, regarding the size and bandwidth of source populations, population dynamical factors and factors defining migration fluxes regarding bat species in the different countries bordering the southern North Sea. Because such data is very rare, a flow model was constructed to produce a preliminary estimate for bats crossing the southern North Sea (roughly 40.000 individuals with a bandwidth between 100 and 1.000.000 individuals). However, the approach can be adapted for use in other regions/study areas. More empirical data and assessment of the population factors is needed to confirm these figures. The developed estimator and especially the current outcome is far from perfect. However, this prototype gives direction and insight into the work and data needed to achieve better estimates.

Detection of bat fight paths and fatalities

In the Netherlands a study to use automated techniques to detect bat fight paths and fatalities has been undertaken (REF46). The study concluded that the use of stereo configuration and analysis methods are promising, but need further improvement so that reliable 3D paths can be derived automatically.

Validation of data

Dirksen (2017) (REF18) wrote a review of methods and techniques for field validation of collision rates and avoidance amongst birds and bats at offshore wind turbines. The inventory shows that, to date, there is no system that has demonstrated detection and recording of bat collisions at (offshore) wind turbines.

5.2 Population impact

KEC (REF1, 3) compares the rough estimates of the cumulative impacts of collisions on bats and barotrauma with the (equally roughly estimated) PBR. As the population data on Nathusius' pipistrelle and other bat species are still rudimentary, this assessment is at best indicative and certainly cannot yet be considered reliable. See also paragraph 0, where different metrics and methodologies are described to assess the population level impacts of impacts associated with proposed offshore wind farms and birds.

5.3 Future developments collision risk bats

Based on the literature review conducted for this inventory and assessment, there are some future developments which could be of relevance. These are included in short bullet points below:

- No specific collision risk model for bats has yet been developed
- Research is being done in the Netherlands on the detection of bat fight paths and fatalities

6 Recommendations

This report has been prepared within the scope of this assignment. An agreed upon set of publicly available literature has been reviewed, resulting in the suite of models and methods included in this report. This suite of models and methods is non-exhaustive, but is the best available based on the agreed upon literature used. In this report only the facts are displayed, there a no conclusions on which models should be used or not. This will be done in a follow-up study.

In the review a few recommendations were done by the CEAF members, these are listed here:

- It is advised to include some more information on data structure requirements for each of the models/methods as this might also be a factor playing into choosing the models for the pilot studies later on.
- The inventory is a good start to help assess the different models and data that can be used for the different elements in a CEAF. The next step should be to install receptor specific technical groups to be created to move the work forward.
- Take also the following criteria into account: transparency, ease of use, ease of updating/refinement.
- Develop the Band model to a model that is able to work better with dynamic data.
- Start discussions on issues that need consideration: Stochastic or deterministic (need to match/pair runs or not)? Density dependent or independent? Agreement on demographic rates that could be used in modelling.

A1 References

As provided by RWS at the start of the project:

1. Framework for assessing ecological and cumulative effects of offshore wind farms. Part A: Methods (https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/)
2. Framework for assessing ecological and cumulative effects of offshore wind farms. Part B: Description and assessment of the cumulative effects of implementing the Roadmap for Offshore Wind Power (https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/)
3. A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea. Authors: Mardik F. Leopold (IMARES), Martijn Boonman (Bureau Waardenburg), Mark P. Collier (Bureau Waardenburg), Nara Davaasuren (IMARES), Ruben C. Fijn (Bureau Waardenburg), Abel Gyimesi (Bureau Waardenburg), Job de Jong (Bureau Waardenburg), Ruud H. Jongbloed (IMARES), Bob Jonge Poerink (The Fieldwork Company), Jonne C. Kleyheeg-Hartman (Bureau Waardenburg), Karen L. Krijgsveld (Bureau Waardenburg), Sander Lagerveld (IMARES), Rob Lensink (Bureau Waardenburg), Martin J.M. Poot (Bureau Waardenburg), Jan Tjalling van der Wal (IMARES) & Michaela Scholl (IMARES). Report number C166/14 IMARES (https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/)
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A2 Overview tables of inventory and assessment of methods and models

