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ERA Acute

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The ERA Acute methodology will be the new industry standard environmental risk assessment (ERA) method on NCS in 2019, replacing the currently used MIRA method.

ERAs are carried out with the purpose to assess and ensure acceptable environmental risk for oil and gas offshore operations, aiming to minimize the risk to the environment. ERA Acute has been developed by leading ERA experts, and provides the mean to evaluate the potential risk from an acute oil spill in the marine environment.

The ERA Acute method includes four environmental compartments: the sea surface, shoreline, water column and seafloor. ERA Acute uses input data from an oil spill trajectory model and biological resource data, and calculates the potential environmental risk (impact and recovery time) for biological resources in all compartments.

The ERA Acute software tool provides relevant visualization of the output results from the ERA Acute method, such as maps, graphs and tables. The tool has applications for environmental risk management, such as a risk matrix and a comparison tool which may support a spill impact mitigation analysis (SIMA).

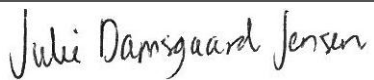## Report 3: ERA Acute Phase 3 – Surface compartment

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The report (2015) presents the ERA Acute method for the sea surface compartment. The report gives a detailed description on how the ERA Acute method calculates the impact and recovery for sea surface resources (e.g. sea birds) after a potential acute oil spill.

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TOTAL

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REPORT

ERA Acute Phase 3 – Surface compartment

Statoil and Total

Revision and Approval Form

TECHNICAL REPORT		
Title		
ERA Acute Phase 3– surface compartment		
Report No.	Revision Date	Rev. No.
37571	22.05.2015	04
Client	Client contact	
Statoil and Total	Anja Johansen Haugerud, Grethe Kjeilen-Eilertsen	

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Rev. No.	Revision History	Date	Prepared	Verified	Approved
01	First draft to customer – impact phase	27.11.2014	AB	JDS	JDS
02	Added lag and recovery phase	03.03.2015	AB	KS	JDS
03	Final Draft	21.04.2015	AB	KS, JDS	JDS
04	Final Report	22.05.205	AB	KS	JDS

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Terms and definitions

Term	Definition and description
Age structure	Age structure refers to cohort size within a population. Parameters related to age structure include: (1) Fecundity (birth rate), (2) Generation time, and (3) Death rate.
Carrying capacity (K)	Ecologists define carrying capacity as the maximum stable population size that a particular environment can support over a relatively long period of time. Carrying capacity, K, is a property of the environment, and it varies over space and time with the abundance of limiting resources. For any given organism, there will be a maximum number of individuals that the environment can support without consistently degrading the environment to the point where it can no longer support that number of individuals. Generally, as population size approaches carrying capacity, the amount of some key resource declines per capita to the point where individuals experience either a higher death rate or a lower fecundity; thus, as population size approaches carrying capacity, the rate of population growth declines towards zero.
Closed population	A population with no net immigration (I) or emigration (E) (I=E=0).
Cohort	A cohort is a group of individuals of the same age. In a typical population, the cohort size will vary with age. In a typical population, younger cohorts will be larger than older cohorts.
Compensating density dependence	Increase in death rate and/or decrease in birth rate exactly offsets any change in population size, so that the population stays at the same size.
Death rate	The rate at which individuals of a certain age die. Note that death rates often vary with age with either the very young or the very old displaying the greatest death rates.
Default value	A value used for missing parameters in the models. They should be either "neutral" or "conservative", with respect to their effect on the variable that is modelled.
Demographics	The vital statistics of a population, particularly those statistics which can impact present and future population size. Two statistics that are of particular importance are a population's age structure and a population's sex ratio.
Fecundity [birth rate]	Refers to the average birth rate associated with a population. The greater a population's fecundity, given everything else is constant, the faster a population will increase in size. Note that fecundity typically varies with the age of individuals. In a matrix model, the fecundities must incorporate two types of survival (1) survival of breeders (from census to next breeding) (2) survival of newborns (from birth to next census).
Fundamental net reproductive rate R (or λ)	Measure of change in population per time. $\ln R = \ln R_0 / T$ where T is length of a generation. See Net reproductive rate R0 and Intrinsic rate of natural increase below (r = lnR).
Generation time	The average span between the birth of individuals and the birth of their offspring. Other factors being equal, a shorter generation time will result in faster population growth. Species which are capable of reproducing more than once will display overlapping generations, meaning that parental cohorts and progeny cohorts can be alive (and potentially competing with one another) at the same time.
Hypothermia	Medical emergency that occurs when your body loses heat faster than it can produce heat, causing a dangerously low body temperature. Normal body temperature for humans is around 37 °C. When the body temperature drops, the heart, nervous system

Term	Definition and description
	and other organs cease to function normally. Hypothermia can eventually lead to heart and respiratory failure and ultimately death.
Intrinsic rate of natural increase (maximum) r_{max} Also referred to in the literature as r, "true", "incipient", "inherent", "Malthusian parameter"	The maximum intrinsic rate of natural increase is the rate of growth of a population when that population is growing under ideal conditions and without limits, i.e., as fast as it possibly can. This rate of growth implies that the difference between the birth rate and death rate experienced by a population is maximized. In most environments a population is not able to achieve this maximum rate of growth (see Realized rate of population increase). A population that is not growing maximally can still experience exponential growth (e.g. the human population). A population with a higher intrinsic rate of increase will grow faster than one with a lower rate of increase. The value of r_{max} for a population is influenced by life history features, such as age at first reproduction, the number of young produced, and how well the young survive."
Iteroparity	Organisms that produce more than one clutch of offspring (progeny) per life time are said to be iteroparous. The advantage of iteroparity is that it allows organisms to display more than one statistical opportunity at producing a successful litter. All species in the sea surface compartment is regarded to display iteroparity.
K-traits	Traits that maximise the chance of surviving in the environment where the number of individual is near the carrying capacity (K) of the environment (high intraspecific competition). The organism are called K-selected species and is characterised by having long life span and slow development, high probability of surviving to adulthood, late reproduction, large body size and low reproductive rate. They typically invest in parental care.
Life history	The traits that affect an organism's schedule of reproduction and survival (from birth through reproduction to death) make up its life history. Examples of some major life history characteristics include: Age at first reproductive event, reproductive lifespan and aging, number and size of offspring.
Net reproductive rate R0	Average number of offspring produced by an individual in its lifetime
Overcompensating	Death rate increases and/or birth rate decreases as population size goes up, so strongly that an initial increase in population size will result in a population decline.
Physiological	Characteristic of an organism's health or normal functioning ability. Physiological effect includes e.g. chemo toxic effects or mechanical soiling effects of plumage or fur.
Population	All the organisms within an area (or volume) belonging to the same species. The area that is used to define a population is such that breeding is possible between any pair within the area and more probable than cross-breeding with individuals from other areas. Technically, genetic relationship is used to distinguish whether an individual belongs to a population or not.
Population size	The number of individuals in a population. If a population is defined in terms of some geographical range, then that population's size is the number of individuals living in the defined area. If a population is defined in terms of some degree of reproductive isolation, then that population's size is the size of its gene pool. Size is a fundamental and important population property but can be difficult to measure directly.
Population density	The number of individual organisms of a certain species per unit area or volume.
Population distribution	The pattern of dispersal of individuals within an area or volume.

Term	Definition and description
	There are three main patterns for population distribution: (1) Clumped distribution (attraction), (2) Uniform distribution (repulsion), and (3) Random distribution (minimal interaction/influence).
Population growth	The simplest case of population growth occurs when no limitations on growth exists within the environment. Two things occur in such situations: (1) The population displays its intrinsic rate of increase and (2) The population experiences exponential growth.
r-traits	Traits that contribute to a high population growth rate. The organism are called r-selected species and is characterised by having short life span and rapid development, low probability of surviving to adulthood, early reproduction, small body size and high reproductive rate. They typically invest little in parental care.
Realized rate of population increase	The rate of growth of a population when that population is growing under natural conditions. The realized growth rate in wild populations is lower than the intrinsic rate of population increase, since wild populations will be affected by different limiting factors. A population in the wild will not experience maximum growth.
Semelparity	Organisms that produce one clutch of offspring (progeny) per life time are said to be semelparous. The advantage of semelparity is that at the point of reproduction few if any resources need be devoted to survival past reproduction. None of the species in the sea surface compartment is regarded to display semelparity.
Sex ratio	The number of males and females in a population. Usually assumed to be 1:1
Undercompensating	Death rate increases and/or birth rate decreases as population size goes up, but the change is not great enough to keep the population from continuing to grow.
Unstructured population model	Model that ignores differences between individuals, and pretends that a total headcount – irrespective of e.g. age structure – provide all the necessary information for predicting future population changes.

Executive summary

This report presents the ERA Acute surface compartment model and includes equations and descriptions of how to calculate *impact* (N), *impact-time* (t_{imp})*, lag-time* (t_{lag}), *restitution time* (t_{res})*, recovery time* (t_{rec}) and a *resource impact factor* (RIF). A look-up table is developed for the necessary parameters.

The surface compartment is comprised of sea turtles, sea birds and marine mammals. The resource unit (N) is a population, which is characterised by (1) population density, (2) population distribution and (3) population size. Populations are assigned to different wildlife groups depending on the species characteristics related to their *individual vulnerability* and *population vulnerability*:

(1) individual vulnerability refers to a species physiological and toxicological sensitivity, and behavioural factors affecting the probability of fouling
(2) population vulnerability refers to vital life history parameters, such as fecundity and survival, affecting the potential rate of growth and long-term population size.

The biological resource data required to run ERA Acute Level B indirectly include other factors that makes a species vulnerable to oil pollution such as population size, habitat usage, flocking and aggregation tendency.

The report is divided into the following four main sections: (1) the impact phase, (2) the lag-phase, (3) the restitution phase and (4) total recovery and resource impact factor. A description of each section with key equations and parameters is presented below.

Impact phase

Impact is reported as number of killed individuals or as population fractions (*N*). The two key impact equations are:

$$(1) \quad N_{let} = \sum_{i=1}^{n} p_{beh} \times Cov_i| > T \times p_{phy}|(Hoil_i > T) \times N_i \qquad \textbf{Eq. 1.1}$$

and

$$(2) \quad N_{let} = \sum_{i=1}^{n} N_i - \left(1 - p_{beh} \times Cov| > T \times p_{phy}\right)^{T_{exp}} \times N_i \qquad \textbf{Eq. 1.2}$$

Eq. 1.1 is a modification of the equation used in ERA Acute Level A.3, and includes two new parameters, p_{beh}, the probability of encountering the sea surface and p_{phy}, the conditional probability of mortality given encounter with oil above an oil film thickness (*T*). Eq. 1.2 is new for Level B and is an approach to incorporate exposure time by including the oil drift statistic parameter T_{exp} in the impact equation.

Both equations utilise a generic look-up table for 13 wildlife groups that is constructed for the parameters, p_{beh} and p_{phy} (Table 1). The look-up table is derived from species-specific look-up tables (Table 10 and Table 11 in Chapter 3.2.2), using a scientifically verifiable method. Uncertainty is handled by providing three estimates for each parameter, low (least conservative), best and high (most conservative).

A new, more conservative threshold level (T) for lethal oil film thickness of 2 μm for seabirds (wildlife group 1- 6) is recommended. For the remaining wildlife groups (7-13) it is recommended to keep the threshold thickness of 10 μm threshold that was derived in ERA Acute Phase 1 due to lack of data supporting another threshold level (Table 1).

Table 1. A generic look-up table for p_{beh} and p_{phy} and T.

NO	Wildlife groups	p_{beh}			p_{phy}			T (μm)
		Low	Best	High	Low	Best	High	
1	Pelagic diving seabirds	79%	79%	89%	80%	90%	100%	2
2	Pelagic surface foraging seabirds	45%	45%	51%	80%	90%	100%	2
3	Coastal diving seabirds	67%	67%	76%	80%	90%	100%	2
4	Coastal surface feeding seabirds	31%	33%	44%	69%	78%	87%	2
5	Wetland surface feeding seabirds	48%	48%	54%	80%	90%	100%	2
6	Wading seabirds	35%	35%	35%	80%	90%	100%	2
7	Baleen whales	35%	53%	88%	0.4%	0.4%	0.4%	10
8	Toothed whale	40%	60%	100%	0.8%	0.8%	0.8%	10
9	True seals, walruses and sea lions	83%	90%	96%	0.4%	2.8%	5.8%	10
10	Fur seals	63%	78%	93%	50%	72%	93%	10
11	Sea cows	95%	98%	100%	0.8%	4.3%	8.3%	10
12	Aquatic mammals	79%	88%	97%	50%	72%	93%	10
13	Sea turtles	95%	99%	100%	3.0%	3.0%	3.0%	10

Lag-phase

The lag-time includes more subtle and potential indirect effects of oil contamination that may result in long-term reproductive impairment, caused by influence on habitat occupancy and usage (especially breeding sites) and possibly food availability and oil ingestion. The lag-time equation incorporates the lag-time of shore line cells ($t_{lag,sh}$) and a resource-specific sensitivity factor (SF), and is given by the following equation:

$$(3) \quad t_{lag,su} = \sum_{i=1}^{n} N_{hab_i} \times t_{lag,sh_i} \times SF_r \qquad \text{Eq. 1.3}$$

Prerequisite knowledge need to estimate the lag-time for the shoreline compartment is resource distribution, breeding sites and general biology of the resource, such as habitat preferences and usage. A practical approach is to pre-define areas as important breeding sites, and use the biological resource data to estimate the population density in the area as an approximation of the relative importance of each habitat site.

Restitution-phase

The restitution time (t_{res}) is estimated by using a discrete logistic population model. A generic look-up table for population growth rate (R) is provided for eight wildlife groups (Table 2). An R–calculator is constructed to help the user estimate population growth rates from populations with limited demographic data available. The calculator is based on several different approximations to the Lotka-Euler equation.

The population model is kept simple to minimize the input data requirement. An impact time (t_{imp}) is included in the model, as 0 or 1 time unit (e.g. years). The model is given by the following equation:

$$(4) \quad N_{t+1} = \frac{N_t R}{1 + (aN_t)^b} \qquad \text{Eq. 1.4}$$

The model includes the following parameter; R = the fundamental net reproductive rate, $a = (R\text{-}1)/K$, where K is the carrying capacity of the population and b = a factor determining the density dependence type.

The key equation used in the R-calculator to estimate the fundamental net reproductive rate is:

$$(5) \quad 1 = pR^{-1} + l_\alpha bR^{-\alpha} - l_\alpha bp^{(\omega-\alpha+1)}R^{-(\omega+1)} \qquad \text{Eq. 1.5}$$

The calculator consists of the demographic parameters: α = age at first reproduction, ω = age at last reproduction, b = annual birth rate of female offspring, lα = pre-reproductive survival probability and p =adult survival probability. Detailed differences in vital rates for different age classes or stages may be included as weighted average values if the necessary demographic data is available.

Table 2. A generic look-up table for population growth rates (R and r).

Wildlife group	Typical species	Families	R	r
Albatross and skuas	Albatross (Southern royal, Grey-headed Antipodean, Northern royal), skua (brown, great, subantarctic), Northern fulmar	Diomedeidae, Stercorariidae, Procellariidae	1.05	4.9%
Auks, petrels and shearwaters,	Auks (razorbill, common guillemot, Atlantic puffin), petrels (black, white-chinned, Chatham), shearwaters (Bullers, flesh-footed), Black-legged kittiwake	Alcidae, Procellariidae	1.10	9.5%
Gannets, penguins, gulls and terns	Gannets (northern, masked australasian), penguins (Snares crested, Southern rockhopper, Fiordland crested), Gulls (black-backed, lesser black-backed, little) and terns (common white, common, sandwich, Caspian)	Sulidae, Spheniscidae	1.15	14.0%
Cormorants, shags, divers, ducks and goose	Cormorant (great), shags (European, Campbell Island, spotted, Auckland Island), divers (red throated), ducks (common eider, common scooter) and goose (barnacle, snow, Bewicks swan)	Anatidae, Gaviidae	1.20	18%
True seals, sea lions and fur seals, baleen whales	Grey seal, harbour seal, ringed seal, Antarctic fur seal, subantarctic fur seal, blue, humpback and southern right whales	Balaenopteridae, Phocidae	1.13	12.2%
Walrus, aquatic mammals	Walrus, polar bear, Eurasia otter, sea otters	-	1.06	6.0%
Toothed whales, sea cows,	Bottlenose dolphin, killer whale, harbour porpoise, Florida manatee	Delphinidae, Phocoenidae, Trichechidae, Dugongidae	1.03	3.0%

Total recovery and RIF

The total recovery time (t_{rec}) and a Resource Impact Factor (RIF) is illustrated in Figure 1 and is given by the following equations:

(6) $t_{rec} = t_{imp} + t_{lag} + t_{res}$ **Eq. 1.6**

and

(7) $Resource\ Impact\ Factor\ (RIF) = \sum_{t=0}^{t=t_{res}} TLR - \left[\left(\frac{N_{t1} + N_{t0}}{2} \right) \times (t_1 - t_0) \right]$ **Eq. 1.7**

The time parameters calculated are calculated in the impact, lag and restitution phases, respectively. TLR is the threshold set for recovery, and is defined as the population size the population must reach in order to be regarded as recovered. As a practical approach TRL may be set to a proportion of K (e.g. 0.95K), where K is defined as the pre-spill population size.
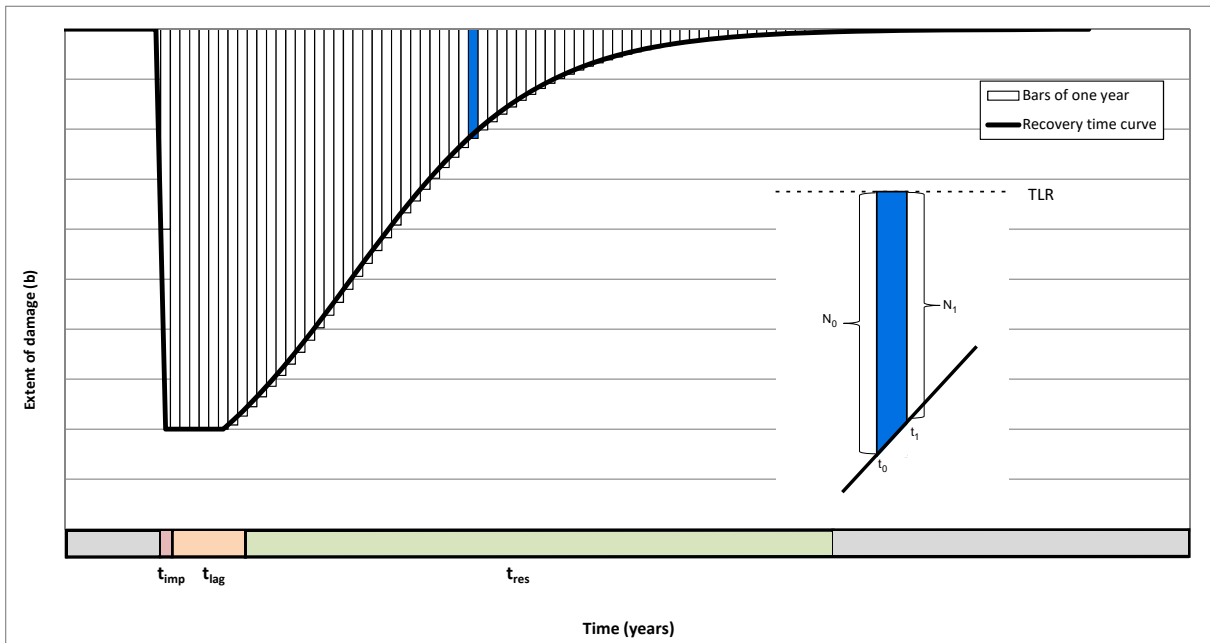
Figure 1. Illustration of the total recovery time (t_{rec}= t_{imp} + t_{lag} + t_{res}) and the RIF.

A schematic diagram of the ERA Acute impact, lag and recovery phase for the surface compartment is presented below. The user setup the oil drift model (OSCAR) to run three stochastic oil drift simulations using three threshold thicknesses for film thickness. One threshold is set close to zero and the two other is set equal to the threshold thickness of the wildlife group of interest. The output from the oil drift model is used to calculate the impact using the same algorithms as Level A.3 but with new impact equations and look-up tables. The impact may be presented on a map or summarised at different levels (simulation, scenario, DSHA) using various statistics.

The lag-time is a separate calculation step, using data from the shoreline compartment and values from the user or a look-up table. The result is added to the impact and restitution time to yield the total recovery time and the RIF. The pre-spill population size (post-population size minus number of killed individuals) for each simulation is used as input to the population model, either as absolute numbers or relative fractions. If the generic population growth look-up table is unsuited for the population of interest, the user may calculate the fundamental net reproductive population growth rate thought use the R-calculator. No aggregation of results

is performed during the calculations. This enables estimation of different statistics at the end of each major calculation step and performing statistical testing.

INPUT TO OSCAR

TFT (Terminal film thickness)

LT1 (lethal film thickness for W1-W6)

LT2 (lethal film thickness for W7-W13)

INPUT IMPACT

Hoil (TFT)

Cov (LT1)

Cov (LT2)

T_{exp} (LT1)

T_{exp} (LT2)

* UTM Grid.txt
* UTM Summary SH
* at arrive ref-log

Algorithm - IMPACT

For each cell and simulation:

For each wildlife group in the surface compartment

If Hoil > Lethal threshold for the wildife group Then

Get p_{beh} and p_{phy} and T from look-up table
Eq.1.1 or 1.2 (using low)
Eq.1.1 or 1.2 (using best guess)
Eq.1.1 or 1.2 (using high)

Else

N_{imp} = 0 (no damage)

End If

Next wildlife group

Note 1: Hoil is read from the UTM Grid.txt file using a threshold thickness of TFT (as thin as the oil drift model allow

Note 2: Cov and Texp is read from different UTM Grid.txt files based on the threshold thickness T:)

Look-up table for p_{beh} and p_{phy} and T

Wildlife group (individual vulnerability)

Species name

p_{beh} (low, best guess, high)

p_{phy} (low, best guess, high)

T (threshold thickness for mortality)

Resource data - population distribution and density

p_{ref} - look-up table for species

Algorithms (pre- and post-processing based on algorithms developed in ERA Acute Level A.3)

| Cell | Simulation | Scenario | DSHA |

Maps

Google Earth

Algorithm - LAG

For each cell and simulation:

For each pre-defined habitat in the surface compartment
If cell i is affected Then
Get N_b and SF from look-up table
Eq. 1.3
Next cell in habitat
Next pre-defined habitat

Sum the lag-time for each pre-defined habitat

To recovery phase

Simulation	$N_{let (low)}$	$N_{let (best guess)}$	$N_{let (high)}$
Sim. 001	5%	12%	23%
Sim. 002	0%	0%	3%
Sim. 003	14%	32%	59%
Sim. 098	0%	0%	0%
Sim. 099	1%	4%	23%
Sim. 100	4%	8%	16%

Examples of statistics

Measure of central tendency	Mean	
	Median	
Measure of variability	Standard deviation	
	Minimum values	
	Maximum values	
Interval estimate	Confidence interval	
Statistical distribution	Quartiles	
	Percentiles	
Discretisation	MRA categores	
	Other categories	

Tables, graphs etc.