Reference to separate excel file

A3 Additional information methods and models for underwater sound marine mammals

A3.1 Similarities and differences between iPCoD and DEPONS

In the table below an overview is given of the similarities and differences between iPCoD and DEPONS (cited from REF7). Both iPCoD and DEPONS use age and life cycle specific survival and birth rates to model harbour porpoise population dynamics. Both models could be used to provide outputs that may be useful for the development of monitoring programmes, such as expected changes in abundance and population age structure as a result of disturbance. The structural differences between the two models make each model better suited to answer a different set of questions. These differences between the two models are likely to result in different predictions of the population impact of particular development scenarios. A direct comparison of model predictions is expected to be useful only if input parameters are aligned and model outputs are carefully analysed (REF7).

Table A1 – Overview of similarities and differences between iPCoD and DEPONS (cited from REF7)

iPCoD	DEPONS
Stage-based matrix model	Individual-based model. More realistic model of porpoise biology
The population is divided into three stages (calf, juvenile, and adult), with the calf stage having a duration of exactly 1 year. The number of calves is determined using the birth rate, which is specified by the user. The number of surviving juveniles and adults is then calculated. No further mortality occurs until the start of the next simulated year. Survival and birth rates are allowed to vary from year to year around a mean value, using parameters obtained by expert elicitation, to mimic the effects of environmental variation. Only females are modelled, but total population size can be readily calculated using an estimate of the population sex ratio	Animals are characterized as either juvenile, adult with calf, or adult without calf. Calves are modelled as independent individuals after they have stayed with their mother for 240 days (the length of the lactation period reported in the literature). Any juveniles that have reached the age at maturity (3.44 yrs) become adult. On the first day of the lactation period, a proportion of the adults become “adults with calves”. This proportion is determined by the birth rate (user specified, but with a default value of 0.68 for harbour porpoises in the Northwest Atlantic). The survival of each calf in a particular time step is determined by the energy level of its mother. The individual animals’ energy levels and survival depend on their foraging efficiency. Only females are modelled, but total population size can be readily calculated using an estimate of the population sex ratio
Operates on a time step of 1 year, but exposure to sound is modelled with a time step of 1 day	Operates on a time step of 30 minutes, and the movements, exposure to sound and energetic status of each animal is updated after each step (30 minutes).
Survival rates are average survival rates derived from data from North Sea animals	Survival rates are modelled from the individuals’ ability to continuously find food. The probability of survival for each individual in a particular time step is determined by the current value of its energy level and the assumed relationship between energy level and survival
The probability that an individual is disturbed by a particular event is calculated from the ratio of the estimated number of animals likely to be disturbed on each day of the activity to the size of the population or sub-population. **The estimates of the number of animals likely to be disturbed on one day of each activity is provided by the user (see text above for possible input data).** The user can specify that all individuals in a population are equally likely to be exposed to disturbance from a particular activity. However, it is also possible to specify that only a sub-set of the population (referred to as the vulnerable sub-population) is exposed to sound from that activity. For example, the user can specify that different vulnerable sub-populations are affected by each wind farm development. At the end of the year, simulated individuals are classified into three disturbance classes (undisturbed, moderately disturbed, or severely disturbed, based on the total number of days of disturbance they have experienced. These are then translated into effects on vital rates using results from an expert elicitation process. New survival and birth rates are calculated for each	The probability that an individual is exposed to disturbance activities depends on the spatial and temporal patterning of disturbances. The spatial distribution of animals depends on their movement patterns, which are calibrated to resemble those of real animals (**input from literature**, like Nabe-Nielsen et al, 2013). Individuals that encounter sound from an activity move away from the sound source, and the extent is progressive with the received level of sound (**input from literature**, like Nabe-Nielsen et al, 2014). This response affects the individuals’ energy levels because they spend more time travelling through the landscape without encountering food patches. These changes in energy level determine the effects of disturbance on the population.

iPCoD	DEPONS
disturbance class and stage. The temporal patterning of disturbances is used to determine the number of simulated animals to be disturbed each day.	
All surviving individuals are assumed to transition into the relevant undisturbed category (i.e. they have no memory of the disturbance they experienced in the previous year).	In the DEPONS model animals have a memory of their foraging success in different areas, which is, in turn, influenced by the amount of disturbance they have experienced in those areas.
iPCoD runs faster than the DEPONS model, making it possible to compare a larger number of different scenarios and to take account of a wider range of uncertainties	Provide detailed predictions of the short-term effects of disturbance that are likely to be valuable for spatio-temporal planning and mitigation.
	DEPONS can provide a wider range of predictions than iPCoD. For example, it can be used to predict how the spatial distribution of porpoises in the North Sea may change in relation to the sources of sound, and how average energetic status and age class distribution of porpoises may vary over time and space.
The predicted population consequences of disturbances are largely determined by the number of animals that are disturbed and the number of days on which an activity that might cause disturbance occurs. Animals within the sound range receive same amount of sound/are deterred at the same level.	The consequences of disturbances are determined by the behavioural reactions of the animals that are exposed to sound, which in turn depends on the received sound level. The animals that are far from the sound source are less deterred than the ones that are close to the source
The predictions of iPCoD are less affected by the spatial distribution of these events because no account is taken of the location of the different construction activities within the boundaries of a vulnerable sub-population.	The effects of the construction schedules and the precise locations of the construction activities are modelled explicitly. As a result, differences in construction schedules among sites may have a greater effect on model predictions. This capability means that DEPONS is particularly suited to investigations of the population effects of different piling schedules for wind farm construction within a year
iPCoD does not currently include density dependent population regulation. As a result, a population that is reduced in size as result of a disturbance activity will only be predicted to recover when the disturbance activity ceases if the population was increasing in size before the disturbance. This limitation means that iPCoD is most suitable for predicting the population level effects of acute disturbance associated with particular events (e.g. wind farm construction) over a relatively short (~10 year) period, rather than chronic disturbance (e.g., shipping sound, wind farm operation)	The DEPONS model does include density dependence. This makes it possible to evaluate how long it takes the population to recover after being reduced by disturbances. It could also make it possible to develop a wind farm construction scenario with a relatively small impact on the population, provided that there are sufficiently long sound-free periods during the construction phase.
Currently only iPCoD incorporates environmental stochasticity (i.e. variations in vital rates from year to year, informed by expert elicitation). iPCoD also accounts for more sources of uncertainty than DEPONS, such as uncertainty in estimates of the number of animals disturbed by a particular source (due to uncertainty in the choice of sound propagation model and in the threshold received level at which animals respond to sound), and potential variation in the effect of disturbance on vital rates. As a result, iPCoD produces a wide range of population-level predictions.	DEPONS model can also be used to investigate how uncertainty in the threshold level affects population estimates, but it is very time consuming

A4 Additional information methods and models for collision risk birds

A4.1 Comparison between Band model and other collision risk models

The table below provides an overview of possible advantages of 9 collision risk models, compared to the commonly used Band model (cited from REF29).