Look-up table for N_b

Wildlife group

Species name

N_b (number of individuals or population fraction in cell)

Sensitivity factor (SF)

DSHA

Scenario

Simulation

ID cell

Lag-time (from shoreline compartment)

INPUT Population model

N – Pre-spill population size

K - The carrying capacity

TLR - Threshold level for restitution

b - Type of density dependence

INPUT R-calculator

α – Age at first reproduction

ω – Age at last reproduction

b - Annual birth rate of female offspring

$l\alpha$ – Pre-reproductive survival probability

p - Adult survival probability

Algorithm - RESTITUTION, RECOVERY AND RIF

For each simulation

Calculate the restitution time   Eq. 4.2
Calculate recovery time   Eq. 5.1
Calculate RIF (relative and absolute) Eq. 5.3

Next simulation

Look-up table for R

Wildlife group (population vulnerability)

Species name

R

R-calculator

Use the R-calculator for species/populations to calculate R or use a generic value from the look-up table

Extent of damage (b)

RIF

Recovery curve (impact-lag-restitution)

t_{imp} t_{lag} t_{res}

Time (years)

| Simulation |

Simulation	$t_{rec (low)}$	$t_{rec (best guess)}$	$t_{rec (high)}$
Sim. 001	0.9	2.2	4.1
Sim. 002	0.0	0.0	0.5
Sim. 003	2.5	5.8	10.4
Sim. 098	0.0	0.0	0.0
Sim. 099	0.2	0.7	4.1
Sim. 100	0.7	1.4	2.9

Examples of statistics

Measure of central tendency	Mean	
	Median	
Measure of variability	Standard deviation	
	Minimum values	
	Maximum values	
Interval estimate	Confidence interval	
Statistical distribution	Quartiles	
	Percentiles	
Discretisation	RISK categories	
	Other categories	

Tables, graphs risk matrix etc.

Algorithms handling scenario and DSHA

| Scenario | DSHA |

Example of a risk matrix

A list of all parameters used in the Level B calculation is given below. The list is divided into the four main parts of the report, each with a description and origin of the parameter. In addition to the parameters presented in this report, the model requires biological resource data.

Impact phase		
Parameter	**Description**	**Origin**
p_{beh}	Probability of encounter of oil	Look-up table
p_{phy}	Probability of lethal effect (given encounter of oil)	Look-up table
Cov	Time average coverage	Oil drift model
p_{exp}	Probability of exposure	Look-up table
N	Resource unit, given as numbers or fractions	Resource data
$Hoil$	Time averaged film thickness	Oil drift model
T	Threshold film thickness for oiling	Look-up table
T_{exp}	Time averaged exposure time	Oil drift model
Lag phase		
Parameter	**Description**	**Origin**
N_{hab}	N_{hab}	Resource data and expert judgment
T_{lag}	Lag-time for the shoreline grid cells within a habitat of interest	Previous calculation (shoreline compartment)
SF	A resource-specific sensitivity factor (0-1).	Expert judgment
Restitution phase		
N_t	Population size (relative or absolute) one time-step after the impact has occurred	Previous calculation (impact phase)
R	The fundamental net reproductive rate	Look-up table or R-calculator
K	The carrying capacity of the environment	Resource data (possible expert judgment)
a	Factor equal to (R-1)/K	Intermediate calculation
b	Measure of different types of density dependence	Standard value or expert judgment
R-calculator		
Parameter	**Description**	**Origin**
α	Age at first reproduction (year)	Literature
ω	Age at last reproduction (year)	Literature
b	Annual birth rate of female offspring	Literature
$l\alpha$	Pre-reproductive survival probability	Literature

p	Adult survival probability		Literature
Recovery phase and resource impact factor			
Parameter	**Description**		**Origin**
t_{imp}			Previous calculation
t_{lag}			Previous calculation
t_{res}			Previous calculation
TLR.	Threshold for recovery		Standard value or expert judgment

New from Level A

Impact:

- Refinement of wildlife groups
- Definition of two new parameters for individual vulnerability of oil contamination. The result is a species-specific and a generic look-up table.
- A new threshold thickness for oiling is suggested for seabirds (wildlife group 1-6).
- Constructed an equation that uses the statistic T_{exp} (exposure time) from the oil drift model.

Lag, restitution, recovery and RIF:

- Developed in the current Phase 3 of the project.

Comparisons with the OLF 2007 / MIRA approach

The major differences between the ERA Acute Level B approach and the MIRA approach is given in Table 3.

Table 3. Comparison of the ERA acute Level B approach and the MIRA approach.

Phase	ERA Acute	MIRA
Impact	- Film thickness and coverage P_{beh} and P_{phy} - Threshold levels - Time variable	- Oil mass - Effect keys - Discrete categories - No time variable
Lag	Included as a separate function	Included in the damage keys
Restitution	- Population model - No aggregation of results	- Damage keys - Aggregation of results

Conclusion

Based on the requirement of building a globally applicable tool we have suggested a relatively simple approach to minimise the number of required parameters to run the model. Generic look-up tables and standard values for most of the parameters are provided and the background data and methodology used to derive the values are documented.

For the impact phase we have performed a refinement of the wildlife groups, and the Level A.3 basic impact equation, as well as suggested new threshold levels for oil film thickness and

constructed an equation to incorporate exposure time as a variable in the impact equations. This adds transparency to the input data used in the model, making it easier to refine and update the input data over time. The new impact expression should yield more realistic results than the Level A.3 equation, especially for seabirds. Including time as a variable in the impact equation ensures that an area polluted with oil over a long time period yields higher impact than an area polluted with oil over a short time period (given everything else equal).

The new, individual vulnerability data is derived from different surveys, scientific studies and expert judgement and the data was normalised to obtain comparable values. Although this method is scientifically sound, the choice of reference study used to select the normalising values is decisive for the final result.

The lag-phase methodology suggested utilising the lag-time calculated from the shoreline compartments and a resource-specific sensitivity factor. The sensitivity factor (SF) allows an "expert user" to make use of her/his site-specific knowledge of the affected area(s) and the ecology of the biological resource in question to include more subtle and potential indirect effect of the oil contamination that is not included in the impact equation. Since it includes subjective evaluation a standard or neutral value may be used depending on the objective of the analysis.

The restitution phase includes a discrete logistic population growth model, a generic look-up table for net fundamental population growth rates (R) and an R-calculator. The model is kept simple to minimise the number of required variables since detailed demographic data is limited for the majority of species and populations in the world. The model is unstructured but detailed knowledge of age- or stage differences in vital rates may be included as weighted average values if this information is known for the impacted individuals and/or the necessary demographic data is available. The R-calculator provides a mean to estimate R-values from species with limited available data (i.e. not detailed demographic data) and may also be used as a tool to improve and refine the generic look-up table for population growth rates over time ("build a library over time").

We have chosen not to include any uncertainty in the life-history parameters or in the population growth rates estimates, partly since the classification is done by subjectively by expert judgment in this report. This may be performed at a later stage when more data is available in the tool.

The model does not incorporate other extrinsic factors than the oil spill. It could indirectly be extended to include environmental stochasticity by allowing the life-history parameters to vary with uncontrolled factors in the environment or indirect factors due to environmental variation. However, this requires temporal correlation among the life-history parameters and the environment factors (e.g. temperature -> survivor, wind –> food availability –> survivor and fecundity), and thus will restrict the use of the model to a few well-known populations. Known extrinsic threats and/or negative population trends should therefore be taken into considerations when evaluating and interpreting the results from the model. More direct effect such as hunting or harvesting of the population can more easily be incorporated, either as a constant (e.g. based on previous years) or as a function of hunting effort and a fixed number (e.g. quota).

To get a better understanding of how the various parameter estimates, equations and models affect the results systematic and thorough and systematic testing should be undertaken.

1 Introduction

ERA Acute is a globally applicable environmental risk assessment tool for oil spills. The goal in the ERA Acute project is to develop a robust, transparent tool for risk assessment. It is intended as an expert tool where the user is skilled in the application and has a fundamental understanding of the methods and input data.

Acona has been given the task to lead the surface compartment in the ERA Acute Level B. ERA Acute Software (SW) consist of four compartments; (1) surface, (2) shoreline, (3) water column and (4) sediment, and is made up of two levels of detail:

- Level A –a risk screening methodology
- Level B - a risk assessment methodology

Input to the impact assessment are oil spill scenarios modelled with an oil drift model. A spill scenario is defined by one release location (e.g. seabed or surface), release rate and release duration and is modelled stochastically based on historical wind and current data. The output from the oil drift model are statistical parameters for each environmental compartment (sea surface, water column, shoreline and sea floor), suitable for determining the exposure and calculating the impact (typically oil volumes, concentrations and film thickness) (cf. Brude & Spikkerud 2014).

1.1 Level A

Level A is a risk screening method which requires a minimum of biological resource data. It is divided into three levels:

- Level A.1 No resource data
- Level A.2: Data on presence/absence
- Level A.3: Data on resource fractions or resource numbers

The basic impact equation, for all levels and compartments are given by the following equation (Spikkerud et al. 2010):

$$Imp_{r,cell,sim,comp} = P_{exp,r,cell,sim,comp} \times P_{let,r,cell,sim,comp} \times N_{r,cell,comp} \qquad \textbf{Eq. 1.1}$$

Eq. 1.1 calculates the impact (*Imp*) for a resource (*r*) in one cell, for one simulation (*sim*) of oil drift in the compartment (*comp*). The calculation steps of impact for simulations, scenarios, defined situations of hazard, as well as calculation of different risk expressions are described in Spikkerud et al. (2010).

The parameter *N* is the biological resource data. At level A.1, N is set to 1, at level A.2 N is either 0 or 1, and at level A.3 is the fraction of the population (0-1) or equivalent resource unit.

The parameter p_{exp} was defined as the probability of an individual being exposed, given that it is present in the grid cell. The parameter was introduced to take into consideration certain factors, e.g. behavioural, that might cause the individual to avoid exposure or have a higher probability of being exposed. In the surface compartment p_{exp} was set equal to the coverage (0-1) of oil in the cell.

The parameter p_{let} was defined as the probability of lethal effect on an individual of the resource in question given exposure in the cell. In the surface compartment p_{let} was set equal to the combined values of the tendency to encounter oil given that there is oil on the sea surface, and the physiological sensitivity towards oil. The values were adapted from French-McCay (2004), with the exceptions of pinnipeds, for which values from the EIF acute project was used (cf. Spikkerud et al. 2005). The wildlife groups and p_{let} values used in Level A are presented in Table 4.

Table 4. p_{let} values for various wildlife groups used in ERA Acute Level A (Spikkerud et al. 2010). The values are adapted from French-McCay (2004), with the exception of pinnipeds, for which values from the EIF acute project was used (cf. Spikkerud et al. 2005).

Wildlife group	p_{let}	Habitat
Dabbling waterfowl	0.99	Intertidal and landward subtidal
Nearshore aerial divers	0.35	Intertidal and landward subtidal
Surface seabirds	0.99	All intertidal and subtidal
Aerial seabirds	0.05	All intertidal and subtidal
Wetland waders and shorebirds	0.35	Wetlands, shorelines, seagrass beds
Surface birds in seaward only	0.99	All seaward intertidal and subtidal
Surface diving birds in seaward only	0.35	All seaward intertidal and subtidal
Surface birds in landward only	0.99	All landward intertidal and subtidal
Surface diving birds in landward only	0.35	All landward intertidal and subtidal
Aerial divers in landward only	0.05	All landward intertidal and subtidal
Surface diving birds in water only	0.35	All subtidal
Aerial divers in water only	0.05	All subtidal
Furbearing marine mammals	0.75	All intertidal and subtidal
Cetaceans	0.001	Seaward subtidal
Manatee, sea turtles	0.01	All intertidal and subtidal
Pinnipeds	0.42	All intertidal and subtidal

1.2 Level B

The work in Level B includes a revision of the current scientific basis for the parameters used in impact phase Level A and development of equations and models for the lag-phase and the recovery phase The basis for level B for the sea surface compartment is based on: (1) the previous work of EIF Acute (e.g. Spikkerud et al. 2006) and (2) the work carried out in previous phases of the ERA acute project (Bjørgesæter 2012b; Bjørgesæter & Spikkerud 2012). These describes the use of impact-time (t_{imp}), lag-time (t_{lag}) and restitution-time (t_{res}) to calculate a recovery time and a resource impact factor (RIF) for each resource assigned to a compartment.

The three time-parameters will be developed in Level B:

- t_{imp}: Time until full impact is observed.
- t_{lag}: Time until contamination has been reduced so much that restitution can start.
- t_{res}: Time from restitution starts until the community is assumed to be intact.

The lag-time will be implemented as a factor and the impact- and restitution-time will be calculated using a population model. The RIF was introduced in Lein et al. (1992), and further used in Moe et al. (2000a; 2000b) and by Brude et al. (2003). The concept of using a geometrical area calculated by extent of impact and time of impact was sustained in the development of EIF Acute (Johansen et al. 2003; Østbye et al. 2003) and used in a linearized form in Spikkerud & Brude (2004) and Stephansen et al. (2005) (Figure 2).

The resource unit (N) for the surface compartment is a population. Minimum required biological resource data for each species in ERA Acute Level B is (1) population size, (2) population distribution, and (3) population density for species. Population size is defined as the number of individuals in a population (e.g. number of individuals in a defined area). The population distribution is defined as the dispersal pattern of individuals within that defined area. Population density is defined as the number of individuals per unit area, where the unit area is the dimension of a grid cell (e.g. a 10×10 km area).

$$RIF = a_{imp} + a_{lag} + a_{res}$$

$$RIF = \frac{\left(t_{imp} \times b_2\right)}{2} + \left(t_{lag} \times b_2\right) + \frac{\left(t_{res} \times b_2\right)}{2}$$
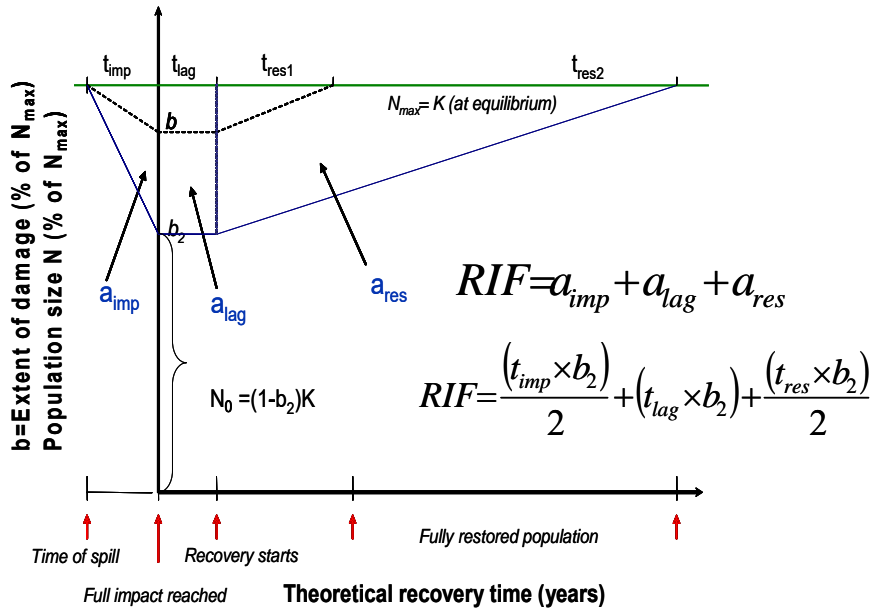
Figure 2. Resource Impact Factor (RIF) calculated from the linear functions of damage and recovery of an oil-sensitive resource. RIF is calculated for a resource as a total over all grid cells, using an average population loss b over all scenarios. Here, two examples are shown, with two levels of impact (b1 and b2). Nmax = size of population before impact assumed to be at ecological equilibrium (denoted K), N0= Population left after full impact, b= size of impact (relative loss of population), timp = duration of impact, tlag = duration of lag-phase before restoration can begin, tres = duration of restitution time years (Spikkerud et al. 2005).

2   Wildlife groups

The wildlife in the surface compartment includes three major wildlife categories; reptiles, birds and mammals. They are organisms with sexual reproduction, discrete breeding season(s) and may breed several times during their lifetime. All relevant species display *K-traits*, although sea turtles also display *r-traits*. The three major wildlife categories are divided further into different wildlife groups each containing different species and populations with different behaviour and sensitivity towards oil spill. The wildlife group presented in this chapter is also as a starting point to create wildlife group based on life history parameter affecting the potential population growth (cf. Chapter 5.3).

In order to perform a semi-quantitative evaluation of existing p_{let} values it was necessary to modify the division of wildlife groups in the look-up table from ERA Acute Level A (cf. Table 4). We aimed to keep as few wildlife groups as possible while at the same time avoiding grouping together species with obvious different behavior with respect to coming in contact with contamination on the sea surface and species with large differences in their vulnerability towards oil. The wildlife groups are reduced from 16 to 13 (Table 5).

Seabirds have been divided into ecological groups as defined by bird ecologists at NINA (e.g. Systad et al. 2007) and in the SEAPOP project (www.seapop.no). These groups are created because the species in each group have similar vulnerability towards oil, similar biological traits and foraging techniques, and most species within each group forage on the same trophic level. For this evaluation, the so-called "dabbling waterfowls" have been taken out of the wildlife group "coastal surface feeding seabirds" and put in a separate group called "wetland surface feeding seabirds". This yields six wildlife groups for birds.

Cetaceans have been split into two groups (baleen & toothed whales). Manatee and sea turtles have been divided into separate groups, and the dugong (*Dugong dugon*) is added to the manatee group, and the group has been renamed to sea cows (Table 5). The original group "furbearing marine mammals" have been split into fur seals & aquatic mammals. Sea lions are grouped with true seals and walruses since they rely solely on their blubber for thermoregulation in water and thus are more similar to these species with respect to the physiological factor of p_{let}.

The habitat description in the look-up table in ERA Acute Level A have been removed since most of the species move between these habitats on a regularly basis and the parameter is not used by the ERA Acute software (ERA-SW).

Table 5. The wildlife groups including description of relevant characteristic for their vulnerability towards oil spills on individual level (behavioural, physiological and toxicological effects).

No	Wildlife group	Description
1	Pelagic diving seabirds	Birds that spend most of their time offshore. The species are skilled swimmers and divers who catch prey in deep water. Some species can dive to more than 100 m (dives down to 200 m have been recorded). The wings are used as flippers when birds dive and the beak is designed so that they can catch fish repeatedly during a single dive. These species usually only come to the coast to breed, often in large colonies. The species spend little time on the wings and are not particularly skilled flyers.
2	Pelagic surface foraging seabirds	Birds that spend most of their time offshore, both swimming on the sea surface and in the air. The species float lightly in the water. Many of the species plunge into the sea from the air to catch prey (deep plunging, pursuit plunging), while others graze at the sea surface or just below. The species are excellent flyers and usually skilled swimmers, but their dive capacity is limited compared to pelagic diving seabirds.
3	Coastal diving seabirds	Birds that spend most of their time in coastal areas on the sea surface. The species are skilled swimmers and divers who catch prey by diving, but in general the species do not dive as deep as pelagic diving seabirds. Several species forage on benthic animals (e.g. mussels) and is for this reason constrained to coastal areas. The species floats heavily in water. Several species are capable flyers. The species in this group spend more time on land than pelagic species, also outside the breeding season.
4	Coastal surface feeding seabirds	Similar to pelagic surface foraging seabirds, but birds in this group spend most of their time in coastal areas. Many of the species plunge into the sea from the air to catch prey (surface

No	Wildlife group	Description
		plunging). The species in this group spend more time on land than pelagic species, also outside the breeding season.
5	Wetland surface feeding seabirds	A subgroup of coastal surface feeding seabirds that are more connected to estuaries, lakes and in particular wetlands than to the "true marine environment" (dabbling waterfowl). The species floats lightly in water. The birds are grazing in shallow water, on the surface or just below the surface.
6	Wading seabirds	Birds that mainly feed on the shoreline. The species typically have long beaks and long limbs compared to other species, which enables them to wade and find food in shallow water. The species do not have webbed feet and do not swim.
7	Baleen whales	Characterized by having baleen plates for filtering food from water, rather than teeth like the toothed whales. The species conserve heat with their large and compact body size and insulating blubber. Oil and vapours may affect exposed sensitive tissues and foul their baleen plates.
8	Toothed whale	Characterized by the presence of teeth rather than the baleen of other whales. The species conserve heat with their large and compact body size and insulating blubber. Oil and vapours may affect exposed sensitive tissues (e.g. eyes, oral cavity).
9	True seals, walrus and sea lions	True seals and walruses conserve heat with their large and compact body size and insulating blubber. More aquatic than otariids (fur seals and sea lions). Sea lions are grouped with true seals and walruses (in contrast among fur seals) since they rely solely on their blubber for thermoregulation in water. Oil and vapours may affect exposed sensitive tissues (e.g. eyes, oral cavity).
10	Fur seals	Otariids (fur seals and sea lions) are more connected to land than true seals. They rely on their fore-flippers for locomotion in a wing-like manner similar to sea turtles. Otariids conserve heat with their large and compact body size and both insulating blubber and fur. Fur seals have dense, waterproof fur and a moderate blubber layer.
11	Sea cows (manatee and dugong)	Fully aquatic, mostly herbivorous marine mammals. Manatees live in warm waters and have a layer of blubber as insulation Although little is known about the effectiveness of manatee blubber as an insulator in cold temperatures it appear that they have limited thermoregulatory capabilities. They may be affected when they inhale volatile hydrocarbons when breathing on the water surface. The dugong is strictly marine, while all manatees use freshwater to some degree.
12	Aquatic mammals	Aquatic mammals such as polar bears, otter and muskrat. The species have dense, waterproof fur but little or no insulating blubber.
13	Sea turtles	Sea turtles are vulnerable to oil at all life stages: eggs on the beach, post-hatchlings and juveniles in the open ocean gyres, sub-adults in near-shore habitats, and adults migrating between nesting and foraging grounds. Inhalation of vapour is of concern for since turtles inhale a large volume of air before submerging when they dive.

THE IMPACT PHASE

3   The impact phase

This section present the results from the impact phase. (1) One activity has been to evaluate the p_{let} values and developing a generic look-up table of the *behavioral* factor and the *physiological* factor for different wildlife groups to be used in the impact equation. (2) Another activity has been to investigate the scientific documentation of threshold values for film thickness and to investigate the possibility to develop a *continuous response curve* for the physiological factor. (3) The last activity was to investigate possibilities to include *time as a variable* in the impact equation.

3.1   Adjusting the Impact Equation

In ERA Acute Level A, the generic impact equation was given by Eq. 1.1 (see Chapter 1.1). To perform activities 1-3 listed above, three adjustments to the impact equation were made.