Table A2 - Possible advantages of other collision risk models compared to Band model

Collision Risk Model	Possible advantages of models compared to the Band model
Tucker (1996)	NA
McAdam (2005)	Uncertainty. The Band model provides a method to express the uncertainty associated with a collision estimate post hoc. McAdam (2005) used a Monte Carlo model to consider joint distributions of wind speed and direction and distributions of flight height to produce collision risk estimates with associated measures of uncertainty.
Smales et al. (2013)	Collisions with stationary components. The Band model includes only the moving rotor in the collision estimate, because it is assumed that birds will avoid non- or slow-moving parts. Smales et al. (2013) however include the stationary turbine tower as well. It is possible that some species, when flying and foraging in open airspace e.g. offshore and if turning their head to look downwards, will have little visual coverage of what lies ahead so making them particularly vulnerable to collisions with obstacles which are built into these otherwise predictably open airspaces (Martin 2012). Therefore for species known to be at risk of collision with these fixed structures it may be important to include them in the collision estimates as well as moving blades. Subsequently, in some circumstances it may result in species being included in collision risk assessments which do not fly at heights which would put them at risk with collision with turbine blades (Johnston et al. 2014). Uncertainty. The Band model provides a method to express the uncertainty associated with a collision estimate post hoc. Smales et al. (2013) suggest that it would be possible to use Monte Carlo methods to introduce stochasticity into the model.
Bolker et al. (2014)	Probability of collision. Bolker et al. (2014) have chosen to use a constant probability of collision rather than calculate a variable collision probability. The use of a single constant probability removes the theoretical calculation of the probability of collision and the associated uncertainty of factors such as avoidance.
Desholm (2006)	Probability of collision. Desholm (2006) has chosen to use a constant probability of collision rather than calculate a variable collision probability. The use of a single constant probability removes the theoretical calculation of the probability of collision and the associated uncertainty of factors such as avoidance.
Podolsky (2008)	NA
Holmstrom et al. (2011)	Angle of approach. Holmstrom et al. (2011) demonstrate that the angle of approach has a significant effect on the probability of collision and thus the estimates of mortality. It is therefore important to ascertain which model is more appropriate for the case study and that this may be different for long distance migration than for breeding seabirds foraging from a colony.
Eichhorn et al. (2012)	Perspective. The models vary in perspective, with the majority, including the Band model, being turbine-based and focussing on the number of birds encountering and colliding with a turbine. Eichhorn et al. (2012) however present an agent-based model which considers collisions from the perspective of the individual and estimates the number of turbines a bird encounters.
U.S. Fish and Wildlife Service (2013)	Onshore and offshore. The U.S. Fish and Wildlife Service model allows for estimates to be updated when information is available. In this case, carcasses provide information on the actual number of collisions. The model was developed for onshore wind farms where carcass searches are possible, however this method would be less applicable for the offshore environment, although new technologies offshore may make this possible. Uncertainty. The Band model provides a method to express the uncertainty associated with a collision estimate post hoc. The U.S. Fish and Wildlife Service model uses Bayesian methods which allows for the consideration of uncertainty. Amount of input. The Band model has many input parameters relating both to the birds (flight speed, morphometrics, etc.) and the turbines (rotor speed, blade width, etc.). In

Collision Risk Model	Possible advantages of models compared to the Band model
	relation to birds, there is still much to be learned about behaviour and therefore our knowledge of aspects required within the models, such as flight speed, is limited. In addition for offshore wind, many of the turbines suggested for offshore projects are still under development and therefore only design envelopes can be provided, i.e. a range of values for any given parameter. The approach developed by U.S. Fish and Wildlife Service (2013) removes some of these data requirements by using a Bayesian framework, however it relies on the ability to collect data on actual collisions to validate the model, and thus currently limits the approach to onshore sites. Therefore a Bayesian method is unlikely to be suitable for offshore sites without development of methods to collate data on collisions.

The table below provides an overview of the model output of different CRMs. It should be noted that the significance of predicted mortality is not determined with collision risk models.