The first adjustment was to include conditional probabilities for relevant parameters in the equation. The conditional probability measures the probability of an event given that another event has occurred (e.g. Gut 2005). For example a p_{let} value of e.g. 0.9 is only valid <u>if</u> the film thickness (*Hoil*) in the cell is above a thickness threshold (*T*) for the resource *r* of interest. This may be symbolised as p_{let} = 0.9 | *Hoil* > T_r. The second adjustment was to divide the p_{let} parameter in two, i.e. $p_{let} = p_{beh} \times p_{phy}$, where the denotation symbolise the <u>beh</u>avioural factor and <u>phy</u>siological factor (chosen to avoid confusion with the denotation for surface compartment and the p_{let} parameter). The third adjustment was to replace the parameter p_{exp} with coverage (oil drift statistic calculated by the oil drift model), symbolised with *Cov* in the equation. This makes it possible to include the behavioural factor p_{beh} and p_{exp}, which is preferred since both affects probability of exposure and not lethality (cf. Eq. 3.4). It should be noted that this rearrangement have no effect on the impact results since impact is a product of factors (cf. Spikkerud et al. 2010; Spikkerud et al. 2005; Tørrhaug et al. 2006). The generic impact equation for the surface compartment for a single cell can then be re-written as,

$$N_{let} = p_{beh} \times Cov| > T \times p_{phy}|(Hoil > T_r) \times N \qquad \textbf{Eq. 3.1}$$

and for a single simulation as,

$$N_{let} = \sum_{i=1}^{n} p_{beh} \times Cov_i| > T \times p_{phy}|(Hoil_i > T_r) \times N_i \qquad \textbf{Eq. 3.2}$$

where N_{let} is the is the total number of individuals (or population fraction) with effect (here lethal), *i* is the cell number and *n* is the number of cells in the data-set grid. p_{beh} is the probability of encounter with the sea surface, *Cov* is the time averaged cell-coverage for time averaged oil film thickness (*Hoil*) thicker than *T*, p_{phy} is the probability of effect given encounter with oil thicker than *T,* and *N* is the number of individuals (or population fraction) in the cell. Whether the effect is lethal or sub-lethal is determined by the value of *T*.

Note that since p_{beh} is separated from p_{let}, the parameter is now independent of a threshold thickness. The probability of an individual in the cell being exposed to oil (i.e. p_{exp}) can now be redefined as the product $p_{beh} \times Cov|>T$. Thus, substituting this product with p_{exp} gives the following equation for a single cell,

$$N_{let} = p_{exp} \times p_{phy}|(Hoil > T_r) \times N \qquad \textbf{Eq. 3.3}$$

Note that the subscripts for the resource (*r*), the grid cell (*cell*), the simulation (*sim*), and the compartment (*comp*) is dropped in the equations in this report for easier reading. It is implicit that parameters related to populations (*N*, p_{beh}, p_{phy}) are valid for different resources.
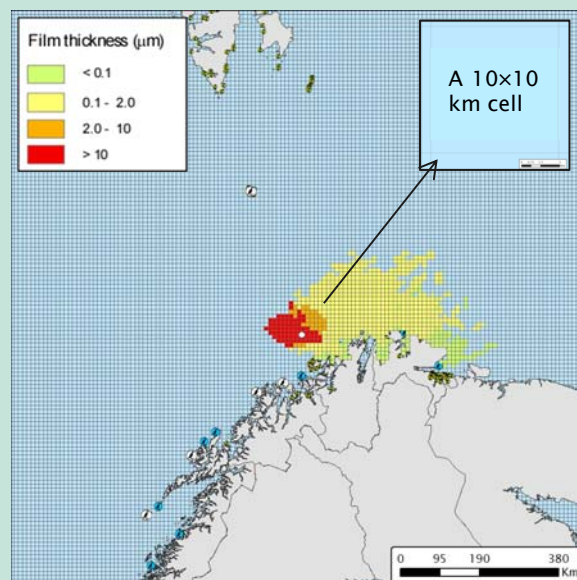
An illustration of the calculation is illustrated in Box 1.

Box 1. Example on calculation of impact for a single cell using equation 3.1

Biological resource data
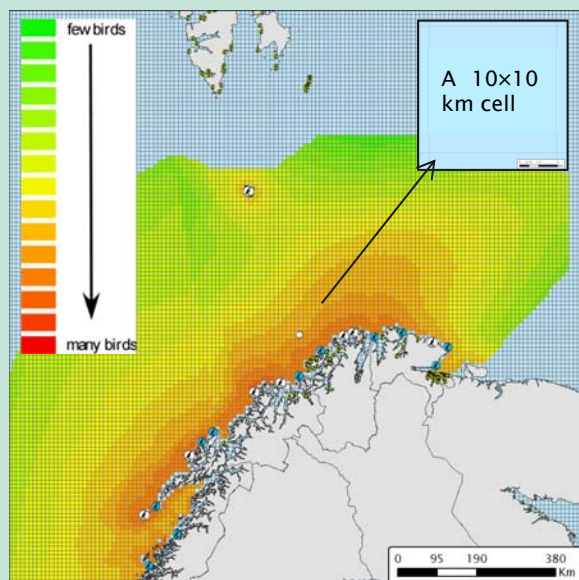
Oil drift (swept area of a single simulation)

Data in one single cell of 10 × 10 kilometer

The Atlantic puffin (*Fratercula arctica*)

An Atlantic puffin taking off from the sea near the Farne Islands, Northumberland ©DarrelBirkett (from the Wikipedia Commons)

N = 170 individuals in the cell (0.002765037 population fraction)

Population size = 61 482

p_{beh} = 0.79

p_{phy} = 0.90

T_r = 2 µm (lethal effect)

Calculation for one single cell of 10 × 10 kilometer

N_{let} = 0.79 × 0.20×0.90×170

= **24.17** indiviuals

or

N_{let} = 0.79 × 0.20×0.90×0.002765037

= **0.000393188** population fractions

Oil drift statstics

Oil skimming vessels in the Gulf of Mexico ©DVIDS (from the Wikipedia Commons)

H_{oil} = 9 µm
Cov (T>2 µm) = 0.20

3.2   Evaluation of p_{let}

The parameter p_{let} for a wildlife group is defined as the combined probability of encountering oil and the mortality once oiled, if present in an area swept by oil exceeding a threshold thickness for oiling mortality (French-McCay 2009; Spikkerud et al. 2010). The parameter is denoted P_w by French-McCay (2009). The p_{let} values used in the ERA Acute Level A (Spikkerud et al. 2010) was based on the work performed by French McCay (e.g. French-McCay 2004; French-McCay 2011; French-McCay 2009) and the EIF project (e.g. Tørrhaug et al. 2006; Spikkerud 2006; Spikkerud et al. 2004; Hoell & Gramme 2004).

The probability of encountering oil is determined by time spent on the sea surface, which is influenced by behavioral factors (e.g. flight, diving and swimming patterns) that increases the probability of fouling and individual tendency to actively avoid oil and thereby decrease the probability of being fouled (cf. Isaksen et al. 1998). This report refers to this concept as *individual behavioral factors,* which is symbolized as p_{beh}.

The conditional probability (i.e. given that the individual is oiled) of lethal or sub-lethal effects is determined by the individual vulnerability for physiological and toxic effects of oil, and includes effects on insulation, irritation sensitive tissues, internal effects of ingested oil and inhalation of vapor (cf. Isaksen et al. 1998). This report refers to this concept as the *individual physiological and toxicological factors,* which is symbolized as p_{phy}.

The objective of activity 1 was to evaluate the existing p_{let} values. Since data for p_{let} was only found as combined values it was not possible to perform this task without dividing the p_{let} parameter into its individual behavioural and physiological factors. The evaluation is performed by using data derived from surveys and scientific studies and data based on subjective expert judgment. The first is the preferred method but the latter is the most common approach due to lack of available information. The result is one species-specific and one wildlife group-specific look-up table that may be used to calculate the impact on VECs in the surface compartment. Missing data is handled by a set of basic rules by using proxy species.

A great advantage of dividing the parameter p_{let} is that it adds transparency to the values. This makes it less demanding to review and evaluate the parameters and to improve and develop the look-up tables over time. Moreover, it opens for the possibility to use continuous dose response curves for the p_{phy} parameters (see Box 3) and makes the parameters in the impact equation more logical and more straightforward to define.

3.2.1   Method

There is a great deal of literature about various vulnerability indexes for seabirds and marine mammals. The evaluation of p_{let} in this report is primarily based on the following work: (1) the oil vulnerability index (OVI) for seabirds (Williams et al. 1995); (2) the oil vulnerability index for marine mammals (Isaksen et al. 1998); (3) the risk analysis model for marine mammals and seabirds (Ford 1985) and (4) the state-of-the-art of biological effects modeling for use in impact and risk analyses (French-McCay 2009; French-McCay 2004; French-McCay 2011). The references are not exhaustive, e.g. Isaksen et al. (1998) oil vulnerability index for marine mammals is based on work by Anker-Nilssen (1987), Jødestøl & Ugland (1993) and Jødestøl et al. (1994). Moreover, the risk analysis model for marine mammals and seabirds by Ford (1985) has been used by French McKay to derive P_w values for her model, and the work by Jødestøl and Ugland has been used to derive effect and damage keys for marine mammals in MIRA (Brude 2007).

Data derived from surveys, scientific studies and expert judgement is normalised according to Ford's (1985) work on a risk analysis model for sea birds and marine mammals. The purpose of normalising the data is to obtain values between 0 and 1. Thus the data chosen as normalising value determine the maximum and minimum value of the final p_{beh} and p_{phy} values.

The following formula is used,

$$P_{letx} = \left(\frac{relative\ score\ for\ the\ current\ species}{maximum\ value\ possible\ to\ score\ for\ a\ species\ in\ the\ study} \right) \times NV \qquad \textbf{Eq. 3.4}$$

where NV is the normalising value.

Ford (1985) evaluated the probability of avoiding the oil spill (Δ) and the probability of death following spill contact (Φ). The p_{beh} which contains factors affecting the probability of coming in contact (in contrast to avoiding) with the oil spill is therefore set equal to 1 - Δ. Three values for both factors are estimated;

- *low* (least conservative)
- *best* (intermediately conservative)
- *high* (most conservative)

The normalising values (NV) are presented in Table 6 and Table 7. If no normalising value exists for the species, a normalising value of another species or wildlife group is used, e.g. the normalising value for the p_{beh} parameters for sea cows was set equal to the highest value of (1 - Δ) for pinnipeds.

Table 6. Wildlife group, normalisation value (1 - Δ) and reference species used for p_{beh}.

Wildlife group		Normalisation value (NV)			Reference species, refer species following from rule	Rule used
No	Name	Low	Best	High		
1-6	Seabirds	0.80	0.80	0.90	Cassin's auklet	-
7	Baleen whales	0.40	0.60	1.00	Common dolphin	Set equal mean toothed whale
8	Toothed whale	0.40	0.60	1.00	Common dolphin	-
9	True seals, walrus and sea lions	0.92	0.96	1.00	Northern elephant seal	-
10	Fur seals	0.92	0.96	1.00	Northern fur seal	-
11	Sea cows	0.95	0.98	1.00	Northern elephant seal (pups)	Set equal to highest values for all pinnipeds
12	Aquatic mammals	0.92,	0.96	1.00	Northern fur seal	-
13	Sea turtles	0.95	0.98	1.00	Northern elephant seal (pups)	Set equal to highest values for all pinnipeds

Table 7. Wildlife group, normalisation value (Φ) and reference species used for p_{phy}.

Wildlife group		Normalisation value (NV)			Reference species, refer species following from rule	Rule used
No	Name	Low	Best	High		
1-6	Seabirds	0.80	0.90	1.00	Cassin's auklet	Cassin's auklet
7	Baleen whales	0.01	0.01	0.01	-	P_w value from French McCay 2009
8	Toothed whale	0.01	0.01	0.01	-	P_w value from French McCay 2009
9	True seals, walrus and sea lions	0.00	0.02	0.05	Northern elephant seal	Northern elephant seal
10	Fur seals				-	
11	Sea cows				-	
12	Aquatic mammals – polar bear and otters	0.47	0.57	0.60	Northern fur seal	Northern fur seal
		0.60	0.80	1.00	Northern fur seal (pups)	Set equal to highest fur seal value
13	Sea turtles (adult, juvenile and hatching)	0.01	0.01	0.01	-	P_w from French McCay 2009
		0.05	0.05	0.05	-	P_w from French McCay 2009

The values from Ford (1985) are presented in Table 21 in Appendix A1. A comparison of the proposed p_{beh} and p_{phy} values with the p_{let} values from ERA Acute Level A (Spikkerud et al., 2011) and the P_w values from French-McCay (2009) is presented in Table 24 in Appendix A1.

Seabirds p_{beh}

p_{beh} values for seabirds are derived from the oil vulnerability index (OVI), constructed to assess the vulnerability of 37 seabird species to surface pollutants in the North Sea (Williams et al. 1995). The raw data from Williams et al. (1995) is derived from surveys and scientific studies and is presented in Table 22 in Appendix A1. The oil vulnerability index contains four factors; *a*, *b*, *c* and *d*, where factor *a* is defined as the sum of the proportion of oiled individuals amongst those found dead (or moribund) on the shoreline and the ratio of time spent on the surface compared to time spent in flight by that species.

Factor (*a*) is scored from 1 to 5. Maximum score is obtained if 81-100% of the dead birds where oiled and the ratio of birds observed on the sea surface was more than seven times as high as those observed flying. Three of the 37 species investigated scored a maximum score of 5 (the auks razorbill, little auk and common guillemot) while the last auk investigated, the Atlantic puffin, scored 4.5 (Table 22 in Appendix A1). These belong to the wildlife group pelagic diving seabirds. Two species scored the minimum; storm petrel and little tern. The first belong to the wildlife group pelagic surface foraging seabirds, while the latter to belong to coastal surface feeding seabirds.

Seabirds are normalised with the highest values evaluated by Ford (Ford 1985), i.e. the values for the auks Cassin's auklet and Xantus's murrelet (Table 6). This means that all seabirds with a score of 5 will get a p_{beh} value of 0.90 (low), 0.80 (best guess) and 0.80 (high), seabirds with a factor of 4.5 will get a p_{beh} values of 0.81 (low), 0.72 (best guess) and 0.72 (high) and seabirds with e.g. a score of 1 will get a p_{beh} values of 0.18 (low), 0.16 (best guess) and 0.16 (high). The p_{beh} values are harmonized with Ford's work and are therefore less conservative than the maximum P_w values (0.99) used for seabirds in the ERA Acute Level A (Spikkerud et al. 2010; French-McCay 2009).

Table 8. Data used to score factor a in the OVI-index (after Williams et al. 1995). Data derived from surveys and scientific studies was used to construct the index. The proportion of each species that was oiled amongst those found dead (or moribund) on the shoreline and the ratio of time spent on the surface compared with time spent in flight by that species, is used to score factor a.

% birds oiled	Score	Ratio of birds on water to birds flying	Score	a-value
81-100	2.5	>7	2.5	5
61-80	2.0	5-7	2.0	4
41-60	1.5	3-5	1.5	3
21-40	1.0	1-3	1.0	2
0-20	0.5	0-1	0.5	1

Marine mammals p_{beh}

p_{beh} values for marine mammals are based on the behaviour (*Be*) and avoidance (*Av*) factor in the the oil vulnerability index for marine mammals (Isaksen et al. 1998). The raw data is given in Table 23 in Appendix A1. Isaksen et al (1998) scored the two factors a value between 1 and 3.

The behavior factor (little = 1, moderately = 2, strongly exposed = 3) is based on expert judgment on *individual behavior* (e.g. diving and swimming patterns) *that will increase the probability of fouling*. An animal that swims much of the time at the surface has a higher probability of being fouled than one that spends much of the time at deep water.

The avoidance factor (strong = 1, moderate = 2, small = 3) is based on expert judgment on: *individual tendency to actively avoid oil and thereby decrease the probability of being fouled*.

The values for polar bear, walrus and true seals (ringed seal, harbour seal, harp seal, and bearded seal) are normalized against Ford (Ford 1985) highest estimate values for true seals (northern elephant seal) (Table 6). The values for toothed whales (white whale) and baleen whales (bowhead whale, northern Minke whale, fin whale and humpback whale) were

normalized against Ford (Ford 1985) highest estimate values for cetacean (common dolphin) (Table 6). No data exists for sea cows, otters and turtles and their p_{beh} values were determined based on values for selected other groups (cf. Table 6).

Seabirds p_{phy}

The p_{phy} values for seabirds are based on Ford (Ford 1985) values for Cassin's auklet and Xantus's murrelet (cf.). This yields an estimate for p_{phy} values for all birds of 0.80 (low), 0.90 (best guess) and 1.00 (high).

Marine mammals p_{phy}

p_{phy} values for marine mammals are based on the toxic vulnerability (*Tv*) and surface contact (*Sc*) factor in the the oil vulnerability index for marine mammals (Isaksen et al., 1998). Isaksen et al (1998) scored the two factors a value between 1 and 3.

The toxic vulnerability factor (small = 1, moderate = 2, high = 3) is based on expert judgment on: *Individual vulnerability for toxic effects of oil. This factor relates to internal effects of ingested oil and inhalation of vapor.*

The surface contact factor (small = 1, moderate = 2, high = 3) is based on expert judgment on: *Individual vulnerability from external contact with oil. The factor includes effects on insulation, movement ability, increased bloodstream to the skin due to inflammation, irritation of eyes and fouling of baleen, etc. The distinction from Toxic vulnerability in some cases might be unclear.*

The values for walrus and true seals (ringed seal, harbour seal, harp seal, and bearded seal) are normalized against Ford (Ford 1985) highest estimate values for true seals (northern elephant seal). The values for walrus and true seals (ringed seal, harbour seal, harp seal, and bearded seal) are normalized against Ford (Ford 1985) highest estimate values for true seals (northern elephant seal. The values for European otter, sea otter and polar bears are normalized against Ford (1985) highest estimate values for fur seals (northern fur seal). Sea cows is normalised to the average of the wildlife group true seal, walrus and sea lions. Ford (1985) found that it was not scientifically possible to score a factor on cetaceans. Cetaceans and sea turtles are normalised against the P_w values from French-McCay (French-McCay 2009) (cf. Table 7).

3.2.2   Look-up table for wild life groups and single species

The resulting look-up table for the 13 wildlife groups with low, best guess and high estimates for the parameters p_{beh} and p_{phy} are presented in Table 9. The product ($p_{beh} \times p_{phy}$) is calculated for comparisons with the P_w values to French McCay (2009) and p_{let} values from the EIF Acute project (Spikkerud et al. 2011).

The values for the wildlife group are the mean of the species in each wildlife group. The estimates for p_{beh} and p_{phy} for the single species investigated are presented in Table 10 and Table 11. An Excel pivot table is provided as an attachment to the report (cf. Appendix A2).

In general, the new values are less conservative for birds belonging to wildlife group 1, 3, and 4 and within the range or more conservative for the other wildlife groups. All the new seabird wildlife groups (1-6) have considerable higher values than the P_w of 5%, used for the group named "aerial seabirds" (cf. Table 4). The largest relative increase in values (more conservative) is for toothed, baleen whales and sea turtles. An increase in conservatism for these groups is in agreement with the general impression from the reporting's from the Macondo accident.

Table 9. p_{beh} and p_{phy} values derived in this study for different wildlife groups. LO = lowest estimate, BG = best guess, HI = highest estimate. The product ($p_{beh} \times p_{phy}$) is compared to the P_w values to

French McCay (2009) and the p_{let} values used in ERA Acute Level A. Red cells are less conservative (lower) than P_w and green more conservative (higher).

NO	Wildlife groups	p_{beh}			p_{phy}			$p_{beh} \times p_{phy}$			P_w	p_{let}
		LO	BG	HI	LO	BG	HI	LO	BG	HI		
1	Pelagic diving seabirds	79%	79%	89%	80%	90%	100%	63%	71%	89%	99%	99%
2	Pelagic surface foraging seabirds	45%	45%	51%	80%	90%	100%	36%	41%	51%	35%	35%
3	Coastal diving seabirds	67%	67%	76%	80%	90%	100%	54%	61%	76%	99%	99%
4	Coastal surface feeding seabirds	31%	33%	44%	69%	78%	87%	21%	24%	33%	35%	35%
5	Wetland surface feeding seabirds	48%	48%	54%	80%	90%	100%	38%	43%	54%	35%	35%
6	Wading seabirds	35%	35%	35%	80%	90%	100%	28%	32%	35%	35%	35%
7	Baleen whales	35%	53%	88%	0.4%	0.4%	0.4%	0.2%	0.2%	0.4%	0.1%	0.1%
8	Toothed whale	40%	60%	100%	0.8%	0.8%	0.8%	0.3%	0.5%	0.8%	0.1%	0.1%
9	True seals, walruses and sea lions	83%	90%	96%	0.4%	2.8%	5.8%	0.4%	2.6%	5.7%	1.0%	42%
10	Fur seals	63%	78%	93%	50%	72%	93%	33%	57%	87%	75%	75%
11	Sea cows	95%	98%	100%	0.8%	4.3%	8.3%	0.8%	4.2%	8.3%	1.0%	1.0%
12	Aquatic mammals	79%	88%	97%	50%	72%	93%	40%	63%	90%	75%	75%
13	Sea turtles	95%	99%	100%	3.0%	3.0%	3.0%	2.9%	2.9%	3.0%	1.0%	1.0%

Table 10. p_{beh} values for different wildlife groups and reference species within each group. NA = No available data.

Wildlife group	Species		Stadium	p_{beh} (species)			p_{beh} (wildlife group)		
				LO	BG	HI	LO	BG	HI
Pelagic diving seabirds	Cassin's auklet	*Ptychoramphus aleuticus*	All	80%	80%	90%	79%	79%	89%
	Xantus's murrelet	*Synthliboramphus scrippsi, S. hypoleucus*	All	80%	80%	90%			
	Razorbill	*Alca torda*	All	80%	80%	90%			
	Little Auk	*Alle alle*	All	80%	80%	90%			
	Guillemot	*Uria aalge*	All	80%	80%	90%			
	Puffin	*Fratercula arctica*	All	72%	72%	81%			
Pelagic surface foraging seabirds	Fulmar	*Fulmarus glacialis*	All	48%	48%	54%	45%	45%	51%
	Manx Shearwater	*Puffinus puffinus*	All	56%	56%	63%			
	Gannet	*Morus bassanus*	All	48%	48%	54%			
	Storm Petrel	*Hydrobates pelagicus*	All	16%	16%	18%			
	Kittiwake	*Rissa tridactyla*	All	48%	48%	54%			
	Lesser Black-backed Gull	*Larus fuscus*	All	48%	48%	54%			
	Great Skua	*Catharacta skua*	All	48%	48%	54%			
	Arctic Skua	*Stercorarius parasiticus*	All	40%	40%	45%			
	Sooty Shearwater	*Puffinus griseus*	All	56%	56%	63%			
Coastal diving seabirds	Common eider	*Somateria mollissima*	All	64%	64%	72%	67%	67%	76%
	Red-necked Grebe	*Podiceps grisegena*	All	72%	72%	81%			
	Long-tailed Duck	*Clangula hyemalis*	All	72%	72%	81%			
	Great Northern Diver	*Gavia immer*	All	80%	80%	90%			
	Goldeneye	*Bucephala clangula*	All	48%	48%	54%			
	Red-breasted Merganser	*Mergus serrator*	All	56%	56%	63%			
	Velvet Scoter	*Melanitta fusca*	All	72%	72%	81%			

Wildlife group	Species		Stadium	p_{beh} (species)			p_{beh} (wildlife group)		
				LO	BG	HI	LO	BG	HI
	Red-throated Diver	*Gavia steilata*	All	80%	80%	90%			
	Black-throated Diver	*Gavia arctica*	All	80%	80%	90%			
	Great Cormorant	*Phalacrocorax carbo*	All	40%	40%	45%			
	Common Scoter	*Melanitta nigra*	All	72%	72%	81%			
	Black Guillemot	*Cepphus gryile*	All	80%	80%	90%			
	Great Crested Grebe	*Podiceps cristatus*	All	64%	64%	72%			
	European Shag	*Phalacrocorax aristotelis*	All	64%	64%	72%			
	Western gull	*Larus occidentalis*	Juvenile	50%	55%	90%			
	Western gull	*Larus occidentalis*	Adult, immature	15%	40%	90%			
	Little Gull	*Larus minutus*	All	48%	48%	54%			
	Little Tern	*Sterna albifrons*	All	16%	16%	18%			
Coastal surface feeding seabirds	Common Gull	*Larus canus*	All	32%	32%	36%	31%	33%	44%
	Herring Gull	*Larus argentatus*	All	32%	32%	36%			
	Black-headed Gull	*Larus ridibundus*	All	32%	32%	36%			
	Common Tern	*Sterna hirundo*	All	24%	24%	27%			
	Arctic Tern	*Sterna paradisaea*	All	24%	24%	27%			
	Sandwich Tern	*Sterna sandvicensis*	All	24%	24%	27%			
	Great Black-backed Gull	*Larus marinus*	All	40%	40%	45%			
Wetland surface feeding seabirds	Scaup	*Aythya marila*	All	48%	48%	54%	48%	48%	54%
Wading seabirds	No species	No species	-	35%	35%	35%	35%	35%	35%
Baleen whales1	Bowhead whale	*Balaena mysticetus*	All	40%	60%	100%	35%	53%	88%
	Northern Minke whale	*Balaenoptera acutorostrata*	All	33%	50%	83%			

Wildlife group	Species		Stadium	p_{beh} (species)			p_{beh} (wildlife group)		
				LO	BG	HI	LO	BG	HI
	Fin whale	*Balaenoptera physalus*	All	33%	50%	83%			
	Humpback whale	*Megaptera novaeangliae*	All	33%	50%	83%			
Toothed whale	Common dolphin	*Delphinus delphis*	All	40%	60%	100%	40%	60%	100%
	White whale	*Delphinapterus leucas*	All	40%	60%	100%			
True seals, walrus and sealions	Northern elephant seal	*Mirounga angustirostris*	Pups	95%	98%	100%	83%	90%	96%
	Northern elephant seal	*Mirounga angustirostris*	Female, immature	90%	95%	100%			
	Northern elephant seal	*Mirounga angustirostris*	Male	90%	95%	100%			
	Walrus	*Odobenus rosmarus*	Female	76%	80%	83%			
	Walrus	*Odobenus rosmarus*	Male	76%	80%	83%			
	Ringed seal	*Phoca hispida*	All	76%	80%	83%			
	Harbour seal	*Phoca vitulina*	All	92%	96%	100%			
	Harp seal	*Phoca groenlandica*	All	92%	96%	100%			
	Bearded seal	*Erignathus barbatus*	All	92%	96%	100%			
	California sea lion	*Zalophus californianus*	Pups	95%	98%	100%			
	California sea lion	*Zalophus californianus*	Female, immature	60%	80%	100%			
	California sea lion	*Zalophus californianus*	Male	60%	80%	100%			
Fur seals	Northern fur seal	*Callorhinus ursinus*	Pups	90%	95%	100%	63%	78%	93%
	Northern fur seal	*Callorhinus ursinus*	Female, immature	50%	70%	90%			
	Northern fur seal	*Callorhinus ursinus*	Male	50%	70%	90%			
Sea cows	Manatees	*Trichechus spp*	All	95%	98%	100%	95%	98%	100%
Aquatic mammals2	Polar bear	*Ursus maritimus*	Female	63%	78%	93%	79%	88%	97%
	Polar bear	*Ursus maritimus*	Male	63%	78%	93%			
	Marine Otter	*Lontra felina*	All	95%	98%	100%			
	European otter	*Lutra lutra*	All	95%	98%	100%			
Sea turtles3	All species	*Chelonioidea*	Juvenile Adult	95%	98%	100%	95%	98%	100%

Wildlife group	Species		Stadium	p_{beh} (species)			p_{beh} (wildlife group)		
				LO	BG	HI	LO	BG	HI
	All species	*Chelonioidea*	Hatchlings	95%	98%	100%			

Table 11. p_{phy} **values for different wildlife groups and reference species within each group.**

Wildlife group	Species		Stadium	p_{phy} (species)			p_{phy} (wildlife group)		
				LO	BG	HI	LO	BG	HI
Pelagic diving seabirds	Cassin's auklet	*Ptychoramphus aleuticus*	All	80.0%	90.0%	100%	80%	90%	100%
	Xantus's murrelet	*Synthliboramphus scrippsi, S. hypoleucus*	All	80.0%	90.0%	100%			
	Razorbill	*Alca torda*	All	80.0%	90.0%	100%			
	Little Auk	*Alle alle*	All	80.0%	90.0%	100%			
	Guillemot	*Uria aalge*	All	80.0%	90.0%	100%			
	Puffin	*Fratercula arctica*	All	80.0%	90.0%	100%			
Pelagic surface foraging seabirds	Fulmar	*Fulmarus glacialis*	All	80.0%	90.0%	100%	80%	90%	100%
	Manx Shearwater	*Puffinus puffinus*	All	80.0%	90.0%	100%			
	Gannet	*Morus bassanus*	All	80.0%	90.0%	100%			
	Storm Petrel	*Hydrobates pelagicus*	All	80.0%	90.0%	100%			
	Kittiwake	*Rissa tridactyla*	All	80.0%	90.0%	100%			
	Lesser Black-backed Gull	*Larus fuscus*	All	80.0%	90.0%	100%			
	Great Skua	*Catharacta skua*	All	80.0%	90.0%	100%			
	Arctic Skua	*Stercorarius parasiticus*	All	80.0%	90.0%	100%			
	Sooty Shearwater	*Puffinus griseus*	All	80.0%	90.0%	100%			
Coastal diving seabirds	Common eider	*Somateria mollissima*	All	80.0%	90.0%	100%	80%	90%	100%
	Red-necked Grebe	*Podiceps grisegena*	All	80.0%	90.0%	100%			
	Long-tailed Duck	*Clangula hyemalis*	All	80.0%	90.0%	100%			

Wildlife group	Species		Stadium	p_{phy} (species)			p_{phy} (wildlife group)		
				LO	BG	HI	LO	BG	HI
	Great Northern Diver	*Gavia immer*	All	80.0%	90.0%	100%			
	Goldeneye	*Bucephala clangula*	All	80.0%	90.0%	100%			
	Red-breasted Merganser	*Mergus serrator*	All	80.0%	90.0%	100%			
	Velvet Scoter	*Melanitta fusca*	All	80.0%	90.0%	100%			
	Red-throated Diver	*Gavia steilata*	All	80.0%	90.0%	100%			
	Black-throated Diver	*Gavia arctica*	All	80.0%	90.0%	100%			
	Great Cormorant	*Phalacrocorax carbo*	All	80.0%	90.0%	100%			
	Common Scoter	*Melanitta nigra*	All	80.0%	90.0%	100%			
	Black Guillemot	*Cepphus gryile*	All	80.0%	90.0%	100%			
	Great Crested Grebe	*Podiceps cristatus*	All	80.0%	90.0%	100%			
	European Shag	*Phalacrocorax aristotelis*	All	80.0%	90.0%	100%			
Coastal surface feeding seabirds	Western gull	*Larus occidentalis*	Juvenile	20.0%	25.0%	30.0%	69%	78%	87%
	Western gull	*Larus occidentalis*	Adult, immature	20.0%	25.0%	30.0%			
	Little Gull	*Larus minutus*	All	80.0%	90.0%	100%			
	Little Tern	*Sterna albifrons*	All	80.0%	90.0%	100%			
	Common Gull	*Larus canus*	All	80.0%	90.0%	100%			
	Herring Gull	*Larus argentatus*	All	80.0%	90.0%	100%			
	Black-headed Gull	*Larus ridibundus*	All	80.0%	90.0%	100%			
	Common Tern	*Sterna hirundo*	All	80.0%	90.0%	100%			
	Arctic Tern	*Sterna paradisaea*	All	80.0%	90.0%	100%			
	Sandwich Tern	*Sterna sandvicensis*	All	80.0%	90.0%	100%			
	Great Black-backed Gull	*Larus marinus*	All	80.0%	90.0%	100%			

Wildlife group	Species		Stadium	p_{phy} (species)			p_{phy} (wildlife group)		
				LO	BG	HI	LO	BG	HI
Wetland surface feeding seabirds	Scaup	*Aythya marila*	All	80.0%	90.0%	100%	80%	90%	100%
Wading seabirds	NA	*NA*	All	80.0%	90.0%	100%	80.0%	90.0%	100%
Baleen whales1	Bowhead whale	*Balaena mysticetus*	All	0.7%	0.7%	0.7%	0.4%	0.4%	0.4%
	Northern minke whale	*Balaenoptera acutorostrata*	All	0.3%	0.3%	0.3%			
	Fin whale	*Balaenoptera physalus*	All	0.3%	0.3%	0.3%			
	Humpback whale	*Megaptera novaeangliae*	All	0.3%	0.3%	0.3%			
Toothed whale	Common dolphin	*Delphinus delphis*	All	1.0%	1.0%	1.0%	0.8%	0.8%	0.8%
	White whale	*Delphinapterus leucas*	AlII	0.7%	0.7%	0.7%			
True seals, walrus and sea lions	Northern elephant seal	*Mirounga angustirostris*	Pups	0.00%	2.00%	5.00%	0.4%	2.8%	5.8%
	Northern elephant seal	*Mirounga angustirostris*	Female, immature	0.00%	2.00%	5.00%			
	Northern elephant seal	*Mirounga angustirostris*	Male	0.00%	2.00%	5.00%			
	Walrus	*Odobenus rosmarus*	Female	0.0%	1.3%	3.3%			
	Walrus	*Odobenus rosmarus*	Male	0.0%	1.3%	3.3%			
	Ringed seal	*Phoca hispida*	All	0.0%	1.3%	3.3%			
	Harbour seal	*Phoca vitulina*	All	0.0%	1.3%	3.3%			
	Harp seal	*Phoca groenlandica*	All	0.0%	1.3%	3.3%			
	Bearded seal	*Erignathus barbatus*	All	0.0%	1.3%	3.3%			
	California sea lion	*Zalophus californianus*	Pups	5.0%	10%	15%			
	California sea lion	*Zalophus californianus*	Female, immature	0.0%	5.0%	10%			
	California sea lion	*Zalophus californianus*	Male	0.0%	5.0%	10%			
Fur seals	Northern fur seal	*Callorhinus ursinus*	Pups	60.0%	80.0%	100.0%	50%	72%	93%
	Northern fur seal	*Callorhinus ursinus*	Female, immature	50.0%	75.0%	100.0%			
	Northern fur seal	*Callorhinus ursinus*	Male	40.0%	60.0%	80.0%			

Wildlife group	Species		Stadium	p_{phy} (species)			p_{phy} (wildlife group)		
				LO	BG	HI	LO	BG	HI
Sea cows	Manatees	*Trichechus spp*	All	0.8%	4.3%	8.3%	0.8%	4.3%	8.3%
Aquatic mammals[2]	Polar bear	*Ursus maritimus*	Female	50%	72%	93%	55%	76%	97%
	Polar bear	*Ursus maritimus*	Male	50%	72%	93%			
	Marine Otter	*Lontra felina*	All	60%	80%	100%			
	European otter	*Lutra lutra*	All	60%	80%	100%			
Sea turtles[3]	Sea turtles	Chelonioidea	Juvenile Adult	1.0%	1.0%	1.0%	3%	3%	3%
	Sea turtles	Chelonioidea	Hatchlings	5.0%	5.0%	5.0%			

3.3 Threshold thickness for lethal dose

The main target of this part is to provide scientific documentation for the threshold film thicknesses for oiling mortality in the different wildlife groups and to conclude on values to be used in the ERA-SW. A complimentary target was to construct continuous "dose-response-curves" describing the relationship between film thickness and probability of lethal and sub-lethal effect(s). This task has however been abandoned during the project due to lack of suitable data from the oil drift model (cf. Bjørgesæter & Krajczyk 2014). To conclude on threshold values for film thickness for potential lethal and sub-lethal impact a literature review has been conducted.

Most seabirds rely on feathers for flight and insulation, and many species also rely on feathers for buoyance (O'Hara & Morandin 2010). The evaluation of film thickness of oil at sea for seabirds may therefore be divided into (1) the relationship between the oil thickness encountered and subsequent feather structure modification and (2) the oil quantity (dose) necessary to affect flight, buoyance and insulation in such a degree that it leads to lethal effects.

In aquatic mammals that depend upon a water-repellent fur to remain a normal state of temperature in water, such as the sea otter, the muskrat, the polar bear, and fur seals external oiling reduces the thermal insulation of the fur, and evokes the same physiological responses as in plumage-contaminated birds (cf. Jenssen 1994 and references therein). True seals, walruses, sea lions and cetaceans depend mainly upon cutaneous fat layer for this purpose and external oiling have little effect on the heat balance for these species. Both groups may come in contact with oil slicks when they surface to breathe. Inhaling hydrocarbon vapours may result in lung injuries and oil that comes in contact with the animals' sensitive mucous membranes and eyes may produce irritations.

3.3.1 Film thickness

The threshold film thickness for for oiling mortality used in the ERA Acute Level A is 10 μm for all wildlife groups (Spikkerud et al. 2010; French-McCay 2009). There is little information linking feather exposure to various film thicknesses and subsequent alteration of feather structure and effects on water penetration and metabolism (O'Hara & Morandin 2010). Film thicknesses evaluated to cause a lethal dose on seabirds and marine mammals range from approximately 1.0 μm (Peakall et al. 1985; Stephenson 1997; see also the review by Hoell & Gramme 2004), 10 μm (French-McCay 2009) and up to 25 μm (Scholten et al. 1996; Koops et al. 2004). In all these studies it is assumed that film thicknesses lower than the reported lethal threshold thicknesses are not deadly. Thus, for seabirds, film thickness of 1.0 μm, 10 μm and 25 μm are believed to cause lethal effect (i.e. LD_{100}) and not be harmful (i.e. LD_0). That is, the uncertainty in film thickness (the predictor) range from 1 μm to 25 μm and the uncertainty in mortality (response) range from 0% to 100% (Figure 3). Due to the large uncertainty (putting equal weight on all studies) it is not possible to derive practical threshold levels directly from these studies.

A detailed study of the feather microstructure of pelagic seabirds (common murre and dovekies, i.e. little auk) indicates that thin oil sheen (0.1 and 0.3 μm) can impact the microstructure of seabird's feathers (O'Hara & Morandin 2010). It is not known if this change in the microstructure will have measurable effect on individual birds. Moreover the dovekie feather structure was not significantly affected by sheen less than 3μm (while the feather from the common murre was) and the feathers from the common murre did not pick up a measurable amount of crude oil when exposed to sheen of 3 μm (while the feather from the dovekie did) (O'Hara & Morandin 2010). The study did not investigate any film thickness between 0.1 μm and 3 μm or assess whether feathers would continue to adsorb oil if re-dipped in the same oil sheen thickness. Exposure to very thin crude oil sheens (0.04 μm) did not impact feather microstructure.
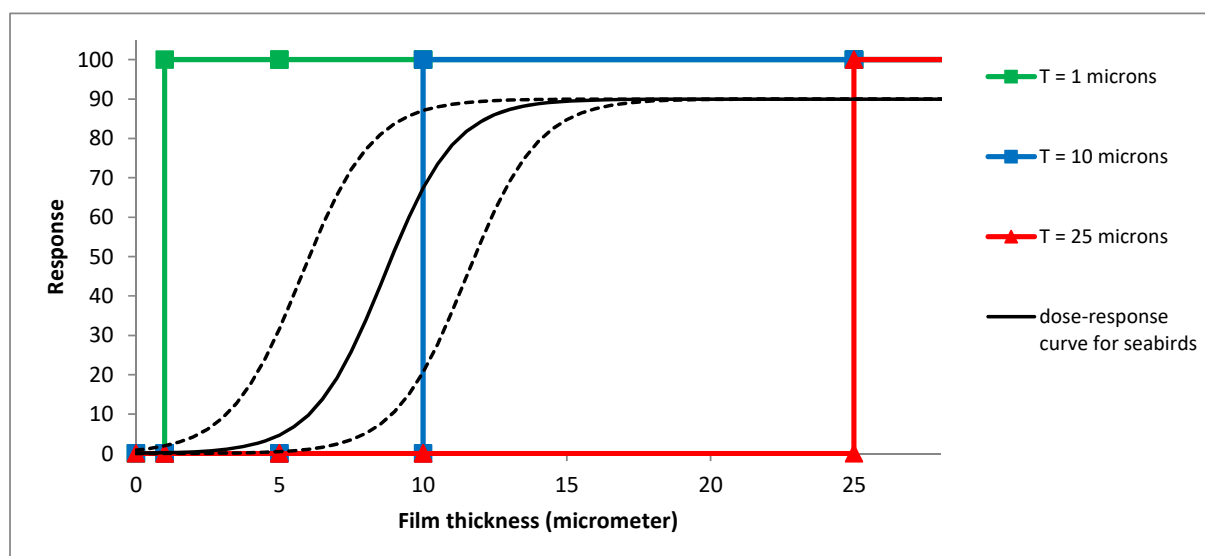
Figure 3. Illustration of different fixed film thicknesses thresholds (T) and assumed response measured in mortality (LD$_0$ and LD$_{100}$), based on available information in the literature (see text for references). A hypothetical dose response curve for seabirds (wildlife group 1 – 6), illustrating an attempt to refine the great existing uncertainty (see Box 4 for more information).

A film thickness of 10 μm evenly spread out on a cell with dimension 10×10 km correspond to approximately 1000 ton of oil and approximately 10 ton for a 1×1 km cell. A thickness of 3 μm is within rainbow sheen and 10 μm is the nominal midpoint for metallic (Table 12).

Table 12. Oil code colours and corresponding film thicknesses.

Oil Code Colour	Film thickness (μm)		Nominal midpoint
	Thinnest	Thickest	
Silver/grey sheen	0.04	0.30	0.1
Rainbow	0.30	5.00	1
Metallic	5.00	50.0	10
Transitional Dark(or True) Colour	50.0	200	100
Dark (or True) Colour	200	10000000	1000
Emulsified	200	10000000	1000

3.3.2   Lethal dose

In the SIMAP biological effect model 350 ml is assumed to be a lethal dose for all wildlife (French-McCay 2009). If the film thickness is above 10 μm, and the spill diameter is larger than 230 meters, the wildlife may obtain a lethal dose and the probability of mortality is determined by the P_w factor and exposure time (French-McCay 2009). For spill sizes less than 230 meters, the lethal thickness is set to 100 μm. For further details, the reader is referred to French McCay (2009) review and arguments for selecting 10 μm as a threshold thickness for mortality and 350 ml for lethal dose for all wildlife groups.

The main results of the literature review are presented in Table 13. Several of the studies in Table 13 are also included in the review by French-McCay (2009). It appears that a lethal dose of 350 ml for seabirds is not particular conservative. Doses of both 12.5 ml and 70 ml have in laboratory tests been demonstrated to be lethal for common eiders (Jenssen & Ekker 1991b; Jenssen & Ekker 1991a), a relative large bird (2000 g) in comparison with e.g. a little auk (180 g). Note, however, that similar lab studies have apparently not been able to demonstrate lethal effects on domestic ducks (*Anas platyrhynchos*) with doses of 500 ml and 2000 ml (Jenssen & Ekker 1989)

The latter studies are in strong contrast with specialists that believe that any contact of a bird with oil may be lethal (e.g. Peakall et al. 1985; Stephenson 1997). Feather fouling from as little as 10 ml of heavy oil is believed to significantly reduce thermoregulation in marine and aquatic birds and may be lethal, especially in colder climates (cf. O'Hara & Morandin 2010 and the references therin). Moreover, the effect of oiling appears to be greatly enhanced when the oil is spread in the plumage due to preening (cf. Jensen & Ekker, 1991ab results in Table 13).

The thickness of the oil slick and the activity of the bird within the slick will be deciding factors in determining the amount of oil that is absorbed into the plumage (Jenssen & Ekker 1991a). As an example it may be useful to investigate what is needed to obtain a lethal dose of 350 ml, here illustrated by calculating swim distances. The distance (meters) an animal must swim to obtain a lethal dose of 350 ml in an oil slick with a thickness of Hoil may be calculated by the following equation,

$$D = \frac{LD_x}{W \times Hoil \times d \times Cov \times ads}$$
Eq. 3.5

where D is the distance in meters, LD_x is the lethal dose (350 ml) and x is the percentage number of exposed animals that is expected to die, W is the width of the animal in meters, $Hoil$ is thickness of the slick in micrometres, d is the density of the oil in ml/g, Cov is the time averaged coverage (0-1) and ads is an adsorption factor of oil that is unknown ($ads = 1$).

Using the example from French-McCay (2009), a common eider with a width of 15 cm (0.15 m) would need to swim 233 meters through a 10 μm thick oil slick with oil of density 1.0 ml/g to obtain a lethal dose of 350 ml (assuming a coverage of 100% and adsorption of 1). To obtain a lethal dose of 70 ml (cf. Jenssen & Ekker 1991a) and 10 ml; the corresponding distance will be approximately 47 m and 7 m.

Table 13. Examples of no effect, sub-lethal and lethal dose of oil on seabirds, marine mammals, aquatic mammals and turtles.