Table A3 – Summary of avian collision risk models (from Masden and Cook, 2016)

Model name and reference	Base model	Includes avoidance behaviour	No. of turbines	Tower included	Wind speed/direction included	Oblique angles of approach	Individual or population	Onshore or offshore example	Stochastic	Model output
Band (Band 2012)	-	Y	Multiple	N	N	N	Population	Offshore	N	Number of birds colliding
Tucker (Tucker 1996)	-	N	Single	N	N	N	Individual	-	N	Probability of collision
Biosis (Smales *et al.* 2013)	-	Y	Multiple	Y	N	Y	Population	Onshore	N	Number of birds colliding
Podolsky (Podolsky 2008)	-	Y	Multiple	Y	N	Y	Individual	Onshore	N	Probability of collision
McAdam (McAdam 2005)	Band	N	Single	N	Speed & direction	Y	Individual	Offshore	Y	Probability of collision
Desholm (Desholm 2006)	-	Y	Multiple	N	Direction	N	Population	Offshore	Y	Number of birds colliding
Eichhorn (Eichhorn *et al.* 2012)	Band	Y	Single	N	N	N	Individual	Onshore	Y	Mortality rate
Hamer (Holmstrom *et al.* 2011)	Tucker	N	Single	N	Speed & direction	Y	Individual	-	N	Probability of collision
Bolker (Bolker, Hatch & Zara 2014)	-	N	Multiple	N	N	Y	Individual	Onshore	N	Probability of collision
USFWS (U.S. Fish and Wildlife Service 2013)	-	Y	Multiple	Not specified	N	N	Population	Onshore	Y	Number of birds colliding

A4.2 Overview of metrics used to estimate population level impacts

In the UK a variety of metrics and methodologies has been used to assess the population level impacts of impacts associated with proposed offshore wind farms (REF33), an overview

Table A4 - Description of metrics used to estimate population level impacts of proposed offshore developments (from REF33)

Metrics	Description
Population growth rate	The population growth rate measures the extent to which the size of the breeding population changes on an annual basis. By considering the growth rate of the population in the presence of an offshore wind farm, it should be possible to consider whether the population will remain stable (growth rate=1), increase (growth rate>1) or decrease (growth rate<1) through the life time of the project.
Probability that growth rate <1	As part of the SOSS programme, guidance was produced for using Population Viability Analysis (PVA) to assess the potential impacts of collision-related mortality associated with offshore wind farms (WWT Consulting 2012). Under a PVA approach, stochastic models are used to simulate the impact of additional mortality on populations of species of interest and the proportion of simulations where the population declines (i.e. growth rate <1) calculated.
Probability that population decreases below initial size	The impact of a development is typically assessed in relation to a baseline population size, which may be either the pre-construction population size, the population size of a protected site at designation, the population size from Seabird 2000 (Mitchell et al. 2004), or some other appropriate value. Using stochastic models, the proportion of simulations in which the