Wildlife type	Dose (ml)	Level	Study Type	End Point	Reference
Sea birds	350	LD_{100}	Expert judgment	Lethal	(French-McCay 2009)
Furbearing aquatic mammals	350	LD_{100}			
Furbearing marine mammals	350	LD_{100}			
Non-fur-bearing pinnipeds, manatee	350	$> LD_1$			
Cetaceans	350	$> LD_{0.1}$			
Sea turtles (juvenile, adult)	350	$> LD_5$			
Sea turtles (hatchlings)	350	$> LD_{50}$			
Common Eider (*Somateria mollissima*)	12.5	LD_{100} (hypothermic)	Lab, allowed to preen	Heat production	(Jenssen & Ekker 1991a)
Mallard (*Anas platyrhynchos*)	12	LD_0 (increased MR by 7% (1h) to 12% (4-14 days after)	Lab		
Common Eider (*Somateria mollissima*)	10	LD_0 (small, transient rise in heat production)	Lab (measuring heat production in	Heat production	(Jenssen & Ekker 1991b))

Wildlife type	Dose (ml)	Level	Study Type	End Point	Reference
	15	LD$_0$ (small, transient rise in heat production)	10 min. intervals, up to 3 h)	Heat production	
	25	LD$_0$ (increased heat production)	N = 12 in total.	Heat production	
	30	LD$_0$ (increased heat production)	Water temperature 4.5 - 6.0 °C,	Heat production	
	35	LD$_0$ (increased heat production - 200-250% above normal)	Air temperature, 3-10 °C,	Heat production	
	40	LD$_0$ (increased heat production - 200-250% above normal)	Not allowed to preen	Heat production	
	50	LD$_0$ (increased heat production -200-250% above normal)		Heat production	
	70	LD$_{100}$ (increased heat production - 400% above normal)[1]		Heat production	
Glaucous-winged gulls	150	LD$_{100}$		Hypothermia	(Hughes et al. 1990)
Domestic Ducks *(Anas platyrhynchos)*	500	LD$_0$ MR increase by 49%	Lab, 21 C	Metabolic rate	Jenssen & Ekker 1989
	2000	LD$_0$ MR increase by 162%	Lab, 21 C	Metabolic rate	

3.3.3   Conclusion and suggestions

Base on the above review and discussion, it appears that seabirds may be damaged by thinner oil than 10 μm and that a lethal dose of 350 ml appears to be insufficiently conservative. It is therefore suggested to lower the lethal film thickness for oiling mortality in seabirds. Based on the review, in particular the study to O'Hara & Morandin (2010) a reasonable thickness appear to be somewhere between 1 μm and 3 μm, and we suggest a film thickness for mortality for seabirds of 2 μm. We do not suggest implementing uncertainties in the film thickness due to practicalities in running the oil drift model with numerous fixed threshold levels (cf. Bjørgesæter & Krajczyk 2014).

With a film thickness of 2 μm, a common eider will obtain a dose of 10 ml after 33 m and a dose of 70 ml after 233 m, given everything else is equal as the example above. A film thickness of 2 μm evenly spread out on a cell with dimensions of 10×10 km and 1×1 km correspond to approximately 200 and 2 ton of oil, respectively (assuming a heavy oil with a density of 1g/mL).

Although external oiling of aquatic mammals and fur seals evokes the same physiological responses as in plumage-contaminated birds, the pelage of aquatic mammals appears inherently less efficient as a provider of thermal insulation and buoyancy in a water environment than the plumage of aquatic birds (cf. Jenssen 1994 and references therein). For the other wildlife groups it is therefore suggested to keep a threshold thickness of 10 μm, as there are little new available data.

In comparison to ERA Acute Level A, the suggestions represent an increase in conservatism. This is in agreement with the logic that lack of data should increase conservatism. A final "tuning" to investigate if the impact is within the range of what is observed in the real world must be implemented before the ERA Acute tool is released. The dose response curve may be implemented on a future update if necessary data is available from the oil drift model.

Box 2. Dose response curves as replacement for the parameter p_{phy}

One target in activity 2 was to refine this large uncertainty in threshold value for lethal film thickness by developing a *lethal dose response curve* for the parameter p_{phy}, based on the reported film thicknesses, MIRA effect keys, the p_{beh} matrix and a lethal threshold dose of oil. One solution is to use a logistic model for the dose response curve (Bjørgesæter 2012b; Bjørgesæter & Spikkerud 2012; Bjørgesæter & Krajczyk 2014). Substituting p_{phy} with a continuous logistic response curve, the impact equation (Eq. 3.1) can be rearranged to yield the following equation,

$$N_{let} = p_{beh} \times Cov| > Hoil \times \frac{a}{1 + b \times e^{(-cHoil)}} \times N \qquad \text{Eq. 3.6}$$

where N_{let} is the total number of killed individuals (or population loss), p_{beh} is the probability of encounter with the sea surface, *Cov* is the time averaged cell-coverage for oil thicker than the time averaged coverage (*Hoil*), *a* is the asymptote coefficient, *b* is the intercept coefficient, *c* is a slope coefficient and *N* is the number of individuals (or population fraction) in the cell.

An illustration of dose response curves (p_{phy}-curves) is presented in Figure 5. The best guess estimate for p_{phy} (cf. Table 9) is used as the asymptote coefficient. The development of the intercept and slope coefficient is not completed due to lack of suitable output data from the oil drift model at this date.

Per today, the time average coverage has to be calculated in retrospective, since Hoil is an average value (that is calculated at the end of the simulation) (Figure 4; see also Bjørgesæter & Krajczyk, 2014 for details). In order to use different threshold levels for different wildlife groups, stochastic oil drift simulations must be run in parallel, one for each threshold level.
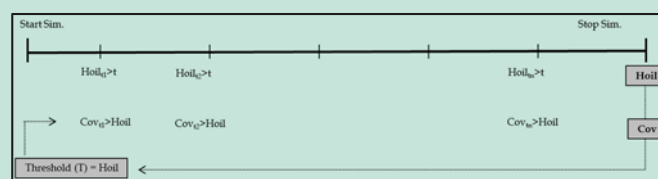
Figure 4. Illustration of calculating time average coverage (Cov) in retrospective. The time average film thickness (Hoil) is used as a threshold value before stochastic oil drift simulation run. The upper line is the time step, where each time illustrates the output interval (e.g. 1 day) for writing data to file (e.g. 1 day). The small t is the terminal film thickness for the surface contaminant.
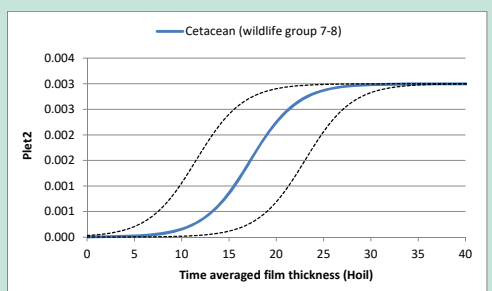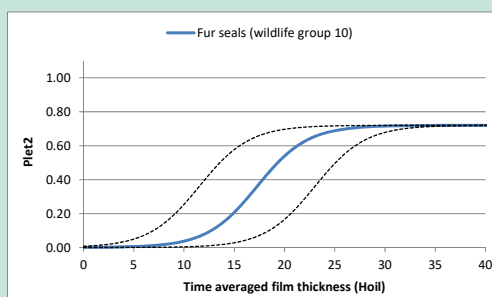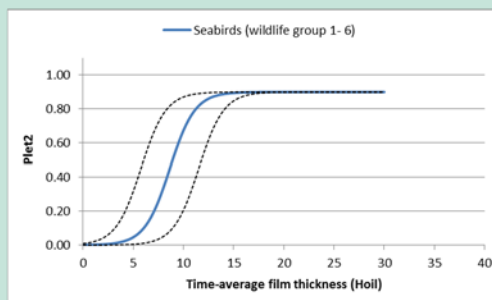
Figure 5. Illustration of dose response curves for different wildlife groups. Note that the scale on the y-axis differs. P_{let2} was a working nomenclature for p_{phy}.

3.4   Time as a variable in the impact equation

Time is an important parameter in damage models. In the biological exposure model implemented in OSCAR ("CBR model") both the contamination and animals (fish, egg and larvae) are modeled in four dimensions (3D plus time) (cf. Brönner & Nordtug 2014 and

references therein for details). Modeling in four dimensions mimics the real world and is the optimal solution for constructing a damage model. In the water column compartment, the animals are represented by spawning products that are released as Lagrangian particles with specific properties and are transported with the same hydrodynamics as the oil (Ute et. al., 2014). In the sediment compartment and the shoreline compartment, the resources remain stationary, and time is therefore only relevant with regards to exposure time and dose response.

In the surface compartment, the animals are represented by their typically population density and population distribution for a given time period, typical with a 3 – 12 months resolution. Within the period the animal's movement is mimicked using p_{beh}, i.e. basically the expected time the animals spend on the sea surface. The contamination is represented by time averaged film thickness (*Hoil*), time averaged coverage (*Cov*) and maximum exposure time (T_{exp}), which are oil drift statistics that is based on the oil slick(s) movements for the whole simulation period.

To represent the wildlife in four dimensions one could (a) construct algorithms to simulate flight and swim behavior of the animals, analogue to using a "Lagrangian particle model" to simulate the movement of planktonic organism and/or (b) recalculate the population density and population distribution for each time step used in the oil drift model. The first would require models that try to simulate the movements of the animals based on field data (e.g. GPS loggers). The latter is similar to increasing the temporal resolution of the biological resource data (population density and distribution), e.g. running a density model during the simulations. Both will require either that 4D data are reported by the oil drift model or that the damage calculations are performed within the oil drift simulations software. These types of more complex solutions are not within the scope of ERA Acute Phase 3.

French McKay (2009) proposes a simpler method to include time as a variable in her damage model. Translated to ERA Acute nomenclature, it is assumed that wildlife is in equal density across each grid cell (i.e. uniform distribution) and they remix within each grid cell each day (or each main time step used in the model). For each day of the simulation, individuals oiled above a threshold dose are assumed to die, and the remainder may be oiled in subsequent days if oil is still present on the water surface. French McKay (2009) summarized the calculation with the following equation:

$$N_{let} = P_w \sum_{t=0}^{t=\infty} A_s \times N_t \times \Delta t$$

Eq. 3.7

where N_{let} is the the total number killed of a wildlife species in a given grid cell, P_w is the probability of oiling and dying given that a surface slick is encountered for the wildlife behaviour group of the species, A_s is the portion of the ecosystem area swept by oil (greater than a threshold thickness T such that an animal would obtain a lethal dose) over the time interval Δt = 1 day, and N_t is the number remaining alive at time t (of the species and ecosystem of concern).

In order to use Eq. 3.7 in the ERA-SW, the oil drift model must report the necessary oil drift statistics (A_s and film thickness) for each time step (here Δt = 1 day). This is not feasible by the oil drift model today or within the scope of the ERA Acute Phase 3. The rest of this chapter therefore focus on finding a method that uses the reported oil drift statistics to include time as a variable in the impact equation(s). The objective is to find an analytic solution for using the exposure time, T_{exp} as a variable as an alternative to get the results reported for each time step. The exposure time is defined as *numberOfHits × timestepDuration*. A hit is registered if the film thickness is larger than a pre-defined threshold thickness.

An analytic solution to the problem was not identified. To investigate other possible solutions we created an example imitating that we could get oil drift statistics at regular output intervals

(time steps) and used Eq. 3.7 to calculate the damage (Box 3). The results using Eq. 3.7 were compared to different approximations to a true analytic solution.

The first part of Box 3 illustrates the reported oil drift simulation results as input to the ERA-SW, based on a single simulation on a dataset grid containing 20 grid cells with ID ranging from 1 to 20. The grey cells illustrate the swept area, defined as cells that have been in contact with surface contaminant (i.e. here oil). Using the impact equation without a time parameter (Eq. 3.1), the absolute impact (measured in number of individuals) is 111 and the relative impact (population fraction) of the pre-exploitation population size (N = 2000) is 111/2000 = 5.6%.

Using oil drift results reported during the simulations, i.e. for each output interval from the different time steps (i.e. data that is not available per today but is mimicked in the example) and Eq. 3.7, the absolute impact is 296 individuals and the percentage population loss is 14.8%. That is, in this example, the effect of using time as a variable, in contrast to not, increases the absolute and relative impact (number of killed individuals or percentage population loss) with a factor of 2.7. This complies with the real world where both p_{beh} and p_{phy} will increase as a function of time as long as there oil in the environment.

Two possible approaches to include time as a variable in the impact equations based on the oil drift statistic reported by OSCAR, i.e. the parameter T_{exp} is described below.

The first approach was used by Fraser et al. (2006) to estimate the number of birds that would be oiled annually by produced water, and was a simple weighted average estimate, calculated by summing the number of estimated dead birds per day in each cell and weight this number by T_{exp}. The result in the example in Box 2 would be 371 dead birds (18.6% population loss). This approach would be in line with how the ERA Acute tool is intended to handle missing data (missing data increases conservatism). However, it would lead to a rapid depletion of individuals in the grid cells and is too conservative compared with the real world.

The second approach is to use the best approximation to an analytic solution identified. The total number of killed individuals (or the population fraction) N_{let} is calculated by the following equation,

$$N_{let} = \sum_{i=1}^{n} N_i - \left(1 - p_{beh} \times Cov | > T \times p_{phy}\right)^{T_{exp}} \times N_i \qquad \text{Eq. 3.8}$$

where N_{let} is the number of killed individuals (or population fraction), i is the grid number, n the total number of cells in the dataset grid, N_i is the number of individuals in grid i, p_{beh} is the probability of coming in contact with the surface, Cov is the time averaged coverage for oil above the thickness threshold T, p_{phy} is the probability of mortality given contact with a slick above the thickness threshold T, and T_{exp} is the maximum exposure time in days.

The equation takes into account that the number of individuals is reduced at different time step, and thus de not deplete the cell for birds in an exponential rate.

Applying this equation to the example in Box 3, the impact is 294 individuals and the percentage population loss is 14.7%, i.e. similar scale of impact as if using Eq. 3.7 (i.e. impact calculated based on result reported for each output interval).

How well the approximation (Eq. 3.8) will do in real calculations still needs further testing. Varying the parameters N, p_{beh}, p_{phy}, Cov manually at random in the example in Box 3, have little effect on the error margin between the "true" and the "approximated analytic solution".

Box 3 (including time as a variable)

Northern gannet (*Morus bassanus*)

p_{beh} = 0.35 (in this example)

p_{phy} = 1.00 (in this example)

Classified Pelagic surface foraging seabirds (deep plunging). Adults are 81–110 cm long, weigh 2.2–3.6 kg and have a 165–180 cm wingspan. Lay one egg on cliffs.

Lethal dose of oil: 350 ml approximated using a threshold thickness T of 10 μm in this example.

Dataset grid and water-surface area swept by oil at end of simulation-01 marked in grey. Numbers are cell-ID.

17	18	19	20
13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

UMT grid file with reported results for each cell for the oil drift simulation-01.

IDScen	IDCell	IDComp	Hoil/Zmix	Texp	Coverage
1	8	1	12	3	50
1	9	1	12	3	52
1	10	1	13	3	57
1	12	1	15	3	50
1	14	1	13	4	65
1	15	1	12	4	44

Biological data (population density and distribution) within the dataset grid at time t = 0. Population size, $N_{t=0}$ = 2000.

100	100	100	100
100	100	100	100
100	100	100	100
100	100	100	100
100	100	100	100

Calculation of impact as number of dead birds and population fraction using the reported result from the oil drift model (the UTM grid file) T = 4 μm.

IDScen	IDCell	N_{let}
1	8	17.5
1	9	18.1
1	10	19.8
1	12	17.5
1	14	22.8
1	15	15.3
N_{let} =		**111**

One Cell (Eq. X)

$N_{let\,(cell8)}$ = 0.35×0.50×1.00×100

= 17.5 individuals

All cells (simulation-01)

N_{let} = 111 individuals

Calculation of impact with time

Development of the oil slick over time t_1 to t_8. The release site is located in cell 9 and the release last for three time steps (Δt = 1day, i.e. 3 days). After three days the oil slicks move away from the release site cell and at the end of the simulation there is only oil in cell 8.

All the cells in this example have film thickness above T (4 μm) and the coverage varies between 25% and 100% (see snapshot of Hoil and Cov as a function of time in the two figures below).
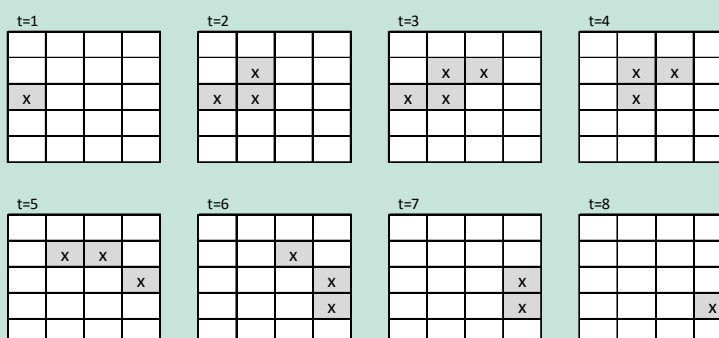
Snapshot of Hoil (μm) as a function of time
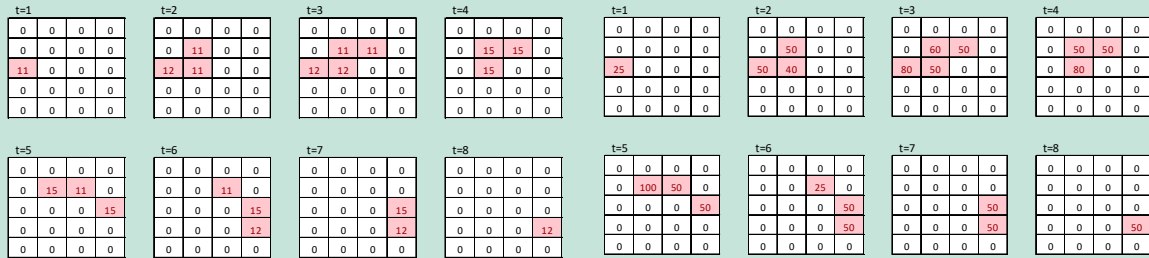
Snapshot of Coverage (%) as a function of time
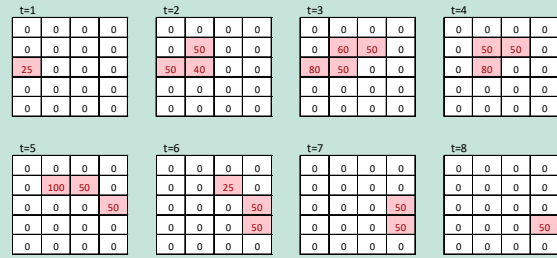
Population size and number of wildlife in each grid cell as a function of time (Eq. 3.7)

The number of dead birds at time t_1 is 2000-1991= 9, at t2, 2000 – 1944 = 56 and so on.

The total number of dead birds N_{let} for the whole simulation period is 2000 – 1704 = 296, and the lost population fraction N_{t8}/N_{t0} is 296/2000 = 14.8%.

Using an approximation to the analytic solution (Eq. 3.8)

$$N_{let} = \sum_{i=1}^{n} N_i - \left(1 - P_{beh} \times Cov| > T \times P_{phy}\right)^{T_{exp}} \times N$$

N_{let} = 294, and the population fraction is 294/2000 = 14.7%, where N_{let} is the number of killed individuals (or population fraction), i is the grid number, n total number of cells in the dataset grid, N_i is the number of individuals in grid i, p_{beh} is the probability of coming in contact with the surface, Cov is the time averaged coverage for oil above the thickness threshold T, p_{phy} is the probability of mortality given contact with a slick above the thickness threshold T, and T_{exp} is the maximum exposure time in days.

3.5   Technical specification - impact phase

The impact equation(s) in this report is does not differ from the equation implemented in ERA acute Level A.3. The same calculation step may therefore be used (Calculation of impact for (1) a single cell is presented in Eq. 1.1 – 1.3 in Chapter 5.2, (2) a scenario in Chapter 5.2, (3) a defined situations of hazard and accident (DSHA) in Chapter 5.3. Calculation of risk is given in Chapter 5.4. A spreadsheet with all calculation steps have been developed (Spikkerud 2011).

The look-up table is different, and if time is included a new variable (T_{exp}) must be collected from the results from the oil drift simulations. A major difference is that the script has to keep track of oil drift results from three stochastic runs. The correct result to use is determined by the threshold thickness for oiling mortality (T), which has been assigned to each wildlife group.

An extract of the *UTM Grid file* showing the parameters used in the impact equations for the surface compartment is illustrated in Table 14 (cf. Brönner 2015 for details). The UTM grid file is a tab-delimited text file, containing the results from the oil drift simulations presented on a UTM projected grid. Information about the UTM projected grid (zone number, central longitude, western edge, eastern edge, southern edge, northern edge, cell size and count) and spill site (longitude, latitude and depth) is given in the *UTM Summary file*. Information about start time (year, month, day, and hour) of each simulation is given in the *simulation log file*.

The ERA Acute software (ERA-SW) reads these files together with input table for the DSHA and resource data for further calculation of impact (cf. Table 2 in Spikkerud 2011).

Table 14. Extract of the UTM Grid file ().

Parameter Name	Description
IDScen:	Simulation number
IDCell:	Cell index number which is calculated by IXcell + (JXcell-1) * NumberOfCellsInXdir
IDComp:	Compartment number: 1 = Surface, 2 = Shoreline, 3 = Water-column
Hoil/Zmix:	if IDComp=1, Hoil: Time-averaged thickness (μm)
	if IDComp=2, Hoil: Accumulated thickness (μm)
	if IDComp=3, Zmix: Time-averaged mixing depth for water concentration (m)
T_{exp}:	Maximum exposure time (days)
Coverage:	Time averaged cell-coverage (%)

3.5.1   Fixed threshold levels for film thickness

In order to obtain Coverage and T_{exp} values that are related to harmful threshold film thicknesses for all the wildlife groups, the user needs to run three parallel simulations; one with no threshold and two with different fixed threshold levels (T1 and T2) for film thicknesses (cf. Bjørgesæter & Krajczyk 2014).

If the VEC belongs to wildlife group 1 – 6, the Cov (and T_{exp}) in the impact equation is collected from the stochastic run that used T1 (cf. Table 15). If the VEC belongs to wildlife group 7 – 13, the Cov (and T_{exp}) in the impact equation is collected from the stochastic run that used T2. The Hoil in the equation is collected from the stochastic run that used no threshold thickness (cf. Table 15).

Table 15. Look-up table for p_{beh} and p_{phy} and threshold values.

Wildlife groups	p_{beh}			p_{phy}			Threshold (μm)
	LO	BG	HI	LO	BG	HI	
Pelagic diving seabirds	88.5%	78.7%	78.7%	80.0%	90.0%	100%	T1
Pelagic surface foraging seabirds	51.0%	45.3%	45.3%	80.0%	90.0%	100%	T1
Coastal diving seabirds	75.9%	67.4%	67.4%	80.0%	90.0%	100%	T1
Coastal surface feeding seabirds	45.1%	33.4%	30.6%	69.1%	78.2%	87.3%	T1
Wetland surface feeding seabirds	54.0%	48.0%	48.0%	80.0%	90.0%	100%	T1
Wading seabirds	35.0%	35.0%	35.0%	80.0%	90.0%	100%	T1
Baleen whales	87.5%	84.0%	80.2%	0.04%	0.04%	0.04%	T2
Toothed whale	100%	60.0%	40.0%	0.07%	0.07%	0.07%	T2
True seals, walruses and sea lions	95.8%	89.5%	82.8%	0.42%	2.83%	5.83%	T2
Fur seals	93.3%	78.3%	63.3%	50.0%	71.7%	93.3%	T2

Sea cows	100%	98.0%	95.0%	0.00%	1.56%	3.89%	T2
Aquatic mammals	100%	96.0%	91.7%	53.5%	68.5%	80.0%	T2
Sea turtles	100%	99.0%	97.5%	3.00%	3.00%	3.00%	T2

Box 4 illustrates an example of the "algorithm" for one simulation (simulation 01) and one cell (cell 15) for a species belonging to wildlife group 9 (California sea lion, i.e. T = 10 μm). The grey cells in the dataset grid (called "habitat grid" in OSCAR) illustrate the swept area of oil thicker than the terminal film thickness for surface contaminant (a value set as low as the oil drift model allows to give reliable results) used in the oil drift simulations. The output (result) for cell 15 is shown to the right for the following three parallel stochastic runs with different threshold levels for film thickness, i.e.:

User input to stochastic simulations 1 - 3

- Run 01: threshold thickness T0 (no threshold)
- Run 02: threshold thickness T1 (harmful thickness for VECs in wildlife group 1-6)
- Run 03: threshold thickness T2 (harmful thickness for VECs in wildlife group 7-13)

Model output from stochastic simulations 1 -3

- Run 01:Hoil
- Run 02: Coverage and T_{exp} to be used in Eq. 3.8for VECs in wildlife group 1-6
- Run 03: Coverage T_{exp} and to be used in Eq. 3.8for VECs in wildlife group 7-13

The algorithm checks first that Hoil is above the harmful thickness for the VEC in question. If positive (Hoil from RUN 01 > 10 μm), the algorithm finds the related Coverage (76%) and T_{exp} (6.7 days) values from RUN 03, and the p_{beh} and p_{phy} values for the VEC from the look-up table (cf. Box 4). The values are used in Eq. 3.8 to calculate the impact for the VEC in Cell 15. If negative (Hoil from RUN 01 < 10 μm), the impact is zero.

To obtain the impact for simulation 01 (i.e. Eq. 3.8), sum the impact in each cell (here cell 8, 9, 10, 12, 13, 14, 15). For one simulation the output is three estimates of the impact; in the example low = 2.0 (0.2%), best guess = 12.2 (1.2%) and high = 22.2 (2.2%). The results are at the cell level and may thus be plotted on a map (cf. Spikkerud et al. 2010; Spikkerud 2011).

Box 4

Habitat grid

17	18	19	20
13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

---->

Results Cell 15

RUN 01 (T0) 28 Hoil

RUN 02 (T1) 5.9 Texp 80% Coverage

RUN 03 (T2) 6.7 Texp 76% Coverage

California sea lion

N = 1000 (population size)

n = 100 individuals in cell 15 or 100/1000 = 10% of the current population

Look-up Table - True seals, walruses and sea lions

p_{beh} (%)			p_{phy} (%)			T
LO	BG	HI	LO	BG	HI	(μm)
95.8	89.5	82.8	0.42	2.83	5.8	10

Algorithm

If Hoil > T2 (10 μm)

 Then

  T_{exp} = 6.7 and Coverage = 76%

$$N_{let\ (low)} = N_{15} - \left(1 - P_{beh\ (low)} \times 0.76 \times P_{phy\ (low)}\right)^{6.7} \times N_{15}$$

$$N_{let\ (best\ guess)} = N_{15} - \left(1 - P_{beh\ (best\ guess)} \times 0.76 \times P_{phy\ (best\ guess)}\right)^{6.7} \times N_{15}$$

$$N_{let\ (high)} = N_{15} - \left(1 - P_{beh\ (high)} \times 0.76 \times P_{phy\ (high)}\right)^{6.7} \times N_{15}$$

Else

$$N_{let} = 0$$

End If

Results for one cell (cell 15)

$N_{let\ (low)}$ = 2.0 or 2.0/1000 = 0.2%

$N_{let\ (best\ guess)}$ = 12.2 or 12.2/1000 = 1.2%

$N_{let\ (high)}$ = 22.2 or 22.2/1000 = 2.2%

The data structure for VECs in the ERA Acute surface compartment comprises is equal to level A and the following two tables.

Biological resource data (population distribution and density in the analysis area)

Column name	Description
ID	Cell ID (or the geographic position of the cell to allow for more flexibility)
Wildlife group	Name of the wildlife group
Species name	Name of the species
Population name	Name of population
Jan	Relative abundance of a pre-defined population or number of individuals in cell
Feb, -Dec	Same as above

Parameters to calculate the impact

Column name	Description
Wildlife group	Cell ID (alternative the geographic position of the cell to allow for more flexibility)
Species name	Name of the wildlife group
Population name	Name of the species
p_{beh} - low	Behavior and avoidance factors that affect the probability of coming in contact with oil on the sea surface. Low = least conservative estimate
p_{beh} – best	Behavior and avoidance factors that affect the probability of coming in contact with oil on the sea surface. Best guess = intermediate conservative estimate
p_{beh} - high	Behavior and avoidance factors that affect the probability of coming in contact with oil on the sea surface. High= most conservative estimate
p_{phy} -low	Physiological factor that affect the probability of mortal effect given that contanct with the oil on the sea surface. Low = least conservative estimate
p_{phy} –best guess	Physiological factor that affect the probability of mortal effect given that contanct with the oil on the sea surface. Best guess = intermediate conservative estimate
p_{phy} -high	Physiological factor that affect the probability of mortal effect given that contanct with the oil on the sea surface. High= most conservative estimate
T's	Threshold film thickness for mortality

3.5.2   Post-processing of the results

For a release scenario (e.g. a topside release with a release rate of 2300 m³/day and release duration of 15 days) represented with e.g. 100 single simulations one will obtain 300 estimates of impact ("100 for low", "100 for best guess" and "100 for high"). The results are exported to a result file for further processing and calculation of various statistics (Table 16). In addition, each estimate off N_{let} is used as input to the population model for calculation of restitution time for each simulation.

The different statistics may be calculated for each of the three estimate of N_{let} or for all combined (e.g. three mean values for each N_{let} estimates, i.e. here for 100 values, or mean of all estimates, i.e. here for 300 values). The statistics in Table 16 are self-explanatory, except the MIRA categories. These are pre-defined categories for population losses (1-5%, 5-10%, 10-20%, 20-30% and 30-100%) which are used in the MIRA methodology. All oil companies operating in Norway have established environmental risk acceptance criteria for these categories.

Table 16. Example of a result file for one scenario, and possible statistic ERA-SW may calculate.

Simulation	$N_{let (low)}$	$N_{let (best guess)}$	$N_{let (high)}$
Sim. 001	5%	12%	23%
Sim. 002	0%	0%	3%

Simulation		$N_{let\ (low)}$	$N_{let\ (best\ guess)}$	$N_{let\ (high)}$
Sim. 003		14%	32%	59%
.		.	.	.
.		.	.	.
Sim. 098		0%	0%	0%
Sim. 099		1%	4%	23%
Sim. 100		4%	8%	16%
Measure of central tendency	Mean			
	Median			
Measure of variability	Standard deviation			
	Minimum values			
	Maximum values			
Interval estimate	Confidence interval			
Statistical distribution	Quartiles			
	Percentiles			
Discretisation	MIRA categories			
	Other categories			

THE LAG PHASE

4 The lag phase

4.1 Introduction

For many of the species assigned to the surface compartment in ERA Acute, a lag-time can be assumed due to a contamination of shoreline habitats used by these animals. A contamination of shoreline habitat used by seabirds, seals and sea turtles may have important long-term consequences, including sub-lethal effects of oil spill exposure, reduced food availability and long-term reproductive impairment, until the oil is reduced or disappeared, either naturally or by beach cleaning.

In the ERA Acute phase 3 – surface compartment working document by Bjørgesæter & Spikkerud (2012) it was suggested to use parameters from the Environmental Sensitivity Index (ESI) to obtain oil-retention times (http://response.restoration.noaa.gov/esi-shoreline-types). Oil degrades at varying rates depending on environment (influenced by shoreline energy regimes, substrate texture and other relevant geomorphic features, in addition to amount and type of oil). When the oil contamination is reduced below an unknown threshold, it is assumed that wildlife in the sea surface compartment can use the areas with no negative consequences.

4.2 Proposed implementation

The time period from oiling to no negative effect on wildlife is set equal to the lag-time ($t_{lag,sh}$) of the shoreline compartment. The lag-time ($t_{lag,sh}$) of the shoreline compartment can then be used to calculate the lag-time of the surface compartment by the following equation,

$$t_{lag,su} = \sum_{i=1}^{\infty} N_{hab_i} \times t_{lag,sh_i} \times SF_r \qquad \text{Eq. 4.1}$$

where N_{hab} is the population fraction that have their habitat oiled, SF is a resource specific sensitivity factor (0-1) of the resource, and i is the number of cells in a single habitat. To obtain the lag-time for the population, the lag-times for each habitat are summed (se calculation example below). The method requires knowledge about the resource distribution, breeding sites and general biology of the resource, such as habitat preferences and usage.

A practical approach will be to pre-define areas as important breeding sites, and use the biological resource data to estimate the population density in the area as an approximation of the relative importance of each habitat site. A simplified example is illustrated below and in Figure 6. Ten areas for population X has been pre-defined (marked with red and black rings). A lag-time ($t_{lag,sh}$) of 3 and 10 years has been estimated for two of the ten areas (red rings). Assuming a SF of 0.7 (e.g. black oyster catcher, a wading birds that could be severely affected by long-term contamination because of their shoreline habits), and the two areas holds 10% (area 1) and 5% (area 2) of the population. Using Eq. 4.1, the lag-time for area 1 would be 3×0.10×0.7=0.21 years and the lag-time for area 2 would be 10×0.05×0.7=0.35 years. The lag-time for population X would hence be 0.21+0.35=0.56 years. If the resource was e.g. a pelagic seabird nesting in cliffs, the SF could be set lower.

Examples of long-term consequences of oil spills, e.g. reproductive impairment in sea birds are often difficult to document due to large natural variation in vital rates, confounding factors and lack of long population data; both pre- and post-spill. Several studies have nevertheless revealed long-term consequences of larger oil spills. Five years after the *Prestige* oil spill the European shag population breeding at oiled colonies was 70% lower than pre-spill counts (cf. Barros et al. 2014 and reference therein). Barros et al. (2014) found that the reproductive success after ten years was reduced by 45% in oiled colonies relative to unoiled ones. Walton et al. (1997) assessed the sub-lethal effects of the *Braer* spill on kittiwakes. They found little effect in breeding behaviour except that the return rate of adults to the breeding site was exceptionally low (44% versus overall mean > 80%) and that nest-site and mate fidelity also

appeared low in comparison with pre-spill conditions. It was suggested that the factor responsible for missed breeding was an altered physiological state caused by oil ingestion.
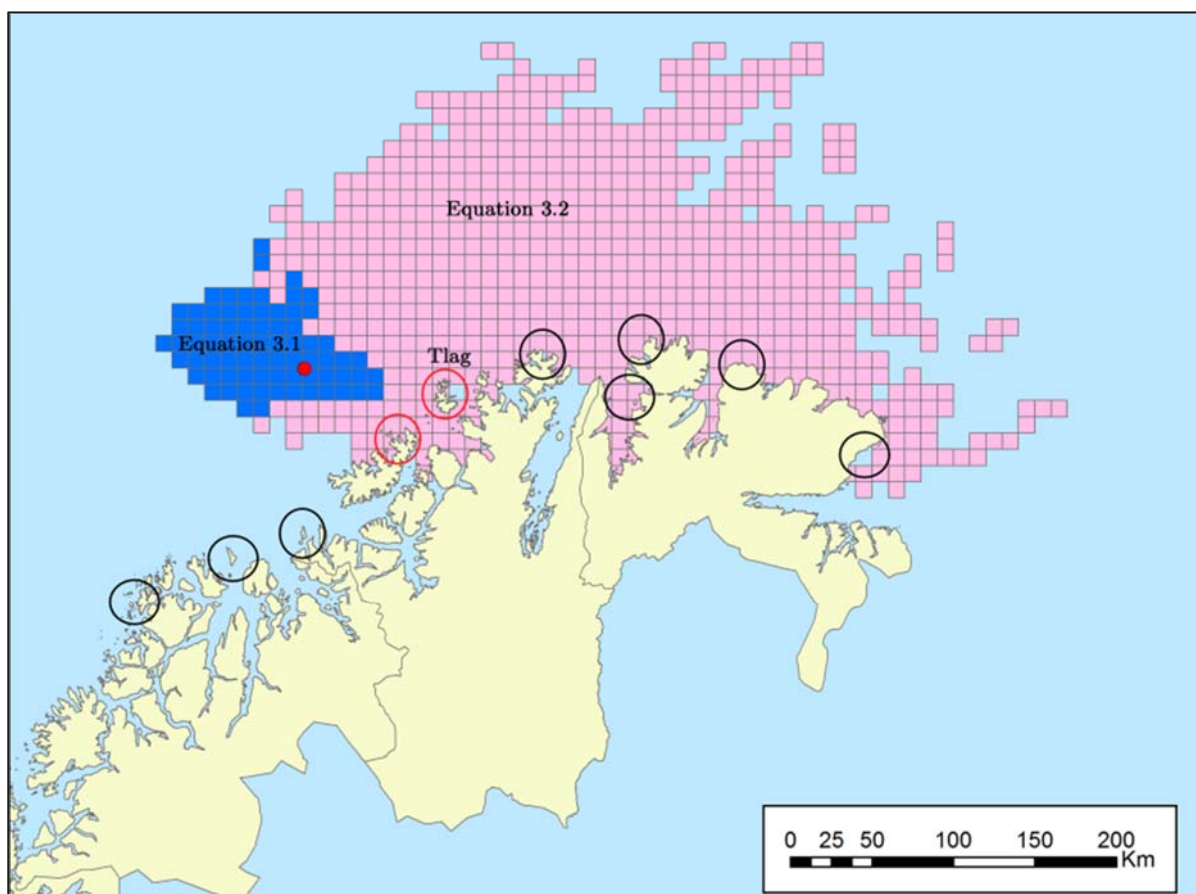

Figure 6. Illustration of pre-defined breeding sites (rings) used to define important habitats and calculate the lag-time. An unaffected breeding site is marked in black and an affected breeding site is marked in red. The figures are from the working document (Bjørgesæter 2012b) and the equations refers to equations in this document. The areas with potential lethal (film thickness > T) are marked as blue cells and the areas with potential sub-lethal effects (film thickness < T) are marked with pink cells. The red dot is the release site. The oil spill is Scenario 2 Simulation 341 from the testing phase (Bjørgesæter 2012a).

THE RECOVERY PHASE

5   The recovery phase

The total recovery time is the sum of all time parameters (impact-time + lag-time + restitution-time). The main time parameter deciding the total recovery time is the restitution time. The RIF is affected by both the size of the impact and the restitution time.

In the ERA Acute project the restitution time of a population is defined as the time from restitution starts until the population is assumed to be intact. The length of the restitution period depends on four parameters; births, deaths, immigration and emigration, and may be expressed by the following equation,

$$N(t + 1) = N(t) + \text{Births} + \text{Immigration} - \text{Deaths} - \text{Emigration} \qquad \textbf{Eq. 5.1}$$

where N_{t+1} is the number of individuals at time $t+1$, N_t is the number of individuals at time t, Births and Deaths is the number of individuals born and deceased between time t and time $t + 1$, Immigration and Emigration is the number of individuals that immigrated and emigrated between time t and time $t + 1$. Eq. 5.1 describes the growth of a population. It is always true, but it is vacuous until we specify the values of Births, Immigration, Death, and Emigration over the time interval t, $t+1$.

In the two working documents from Bjørgesæter (2012b) and Bjørgesæter & Spikkerud (2012), a short review of the population models used in the EIF project and the damage keys used in the MIRA methodology was presented, together with population matrix models (e.g. Caswell 2001; Leslie 1945) and two discrete logistic models; (1) the Ricker model (1954) and (2) the Maynard-Smith & Slatkin model (1973).

It was decided to use population models to calculate the restitution time in contrast to discrete keys. It was concluded to use the discrete logistic model suggested by Maynard-Smith & Slatkin (1973). This is a single species dynamic population model that has the flexibility lacking in the population models used in EIF Acute. Although simple compared to a complex nature, the logistic population model is a valuable tool for modeling fluctuating populations and has been shown to describe the pattern of density regulation in population dynamics quite well in many mammals and also seabirds (Sæther & Engen 2002; Erikstad et al. 2013).

A crucial parameter in the model is the fundamental net reproductive rate, *R*, which is the finite rate on population increase assuming a stable and deterministic environment (constant birthrate, death rate, emigration and immigration over time). An important activity in the recovery phase has been to develop a framework to derive the parameters needed to run this model from a minimal of demographic data. A simple calculator has been made in Excel to demonstrate the framework and calculation steps (see Appendix B2).

5.1   The population model

The population model in the ERA-SW is kept simple to ensure it is sufficiently general to be applied to all species in the surface compartment. A simple model minimise the number of required variables, which is important as detailed demographic data is limited for the majority of species and populations in the world. If data exist, the model should be able to utilise this, and if data is missing it should be able to find the necessary data without extensive research. The discrete logistic growth model, by Maynard-Smith & Slatkin (1973) fulfils these criteria:

$$N_{t+1} = \frac{N_t R}{1 + (aN_t)^b} \qquad \textbf{Eq. 5.2}$$

where N_t is the populations size at time t. R is the *fundamental net reproductive rate*, *a* is (R-1)/K, where K is the *carrying capacity* of the population and *b* is a factor determining the kind of density dependence (see text below for more detailed explanation of the parameters).

The model estimates the population size in generation $t + 1$ as a function of the number of individuals in the previous generation and is appropriate for organisms with discrete

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generations (e.g. wildlife that breed seasonally such as reptiles, seabirds and marine mammals). It includes density dependent population growth (i.e. intraspecific competition) by assuming a negative feedback of the population size on the fundamental net reproductive rate. A plot of N_t with respect to time (t) yields a sigmoidal (S-shaped) curve of the population size, where growth is approximately exponential when N is close to zero, and slows to equilibrium at $N = K$ (cf. Figure 5). The maximum slope of the growth curve is known as the maximal sustainable yield (MSY). This occurs at the inflection point (were the curve changes from being convex to concave). The model includes a lag-time, τ, equal to the interval of the discrete time steps t, i.e. here 1 year.

The variable b introduces the possibility to include different types of density dependence in the model (intraspecific competition). By the choice of the appropriate values for b, the model can portray *undercompensation* ($b < 1$), *perfect compensation* ($b = 1$), *scramble-like overcompensation* ($b > 1$) or *density independence* ($b = 0$).

The model has the potential to overshoot a fixed point, e.g. the carrying capacity K (Figure 11). As the population size approaches K, more offspring is born than the environment can support and the population size exceeds K. After a period this will lead to lack of resources and some individuals dies because of insufficient resources (e.g. food, nesting or breeding sites, parasites). This type of fluctuations or oscillations around (or below) the carrying capacity is not unusual in iteroparous species with high juvenile survival rate (Neubert & Caswell 2000). The potential to overshoot is determined by adjusting either R or b, or both. Thus, the model adds another dimension of generality that the original proposed Ricker model lacked.

Five examples of the flexibility of the model are illustrated in Figure 7, Figure 9, Figure 8, Figure 11 and Figure 11. All figures illustrate a hypothetical species with a pre-spill population size of 1000 and a post-spill population size of 10 individuals (i.e. impact = 990 individuals or a population fraction of 99%). A large impact was selected to illustrate the model characteristics at a large range of population sizes.

In the first four figures the fundamental net reproductive rate is 1.3 (annual population growth of 26%), and the only parameter that changes is the type of density dependence (b). At $b = 1.0$ we have perfect compensation, meaning that the population growth operate on a faster time scale than the interval of observation (1 year time step) and the model is in practice equal to a continuous logistic growth model (Figure 7). At $b = 0.0$, we have density independence and the model is in practice equal to an exponential growth model (Figure 8). At $b = 1.4$ we have scramble-like overcompensation, meaning that the population will return quickly to equilibrium and tend to overshoot the equilibrium (Figure 9). At $b = 0.7$ we have undercompensation, meaning that the population will return slowly to equilibrium (Figure 10). Finally in Figure 11, we have an example where the combination of R (1.6) and b (5) results in oscillations around equilibrium and in this example the population settles at equilibrium after a while.

The correct setting of b requires information about the negative feedback processes (density dependent) in the population of interest and should be performed with care by experts. A more practical use of b is fine-tuning of model results against observations (or against more advanced models), in addition to the possibility of including density dependence and independence in the same model. A suggested standard setting for b is therefore for 1 or 0.
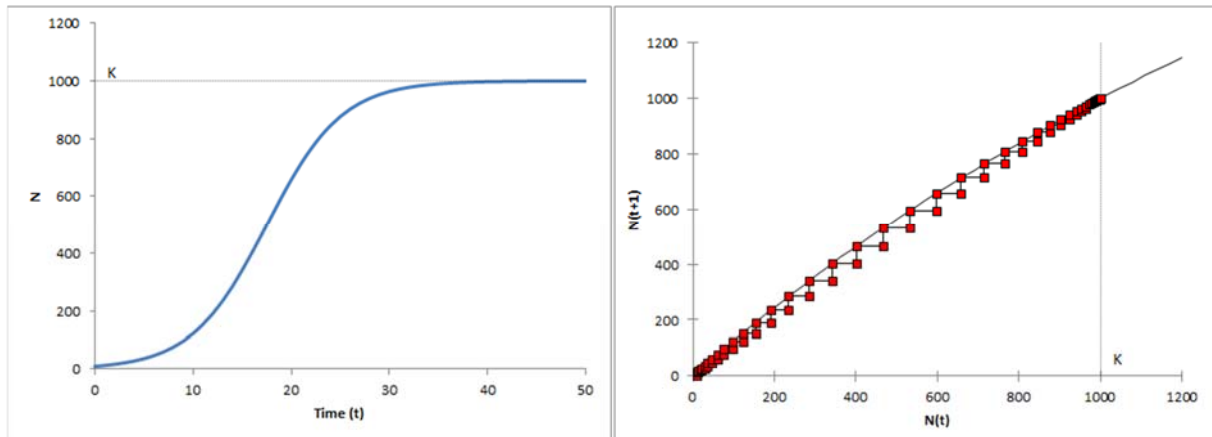
....