Metrics	Description
	population drops below this baseline, either at any point in the lifetime of the project or by the end of the project, could be assessed. Alternative baseline populations, for example, the size of the population at designation in the case of a breeding colony at a protected site, could be used. Mathematically, this metric is nearly identical to the previous metric.
Probability of a population being a given magnitude below the median size predicted in the absence of an impact	With the simulations from stochastic models, rather than looking at the probability or magnitude of a decline, it may be more meaningful to estimate the median population size estimated across all simulations. This could be done either for a single fixed point in time, or at given intervals. A metric to assess the population level impact of a development could be derived by estimating a median size for a population in the absence of it and then calculating the proportion of simulations for a population in the presence of the development that are (a given magnitude) below this median population size.
Ratio of median impacted to unimpacted growth rate	Considering the growth rate of a population only in the presence of an offshore development enables an assessment of whether the population will remain stable, increase or decrease over time, but it does not make it possible to quantify the impact of the development on that growth rate. By comparing the growth rate of the population in the presence of a development to that expected in its absence it is principle possible to quantify what annual impact the development is having on a population.
Ratio of impacted to unimpacted population size	Population models can be used to estimate the size of a population through time both with and without the impact of an offshore development. Comparing the ratio of the size of these two populations offers a relatively easy to interpret statistic with which to assess the population level impact. The ratio could be derived either from a simple deterministic model, or taken from the mean or median values simulated using a more complex stochastic model, with or without density-dependence. The ratio of population sizes could be estimated either at a fixed point in time, e.g. the end of a project, or at a series of intervals throughout the life time of a project.
Change in probability that growth rate <1	Where simulations show that a population may already be at risk of declining in the absence of a development, for example if more than 50% of simulations have a growth rate <1, simply quantifying the probability of a population decline in the presence of an offshore development may not be meaningful. To assess the population level impact it would be necessary to determine how much greater the probability of a decline is in the presence of the development than in its absence. This could be done either at a single fixed point in time, or at intervals throughout the life time of the project.
Change in probability of a population decreasing by a given magnitude	At many colonies throughout the UK, seabird populations are already declining (JNCC 2014). As a consequence, the presence of a development is unlikely to increase the probability of the growth rate at these colonies being <1, especially if all the simulations from the baseline scenario already have a growth rate <1. However, the presence of the development may cause a further reduction in the magnitude of growth rate. It may, therefore, be more meaningful to consider the change in probability of a population decreasing by a given (though almost certainly artificial) threshold, e.g. a 10% increase in the probability of a 5% decline.
Probability of growth rate being x% less than unimpacted growth rate	With growth rates simulated from stochastic models, it may be desirable to estimate a mean or median value for the unimpacted population and calculate the proportion of simulations in which the growth rate of the impacted population is lower, or a given percentage lower, than this value. This approach has the advantage of allowing a probabilistic forecast of the impact of the offshore development on a population, e.g. there is a 50% chance that the development will reduce the population growth rate by 10%.

A5 Additional information methods and models for habitat use birds

Studies on the degree of avoidance, the cost of avoidance and the availability of alternative foraging habitat are aimed at calculating expected changes in vital rates (growth, reproduction, survival) given the offshore wind farm development scenario under study. These changed rates are then used to study the effects of each scenario on the population dynamics (Van Kooten et al, 2017 (REF12)).