Figure 7. Illustration of the model for *R* = 1.3, *b* = 1.0 and *K* = 1000 (left). The starting point is 10 individuals. N_{t+1} as a function of N_t(right). The increase in population size is low when *N* is low and when *N* approaches *K*, and approximately 0 at *K* (left and right).
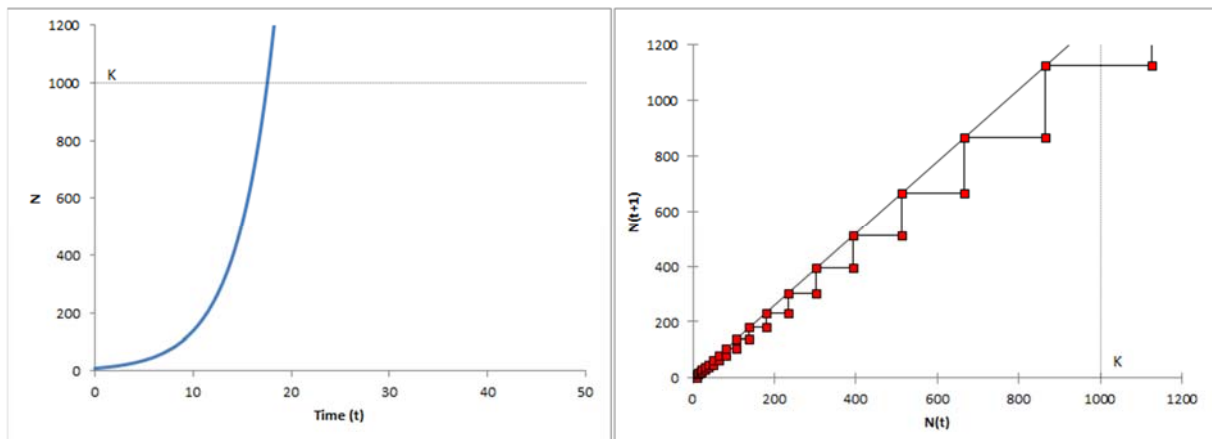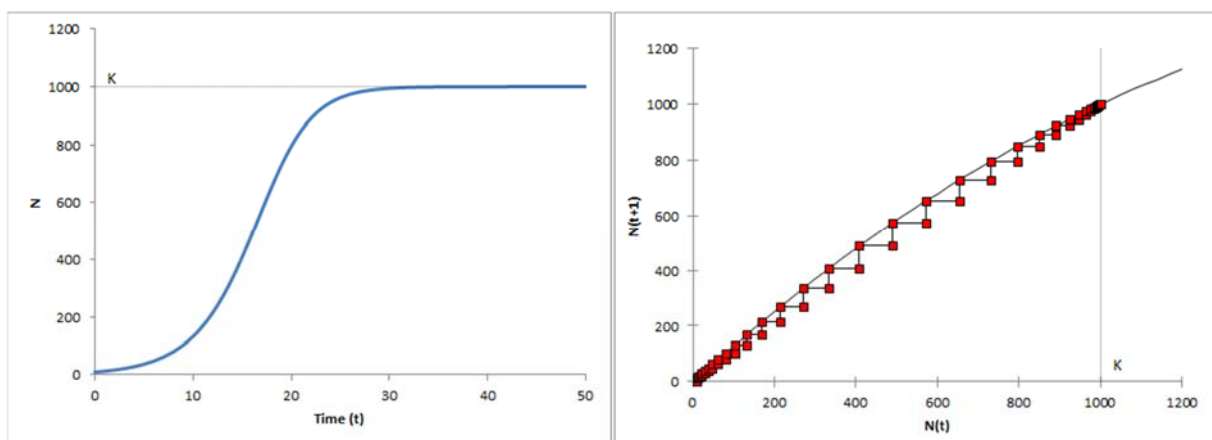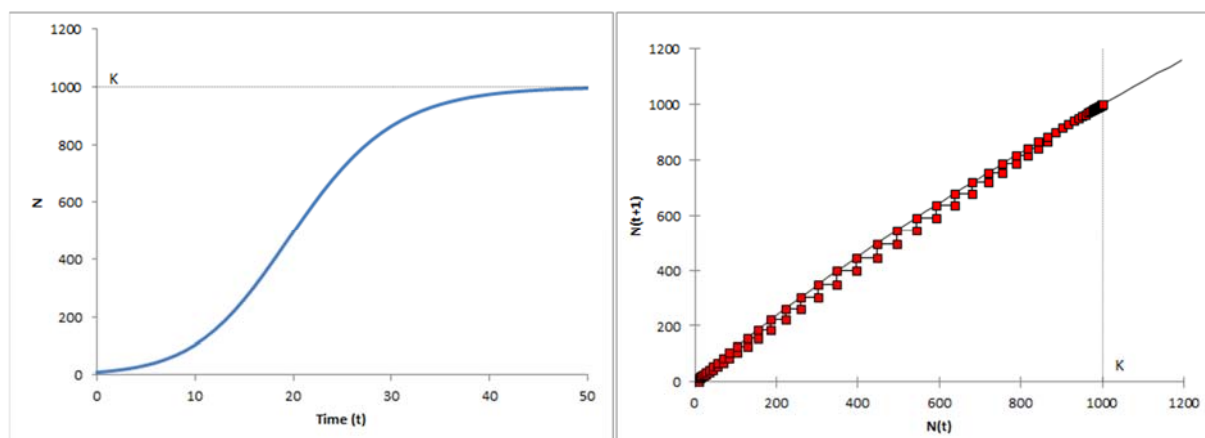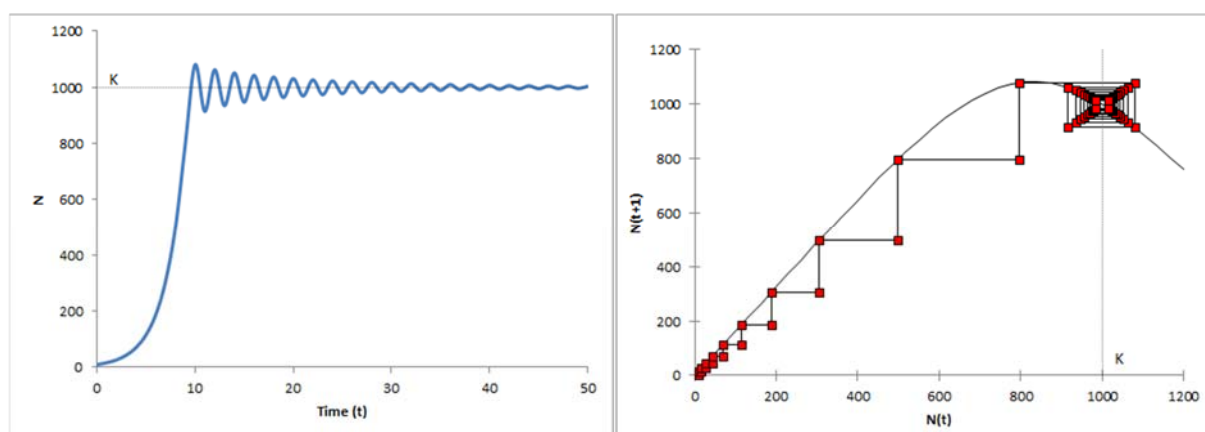

Figure 8. Illustration of the model for *R* = 1.3, *b* = 0 and *K* = 1000 (left). The starting point is 10 individuals. N_{t+1} as a function of N_t(right). The increase in population size is low when *N* is low and when *N* approaches *K*, and approximately 0 at *K* (left and right).

Figure 9. Illustration of the model for *R* = 1.3, *b* = 1.4 and *K* = 1000 (left). The starting point is 10 individuals. N_{t+1} as a function of N_t(right). The increase in population size is low when *N* is low and when *N* approaches *K*, and approximately 0 at *K* (left and right).

Figure 10. Illustration of the model for _R_ = 1.3, _b_ = 0.7 and _K_ = 1000 (left). The starting point is 10 individuals. N_{t+1} as a function of N_t (right). The increase in population size is low when _N_ is low and when _N_ approaches _K_, and approximately 0 at _K_ (left and right).

Figure 11. Illustration of the model for _R_ = 1.6, _b_ = 5 and _K_ = 1000 (left). The starting point is 10 individuals. N_{t+1} as a function of N_t (right). The increase in population size is low when _N_ is low and when N approaches _K_ it overshoots and fluctuates around _K_ and finally settles at K(left and right).

5.1.1   Assumptions of the population model

The proposed model has some assumptions of the population and the population dynamic(s). A description of the assumptions is presented below.

Closed population

The model assumes a closed population. In a closed population immigration and emigration are assumed to not happen (I = E = 0) or cancel each other out (I - E = 0). Immigration and emigration are important demographic processes which can have a strong impact on population dynamics. However, estimating and modelling these processes are difficult and requires large amount of data e.g. capture–recapture data. The methods that have been developed either requires strong assumptions or combine in a piecewise manner the results from separate analyses (Abadi et al. 2010). Attempting to include immigration and emigration would not be in line with a simple and global applicable population model.

Unstructured population

The model is unstructured, i.e. it ignores differences between individuals, and assumes that a total headcount, irrespective of e.g. age structure, provide all the necessary information for predicting future population changes. This is not true in real life and a method to take this

fact into consideration is to construct age- or stage-structured matrix models. Matrix models are the basis for the *fundamental net reproductive rate calculator* presented in Chapter 0.

The calculator is a tool to calculate the population growth rate based on minimal demographic information but also allow the use of more detailed information such as data of age-specific survivorship if this is available. This implies that although one does not model the population growth of specific age-classes or stages, the population growth rate used in the model is partly based on average values for death and birth rates for the whole population. This should be adequate for ERA Acute since the target is estimating the restitution time for the whole population. Moreover, if suitable complete life tables for the population in question are available in the peer-reviewed literature, the calculator can be used to calculate the population growth rate. In the latter case, however, most likely the fundamental net reproductive rate (or similar measures for population growth) will be stated in the article of the study.

Since life tables and matrix models are the basis for the calculator, and are popular tools used to estimate and analyse populations and population growth, Chapter 5.2.1 is devoted to this method. It is crucial to understand the difference between "realized population growth rate" and "potential population growth rate". If the study deals with a population located at, or close to, carrying capacity (i.e. strong influence of density dependent factors) or is exposed to disease or other population limiting factors, the population growth rate is not suitable for the population model. However, it may be suitable if similar factors affect the growth of the population of interest. It is important to have in mind that the proposed population model includes density dependence and this may lead to double accounting of this parameter.

An illustrative example of different population growth rates of the same species is given in Appendix B3. Figure 17 illustrate the number of breeding pairs for different populations of the Great Cormorant (*Phalacrocorax spp.*). There are, however, also examples of populations that are now apparently stabilizing around their carrying capacity without evidence of past exponential population growth (e.g. Southern Elephant Seals (*Mirounga leonina*) and Harbour Seals (*Phoca vitulina*)) (cf. Keith 2008 and references therein).

The parameter *b* may be used to increase or relax the density dependence of the model, and thus the user may take subjective expert judgments based on the available information. In standard analysis it is recommended to keep *b* constant and at a value of 1.

Sex ratio

The model assumes a sex ratio of 1:1. Only females are modelled, since *R* includes the birth rate. This is probably correct for most of the species classified in the sea surface compartment. If the sex-ratio of the killed animals is known, this ratio may be included in the model by adjusting the N_{let} values accordingly. However, the standard adjustment is suggested to be set to 1 (to avoid adjusting the biological resource data and (or) the pre-exploitation population size).

The carrying capacity

The carrying capacity of the environment (*K*) is the maximum population size that the environment can sustain. A population cannot continue to increase indefinitely, and as it approaches the carrying capacity, births and deaths must attain equilibrium. A stable population that is neither increasing nor decreasing in size is said to be stationary. In nature populations do not typically remain at a steady state continually but instead tend to fluctuate or oscillate around some characteristic density. Most populations never reach the carrying capacity but instead remain at lower levels because of the combined regulating effects of both abiotic and biotic factors. A common approach is to quantify the carrying capacity as the pre-spill population size. In accordance with what is proposed for the global fish model in ERA Acute Level B (Jonsson & Ugland 2015), the carrying capacity is suggested defined as "*the long term average population size*".

The current model is a logistic model and the carrying capacity forms an asymptote. Consequently, the population size never comes back to "equilibrium"; it only comes closer and

closer. Mathematically this means that the restitution time is infinite for this class of models. With regard to risk analyses this is undesired because the risk assessment is based on the total recovery time.

Many sustainable harvest models assume that a species' population size is at some proportion of K (quantified in terms of individuals), for example 0.65K or 0.9K. A possible solution is therefore to assume that the pre-spill population sizes are at different proportions of K (e.g. 0.90, and 0.95). In EIF acute it was for instance, indirectly, assumed that the carrying capacity for all populations was located at 0.95K (this was referred to as an "overshoot" and was incorporated as a mathematical adaptation to bring the population back to 1 when using a continuous logistic growth model) (e.g. Tørrhaug et al. 2006). In the proposed model, the population size approaches the value that b takes in the equation (in contrast to K), and thus introduce a possible mathematical adaptation to bring the population back to 1 (i.e. its pre-exploitation population size).

Until this parameter is tested with larger datasets, it is suggested to define threshold levels for recovery (TLR) as proportions of K, where K is defined as the long term average population size which is approximated using the pre-spill population size. If little is known about density dependency of the population(s) of interest, a standard value of 0.95K appears reasonable.

5.1.2   Trade-off between realism, functionality and general applicability

To build a population model some information of the population must be known. In a closed population only two factors control population growth; the birth rate and death rate. However, there are numerous other factors that control these two factors, including stochastic events such as weather or natural catastrophes.

It is tempting to try to add as much details as possible in the model to obtain the most accurate estimate as possible of the population growth. But one can also get into trouble by including too much detail, because it means more parameters to estimate, for which data may not be available. More detail requires more parameters, so the number of observations going into each parameter goes down, and eventually all parameter estimates may end up being unreliable (Ellner 2010). If many of the parameter values must be based on subjective expert judgment and (or) assumptions it may be more trustworthy to use a model that is not dependent on these parameters. Moreover, the ERA-SW is aimed to be a global tool for estimating environmental impact and risk and not a tool to explain the population growth or investigate e.g. different management alternatives.

Finally, it is important to focus on the parameters that matter, both in the impact phase and restitution phase. Crucial parameters (beside the biological resource data) are for example the threshold film thickness, the behavioural and physiological factors, the fundamental net reproductive rate and the threshold level for recovery (TLR). All will have significant effect on the length of the restitution time and RIF, considerable more than e.g. a possible lag-phase or sub-lethal effect on part of the population.

5.2   Population growth rate calculators

The basic for the population growth calculator is various simplifications of the Lotka-Euler equation. Based on detailed demographic data and matrix calculations, this equation allows for an estimation of how a population is growing. To understand the background, usage and how to obtain relevant data for the calculator, it is important to understand the concept of matrix population models.

Important terms

The two fundamental growth parameters are the fundamental net reproductive rate (R) and the intrinsic rate of natural increase (r). R is the per capita change in population size over a discrete time interval t. If $R = 1$, then individuals in a population just manage to replace themselves and population size is stable (i.e. constant). If $R > 1$ the population increases and

if $R < 1$ it decreases. The two rates are related by $r = \ln(R)$ or $R = e^r$. Thus, if $r > 0$ the population increases and if $r <$ the population decreases.

It is also useful to remember the distinction between "*realized population growth rate*" and the "*potential population growth rate*". If a population is growing without limiting factors we denote the rates with a *max* or *m*, e.g. r_{max}. R_m This is the interpretation of the term *max* (in this report and in the articles that is referred to regarding this term), but another, and possible more correct interpretation is that the term *max* is the increase the population achieves under constant ecological conditions when age structure has stabilized. Estimating r_{max} requires long term observations of a population with no limiting factors, e.g. an animal population that have been reduced to low densities under suitable conditions and then estimating population size at standard intervals as the population increases.

5.2.1 Matrix models

One of the most popular tools in targeting ways to estimate population growth is matrix population models (e.g. Caswell 2001). As originally formulated these models were based on an age-structured population with an annual time step (Lewis 1977; Leslie 1945; Lewis 1942). Lefkovitch (1965) demonstrated that the matrix approach would work just as well with stage- or size-based models. A hypothetical example of an age-structured model is illustrated below. Examples from long-term studies of real populations are illustrated in Box 5 (stage-based model) and Box 6 (age-based model).

5.2.2 The Euler-Lotka equation and population matrix models

An unstructured population model assumes that all individuals (females) give birth and die at identical rates. This is not true in real life and a method to implement the variation is to construct an age structured model. In an age structured model it is assumed that all individuals with equal age give birth and die at identical rates. An example of a hypothetical life table or a so-called $l_x m_x$ schedule and a life cycle diagram is illustrated in Table 17. The l_x is the average probability of survival from birth to age x, and the m_x is the average number of offspring that a female can expect to acquire when she reaches age x. The probability to survive to age 2 is 0.25 and the annual survivor probability is 0.5 ages 0, 1 and 2.

Table 17. A life table and a life cycle diagram of a hypothetical population. The example is from the Populus software by D. N. Alstad at the University of Minnesota (Alstad 2015) and the life cycle diagram is made with PopTools (Hood 2011).

x	l_x	m_x	Life cycle diagram
0	1.00	0.0	
1	0.50	1.0	
2	0.25	5.0	
3	0.00	0.0	

To obtain data to construct a life table one need long term studies of the population of interest, e.g. age-specific data on survival and fecundity that includes information about the proportion that breed. The life cycle diagram illustrates the demographic projection of a Leslie matrix A, which has the following general form,

$$A = \begin{bmatrix} f_1 & f_2 & f_3 & \cdots & f_n \\ p_1 & 0 & 0 & \cdots & 0 \\ 0 & p_2 & 0 & \cdots & 0 \\ 0 & 0 & . & \cdots & . \\ 0 & 0 & 0 & p_{n-1} & 0 \end{bmatrix}$$

Eq. 5.3

where the first row of the matrix (f_x) is the number of offspring that are expected to be alive at the next projection interval (e.g. next breeding season), and the diagonal (p_x) is the survival probabilities from age $x-1$ to x, or from age x to $x+1$. The equations used to derive the Leslie matrix for post-breeding census is given by,

$$p_x = \frac{l_x}{l_{x-1}} \quad \text{and} \quad f_x = p_x m_x$$

Eq. 5.4

and for pre-breeding census by,

$$p_x = \frac{l_x + 1}{l_x} \quad \text{and} \quad f_x = l_x m_x$$

Eq. 5.5

where the parameters are as defined above.

Based on the life table, the Leslie matrix for the hypothetical population can be calculated using for example Eq. 5.4, i.e. post-breeding census.

$$A = \begin{bmatrix} 0.5 & 2.5 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix}$$

Eq. 5.6

As seen f_1 is equal 0.5 since individuals of age 0 (new-borns) have an annual survival probability of 0.5, f_2 is 2.5 since each female of age 2 is expected to acquire 5 offspring which have an annual survival probability of 0.5. Similar both p_1 and p_2 is 0.5 since the annual survival probability is 0.5.

The growth of the hypothetical population at time $t+1$ may be projected by multiplying the matrix with a population state vector representing the initial population (cf. Eq. 5.7 and Table 18). The product (S_x) is the number of survivors (i.e. the number of individuals) in each age class (Eq. 5.7).

$$\begin{bmatrix} S_1(t+1) \\ S_2(t+1) \\ S_3(t+1) \end{bmatrix} = \begin{bmatrix} 0.5 & 2.5 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix} \times \begin{bmatrix} 30 \\ 10 \\ 10 \end{bmatrix}$$

Eq. 5.7

If l_x and m_x is constant over time, the ratio of successive population sizes (N_{t+1}/N_t) will converge on a constant value (R), and the proportion of individuals in each age class will reach a stable age distribution. This is illustrated in Table 4, for eight time intervals (years). The population state vector $S_x(0)$ (representing the initial population) is selected arbitrary but the closer it is to the final stable age distribution of the population, the fewer time steps are needed until the fundamental net population growth rate R stabilises.

....

The fundamental net population growth rate after one year is 1.200 (60/50) and stabilise at 1.397 (625/447) after eight years. This is very close to the true rate (1.396), i.e. the rate that we would obtain if we continued to project the population for infinite intervals. Note that the population size would have continued to grow exponentially (with an increase of 33.4% per year) since no density dependent factors are included in the projection process.

Table 18. Projecting the Leslie matrix using a population state vector of 30 individuals in age 0, and 10 individuals of age 1 and 2. No individuals survive to age 3 and this age is therefore not shown. *N* is the population size (sum of all individuals), *R* is the fundamental population growth rate and *r* is the exponential growth rate (*r* = ln(*R*)).

Age	$S_x(0)$	$S_x(1)$	$S_x(2)$	$S_x(3)$	$S_x(4)$	$S_x(5)$	$S_x(6)$	$S_x(7)$	$S_x(8)$
0	30	40	58	79	111	154	216	301	420
1	10	15	20	29	39	56	77	108	150
2	10	5	8	10	14	20	28	39	54

N =	50	60	85	118	165	229	321	447	625
R =	-	1.200	1.417	1.382	1.404	1.390	1.399	1.393	1.397
r =	-	0.182	0.348	0.324	0.340	0.329	0.336	0.332	0.334

It is possible to project the constant growth of an age-based model using weighted averages. The average number of female offspring produced by an individual female in the population is calculated as,

$$R_0 = \sum l_x m_x \qquad \textbf{Eq. 5.8}$$

where R_0 is the basic reproductive rate, and l_x and m_x is as defined above. The equation is the sum of the individual females' offspring during her lifetime weighed with the probability of surviving each age class. To determine the fundamental net reproductive rate *R* of the populations, the Lotka-Euler equation can be used,

$$\sum e^{-rx} l_x m_x = 1 \qquad \textbf{Eq. 5.9}$$

where l_x is the probability of surviving from birth to age *x*, m_x is the number of female offspring born to a female in the age interval *x+1*, and ω is the age of last production. The equation cannot be solved directly and must be solved using numerical methods (e.g. by trial and error, i.e. by iterations using a computer).

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Box 5. Life tables from real populations

Generic stage based matrix

	stage1	stage2	stage3	stage4
stage1	0	F_2	F_3	F_4
stage2	G_1	P_2	0	0
stage3	0	G_2	P_3	0
stage4	0	0	G_3	P_4

Killer whales live in stable social groups called pods. The life history data is collected from long term field studies of killer whales in the Pacific Northwest (Bigg et al. 1990) and a study by Brault & Caswell (1993). The study contains two sub-populations and 18 pods, where each pod contains between 5 and 63 individuals.

Estimated maximum age for females is 80-90 years (50-60 years for males). Sexual maturity for males and females are 10-18 years, but males become physically mature approximately 6 years after sexual maturity. Females produce one single calve (rarely twins) with inter-birth interval of $4-6$ years. Females become reproductively senescent between 35 and 45 years of age.

This is a stage-based matrix model (or a Lefkovitch matrix), i.e. categories other than age are used. This implies that individuals can both remain in the same stage class and? move on to the next one (this probability is denoted with G). All individuals in a stage (or category) are assumed to be identical (i.e. they give birth and die at identical rates).

The stages in the killer whale studies was yearlings (stage 1), juvenile (stage 2), mature (stage 3) and post-reproductive (stage 4). The interval of stage 1 is defined as 1 year, and thus the probability of staying in this stage is zero (one either die or move to stage 2).