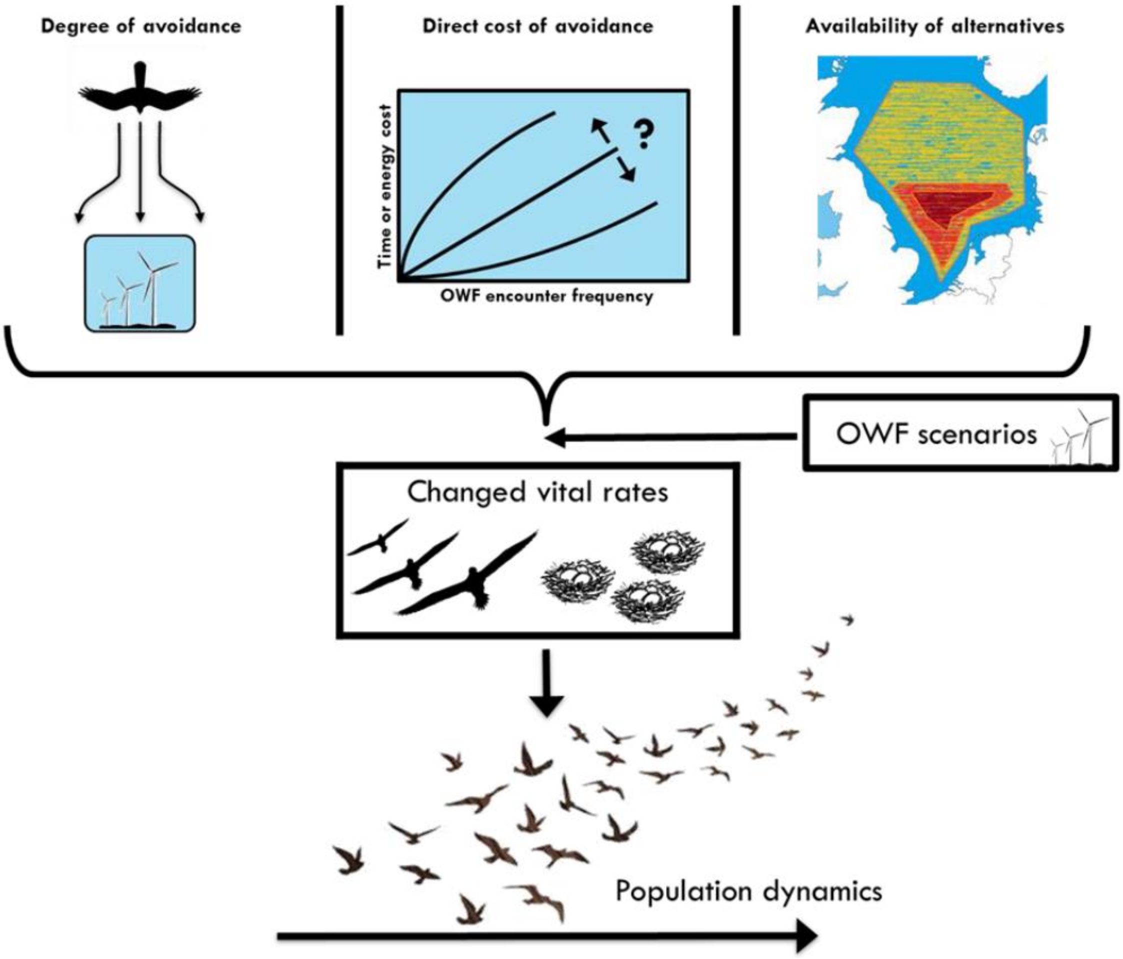
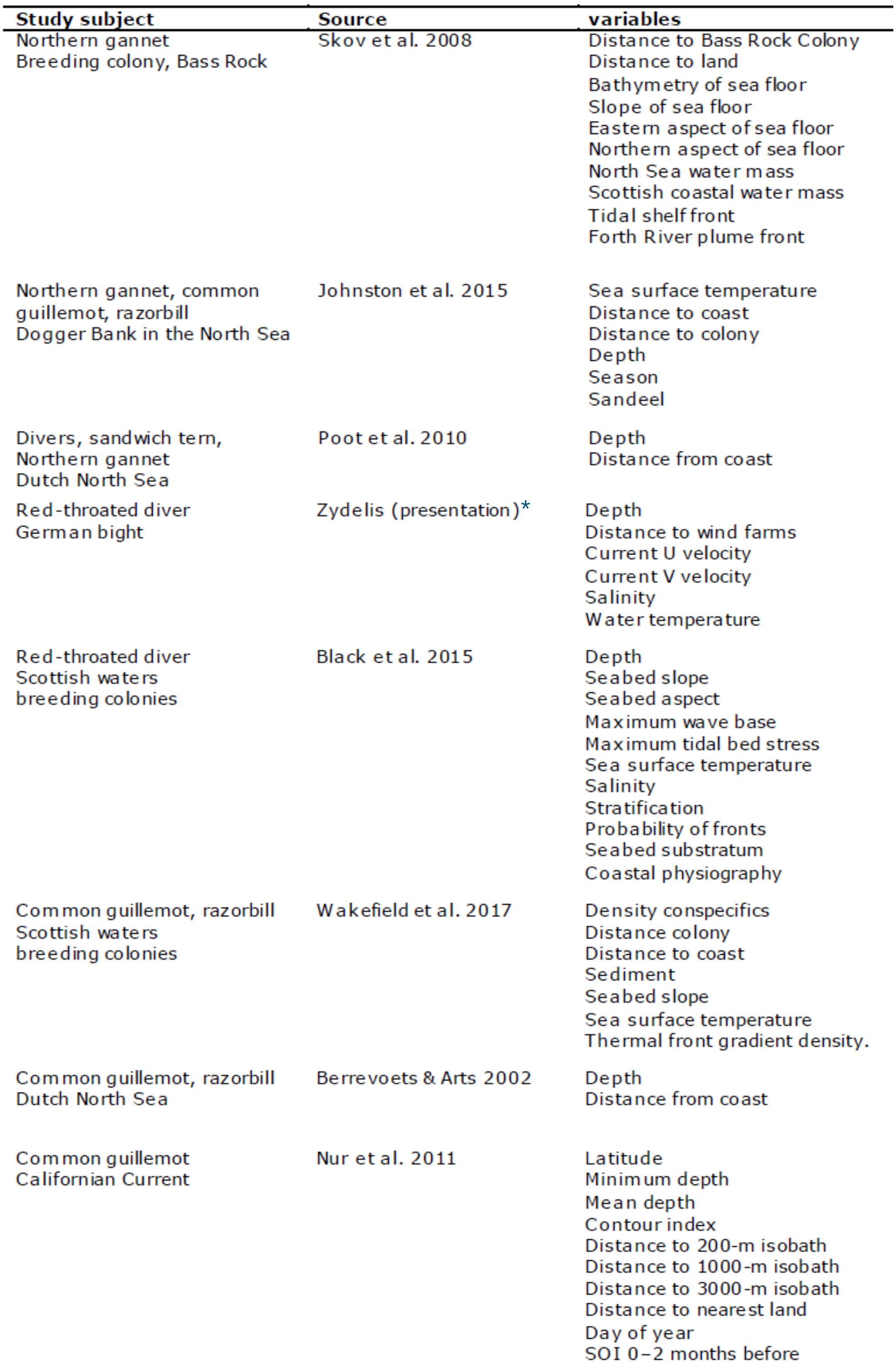


Figure A1 – Schematic representation of proposed analysis of habitat loss related to birds (REF12)

Table A5 – Variables in existing (non-dynamical) habitat modelling studies of the Northern gannet, common guillemot, razorbill, red-throated diver and sandwich tern (source: REF12)



Study subject	Source	variables
Northern gannet Breeding colony, Bass Rock	Skov et al. 2008	Distance to Bass Rock Colony Distance to land Bathymetry of sea floor Slope of sea floor Eastern aspect of sea floor Northern aspect of sea floor North Sea water mass Scottish coastal water mass Tidal shelf front Forth River plume front
Northern gannet, common guillemot, razorbill Dogger Bank in the North Sea	Johnston et al. 2015	Sea surface temperature Distance to coast Distance to colony Depth Season Sandeel
Divers, sandwich tern, Northern gannet Dutch North Sea	Poot et al. 2010	Depth Distance from coast
Red-throated diver German bight	Zydelis (presentation)*	Depth Distance to wind farms Current U velocity Current V velocity Salinity Water temperature
Red-throated diver Scottish waters breeding colonies	Black et al. 2015	Depth Seabed slope Seabed aspect Maximum wave base Maximum tidal bed stress Sea surface temperature Salinity Stratification Probability of fronts Seabed substratum Coastal physiography
Common guillemot, razorbill Scottish waters breeding colonies	Wakefield et al. 2017	Density conspecifics Distance colony Distance to coast Sediment Seabed slope Sea surface temperature Thermal front gradient density.
Common guillemot, razorbill Dutch North Sea	Berrevoets & Arts 2002	Depth Distance from coast
Common guillemot Californian Current	Nur et al. 2011	Latitude Minimum depth Mean depth Contour index Distance to 200-m isobath Distance to 1000-m isobath Distance to 3000-m isobath Distance to nearest land Day of year SOI 0–2 months before

* In addition to REF12: Garthe et al (REF26) published an analysis of spatio-temporal patterns of divers in the German North Sea. By merging data from scientific projects and environmental impact, they were able to interpolate distribution patterns on a 1 km x 1 km grid. These reflect certain regional, annual variability that can most likely be explained by varying abundance in bentho-pelagic fish stocks as well as by variances in the hydrodynamic systems.