Projecting the matrix yields a fundamental net reproductive population rate of 1.025, ($r = 0.0251$), i.e. an annual population growth rate of 2.5%.

Figure 12 shows how the killer whale population would increase over a period of 50 years, starting with a population size of 800 individuals and a stable age distribution (stage 1 = 3.7%, stage 2 = 31.6%, stage 3 = 32.3% and stage 4 = 32.4%).The relative low net reproductive population rate indicates that the population was influenced by density-dependent processes.

The results are similar to an extensive study by Olesiuk et al. (1990), which calculated an annual population growth rate of 2.92% for a killer whale population in the coastal waters of British Columbia and Washington State. They concluded that the population was stable and lived below their carrying capacity (i.e. less influenced by density-dependent processes).

In comparison Wade (1998) used a generic value of $r_{max} = 0.04$ (R = 1.041) for calculating limits for allowable human caused morality of cetacean and pinnipeds (where max means that this is without density dependence). The value was used in a model that includes density dependency.

Life cycel graph
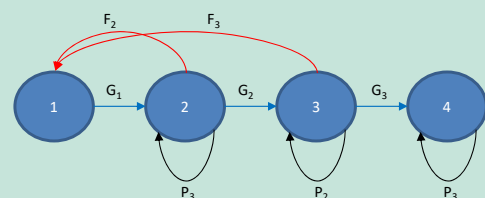
Stage based matrix

$$A = \begin{bmatrix} 0 & 0.0043 & 0.1132 & 0 \\ 0.9775 & 0.9111 & 0 & 0 \\ 0 & 0.0736 & 0.9534 & 0 \\ 0 & 0 & 0.0452 & 0.9804 \end{bmatrix}$$
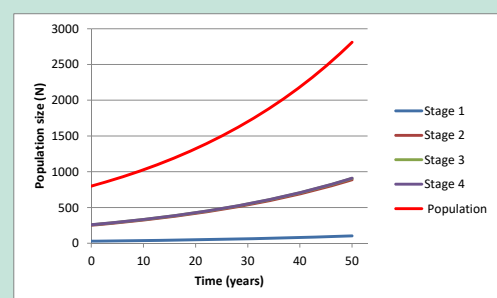

Figure 12. Population growth of a killer whale population with a fundamental population growth rate of 1.025 and no density dependence included. Note that some of the curves are identical and therefore not visible in the plot.

Box 6. Life tables from real populations

Generic age based matrix

	age1	age2	age3	age4
age1	f_1	f_2	f_3	f_4
age 2	p_1	0	0	0
age3	0	p_2	0	0
age 4	0	0	p_3	0

An age-structured population model was created based on demographic data from long-term studies of the great cormorant (*Phalacrocorax carbo*) at the Danish colony Vorsø. The data are from Frederiksen et al. (2001).

The colony expanded rapidly until 1991, after which decreases in adult survival, fecundity and breeding propensity became apparent when the colony stabilized and later declined. During colony growth, annual adult survival was approximately 0.89 (range 0.86–0.93) and first-year survival varied around 0.60 (0.50-0.75). Fecundity increased with age until 5 years, when 2-3 chicks were fledged per breeding female. Cormorants started to breed at ages 2-8 years, females earlier than males; approximately 45% of 2-year-old females bred.

The demographic used to construct the age based matrix is collected from the period prior to 1990, i.e. before obvious declines (cf. Frederiksen et al. 2001).

The rate reported by Frederiksen et al. (2001) was 1.185 (modified fecundities values) and 1.224 (original fecundities estimated from Vorsø). The age-based matrix yields however a net reproductive population rate (R) of 1.343 (r=29%), which apparat to be top high for this population.

An annual population increase of 29% is within the range of other studies *R* = 1.271 based on population data derived from the Wetland Bird Survey winter cormorant counts for England, from 1986 to 2004 (Chip Weseloh & Ewins 1994).Even higher rates have been estimated and observed in the closely related species; e.g. the double-crested cormorant (Phalacrocorax auritus) on the Little Galloo Island in Lake Ontario (Canada), which have increased on average 36% per annum since colonization in 1974 (Chip Weseloh & Ewins 1994), with as high as 56% annual increase between 1974 and 1982 (Wires et al. 2001). Wires et al.(2001) concluded that based on the life history of the double-crested cormorant, immigration was not necessary for the observed annual growth.

Figure 12 shows how the cormorant population would increase over a period of 20 years, starting with a population size of 100 individuals (the y-axis is cut of at a population size of14 000 individuals.

Life cycel graph

Age based matrix

$$A = \begin{bmatrix} 0.23 & 0.41 & 0.63 & 0.79 & 0.84 & 0.86 & 0.87 \\ 0.88 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.89 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.89 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.90 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.90 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.90 & 0 \end{bmatrix}$$
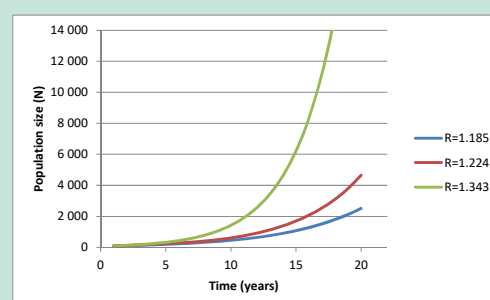

Figure 13. Population growth of cormorant' populations with different fundamental population growth rates and no density dependence included.

5.2.3   Proposed implementation of the calculator

The following proposed implementation is based on the literature review that is presented in Appendix B1. An overview of different methods reviewed and required demographic data is presented in Table 19. Based on the review we recommend that the fundamental net reproductive rate calculator is built around the work by Niel & Lebreton (2005) and Slade et al. (2008), in addition to the Lotka-Euler equation.

The model by Niel & Lebreton (2005) requires little data and have been utilized in studies for assessing the potential impact of human-caused mortalities on seabird populations by commercial fisheries (Richard et al. 2013; Richard & Abraham 2013b), wind farms (Poot et al. 2011), but also more generic studies (Dillingham & Fletcher 2008; Richard & Abraham 2013a). The model by Slade et al. (2008) has the generality that Coles (1954) and Robinson & Redford (1991) lacks as it can incorporate either assumption or empirical values of age specific survivorship (and p) depending on what data are available (e.g. setting the survivorship equal to 1 the model is a special form of Coles (1954) equation).

Table 19. Different methods that may be used to estimate the growth rates parameters R (or λ) and r from minimal information of demographic data (see text and Appendix B1 for references).

Demographic data	Description	Cole	Robinson & Redford	Slade	Niel & Lebreton	Hone
α	Age at first reproduction (year)	x	x	x	x	x
ω	Age at last reproduction (year)	x	x	x	-	-
b	Annual birth rate of female offspring	x	x	x	-	-
$l\alpha$	Pre-reproductive survival probability (0 - 1)	-	-	x	-	-
p or (s)	Adult survival probability (0-1)	-	-	x	x	x
f_{RR}	Factor for maximum life-span (0.6, 0.4 or 0.2)	-	x	-	-	-

The calculator consists of the demographic parameters in Table 19, Eq. 5.10, Eq. 5.11, Eq. 5.12 and Eq. 5.13 along with four rules for handling missing survivor data.

I.
$$\sum e^{-rx} l_x m_x = 1$$
Eq. 5.10

and

II.
$$1 = pR^{-1} + l_\alpha b R^{-\alpha} - l_\alpha b p^{(\omega-\alpha+1)} R^{-(\omega+1)}$$
Eq. 5.11

and

III.
$$0 = exp\left[\left(\alpha + \frac{s}{R-s}\right)^{-1}\right] - R$$
Eq. 5.12

and

IV.
$$\lambda_{max} \approx \frac{(s\alpha - s + \alpha + 1) + \sqrt{(s - s\alpha - \alpha - 1)^2 - 4s\alpha^2}}{2\alpha}$$
Eq. 5.13

where R is the fundamental net reproductive rate and the other parameters as defined in Table 19.

Equation Eq. 5.11 and Eq. 5.12 can be solved using numerical methods (e.g. by trial and error using stationary iterative methods). An Excel sheet is provided in Appendix B2 with examples and instructions in order to help implementation of the calculator in the ERA-SW.

The four rules to postulate (guess) various survival schedules using lifespan data are (Slade et al. 2008):

1. Assume that lα and p both equal to 1. This is the same as using Coles (1954) equation. We denote the resulting fundamental net reproductive rate as R$_C$ after Cole (C = Cole).

$$1 = R_C^{-1} + bR_C^{-\alpha} - b^{(\omega-\alpha+1)}R_C^{-(\omega+1)}$$

<div align="right">**Eq. 5.14**</div>

   where R$_C$ is the fundamental net reproductive rate.

2. Use a modification of Coles equation suggested by Robinson & Redford (1991) by using the formula suggested Slade et al. (2008),

$$R_{RR} = 1 + (R_C - 1)f_{RR}$$

<div align="right">**Eq. 5.15**</div>

   where R$_{RR}$ is the fundamental net reproductive rate (denoted RR after Robinson & Redford), R$_C$ is the fundamental net reproductive rate calculate from Coles equation (i.e. setting lα and p equal to 1 in Eq) and f$_{RR}$ is a factor of 0.6, 0.4, or 0.2 depending on the maximum length of life being < 5 years, between 5 and 10 years or larger than 10 years, respectively.

3. Use a single value for yearly survival of all groups, assuming that maximum longevity is synonymous with age at last reproduction (ω) and that 1% of the cohort survives to that age. The pre-reproductive survival probability (lα) is then,

$$l_\alpha = p^\alpha$$

<div align="right">**Eq. 5.16**</div>

   where p is the adult survival probability (Eq. 5.17) and α is the age at first reproduction. The adult survival probability (p) is

$$p = 0.01^{1/\omega}$$

<div align="right">**Eq. 5.17**</div>

   where ω is the age at last reproduction. Note that in large social K-selected species such as the killer whale, sperm whale and possible sea cows, females may become reproductively senescent long before they reach their maximum longevity (e.g. female killer whales get reproductively senescent around 35 and 45 years of age, while estimated maximum age for females is 80-90 years). The assumption that 1% of the cohort survives to the age at last reproduction may therefore not appropriate for these species.

4. Similarly as above, assuming an adult survival probability consistent with a 1% probability of surviving to maximum longevity. The pre-reproductive survival probability (lα) is known.

$$p = \left(\frac{0.01}{l_\alpha}\right)^{1/(\omega-\alpha)}$$

<div align="right">**Eq. 5.18**</div>

   where lα is the pre-reproductive survival probability, ω is the age at last reproduction and α is the age at first reproduction.

5.3   Categorisation of life histories

The life history of the species classified in the surface compartment varies widely, from the K-selected right whale (high annual survival rate, few offspring's and high parental care) to the more r-selected sea turtles (low to high annual survival rate, many offspring's, and little

parental care). Between these two extremities there is a spectrum of different life histories, also within the thirteen wild life groups (Figure 14).

In order to perform a discretisation (classify) of population growth rate estimates (R), one need estimates of this factor for species with different life history traits. Currently few values exist (as the ERA Acute SW is under development). A discussion on how the life history traits related to population growth in different species differentiate between and within the thirteen wildlife groups (individual vulnerability) is presented below. A categorisation of wildlife groups based on life history ("population vulnerability") is performed and presented. Combining individual vulnerability and relevant population life history traits related to population growth is two important factors that make up the VECs vulnerability towards oil spills.

Even with an extensive library, note that adequate knowledge of the local population(s) of interest is always important, especially for species with high variation (plasticity) in essential life history traits. Differences between various estimates of intrinsic vital rates may reflect distinct genetic differences between populations, effects of density-dependent factors variation in the study methods and available data. Possible extrinsic threats to the population should be taken into considerations when evaluating and interpreting the results from the ERA Acute SW.
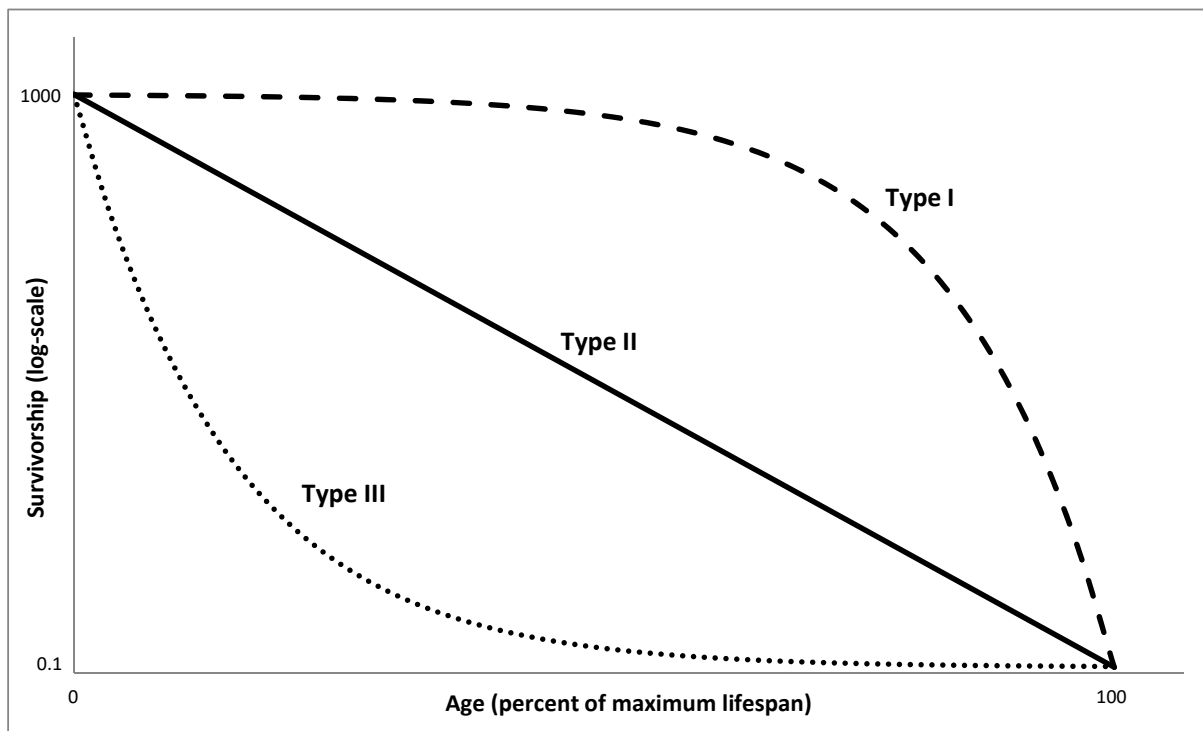

Figure 14. Classification of survivorship curves. Type I survivorship curve is characteristic of a population in which most individuals survive well past the midpoint. Humans and animals in zoos and pets may show this pattern of survivorship. The wildlife group that best classify in this type is the baleen whales. Type I survivorship curve is characteristic of a population in which survivorship decreases at a constant rate throughout the lifespan. Some birds and small mammals may show this pattern of survivorship. Type I survivorship curve is characteristic of a population most individuals die in early life and those that remain have a relative high constant survivorship for the rest of their lifespan. This is true for many marine fish populations. The wildlife group that best classify in this type is sea turtles.

Seabirds (wildlife group 1-6) are in general more K-selected than most other bird species. In general they live longer, are older at first breeding, have higher annual adult survival rate and invest more effort into fewer young (one clutch and many species one egg per season). In theory or figurative, seabirds can be placed above type 2, and most other birds can be placed below the type 2 survivorship curve in Figure 14.

The species grouped in wildlife group 1 – 6 have different life history traits with respect to the intrinsic factors affecting population growth and thus "population vulnerability". Using the demographic invariant suggested by Niel & Lebreton (2005), the net fundamental population growth rate, R have been calculated for 102 seabird species. Figure 15 show a histogram of the R-estimates in intervals of 0.3 and the species divided into order and family.

The histograms reveal some clear distinctions between the different orders and families. For instance, on the left side of the plot we find species belonging to the family *Diomedeidae* with an average *R* of 1.06 (n=13). This family includes large albatross, with age of first reproduction on average at 9.2 years, high adult survivorship, one single egg, often every second year. On the other side of the plot we find ducks, goose (*Anatidae)* and divers (*Gaviidae*) with an average *R* of 1.19 (n=8). Species belonging to these two families reproduce early (2.6 years); have medium adult survivorship and a large, yearly clutch size.

Based on the data, a categorisation of seabird is given below (and in Table 20).

- Seabird group 1: Albatross and skuas
- Seabird group 2: Auks, petrels and shearwaters
- Seabird group 3: Gannets, penguins, gulls and terns
- Seabird group 4: Cormorants, shags, divers, ducks and goose

The suggested R-values are given in intervals of 0.05 to emphasise that the values are not calculated directly from raw data (i.e. there will be species in the groups that deviates from the typical R-value for the group). The dataset is heavily skewed with respect to families dominated by albatrosses, petrels, shearwater shags and penguins, and the estimates is based on age at first reproduction and adult survivorship only.
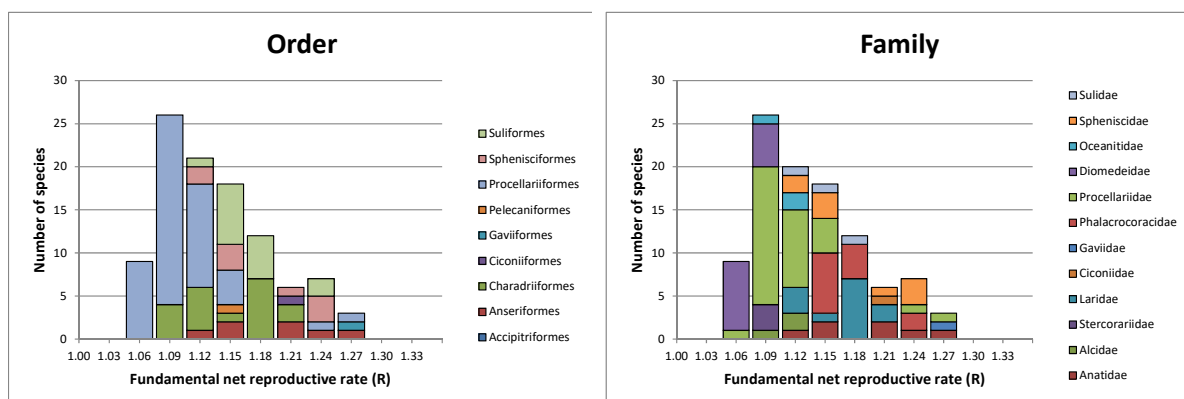

Figure 15. Histogram of estimated R-values for different seabird orders (right) and families (left).

Baleen whales (wildlife group 7) become sexually mature when 5 to 10 years old on average, with blue (*Balaenoptera musculus)* and humpback whales (*Balaenoptera novaeangliae*) maturing as early as 4-5 years. In most species, a 2 to 3-year calving period is the norm but females of some species area capable of having on calf per year. Twins are rare (and if occurring, only one calf usually survives). The average rate of increase (e^R) per annum for baleen populations range from 4.3% for Antarctic blue whales (*B. m. intermedia*), to 7.2 % for the southern right whales (*Eubalaena australis*) (cf. Branch 2008 and references therein). The latter is almost equal to the 6.9 % growth rate that has been registered from surveys (Best et al. 2005) and is considerably higher than the growth rate of only 1 % found in the study of the northern right whale (*E. glacialis*) (cf. Keith 2008; Fujiwara & Caswell 2001). The maximum rates are 11.9 %, 12.6 % and 10.6 & 13.8 %, for blue, humpback and southern right whales, respectively.

Toothed whales (wildlife group 8) become sexually mature at 5 to 18 years of age. Many toothed whale species take longer to reach sexual maturity than baleen whales and there tends to be a larger gap between the sexes in age of onset of sexual maturity. In most species, a 2-

to 6-year calving period is the norm. Small species generally have shorter inter-birth intervals (e.g. the harbour porpoise, *Phocoena phocoena* 1 – 3 years) than the larger species (e.g. killer whales and sperm whale 4–6 years and possible longer). Similarly, smaller dolphins (e.g. the bottlenose dolphin, *Tursiops truncatus*) may suckle their calves for 18 to 20 months while the mean duration for sperm whales is 2 years (lactose has been found in 7.5 to 13 years old sperm whales, indicating a considerable longer suckle period) and short-finned pilot whales (*Globicephala macrorhynchus*) 4–5 years. Wade (1998) used a maximum intrinsic population growth rate of 4 % for cetaceans to calculate limits to the allowable human-caused mortality.

Based on their life history, a lower intrinsic population growth rate is expected for toothed whales than baleen whales. The intrinsic population growth to the well-studied killer whale population (cf. Box 5) ranges from 2.5% to 2.9% (Brault & Caswell 1993; Bigg et al. 1990). Härkönen et al. (2013) reported a 4% intrinsic growth rate for harbour porpoise based on metadata from Danish, German and Swedish surveys. Stolen & Barlow (2003) estimated a 4.6% intrinsic growth rate for the bottlenose dolphin population in Florida. As mentioned, Wade (1998) used a maximum population growth rate of 4% for all cetaceans in his study.

True seals, walrus & sea lions and fur seals (wildlife group 9 and 10) generally become sexually mature when 3 to 5 years old, with walrus maturing as late as 6.5-10 years. In most species, a 1-year inter birth interval is the norm, but longer in some Otariidae (Galapagos fur seals, *Arctocephalus galapagoensi*s – 36 months) and Phocidae (monk seals, *Monachus spp.* – 15 to 24 months) species, and typically 2-3 years for walrus (*Odobenus rosmarus*). Each adult female produces one offspring per season (twins are rare). Maximum lifespan is in the order of 20 to 40 years. The length of the lactation period varies extensively in pinnipeds from the 2 years of walruses to the eight to 12 days of harp (*Phoca groenlandica*) and hooded (*Cystophora cristata*) seals. Typically, true seals have a lactation period less than 2 months and sea lions and most fur seals have a 12-month lactation period. Antarctic (*A. gazelle*) and Northern (*Callorhinus ursinus*) fur-seal lactate for only three to four months, while the Galapagos fur seal lactate for 36 months. The life history of sea lions, fur seals and walrus suggest splitting them into three groups (true seals, sea lions and fur seals and walrus).

True seals: Härkönen et al. (2013) reported a 10% intrinsic population growth rate for the Baltic Sea grey seal population and the Bothnian Bay ringed seal population. A higher population growth have been estimated for the grey seal population at Sable Island, Nova Scotia (Canada), one of the largest grey seal colonies in the world that has been increasing exponentially at an annual rate of 12.8% for four decades in the face of considerable environmental variability (Bowen et al. 2003). Reported population growth rate estimates for harbour seal populations in the Baltic Proper, Kattegat (Härkönen et al. 2013) and North Sea (Hansen & Harding 2006) is 12%.

Sea lions and fur seals: Hucke-Gaete et al. (2004) examined natural population growth of the Antarctic fur seal at the South Shetlands (Antarctica), and estimated an intrinsic population growth rate of 26% for the period 1966 to 2002. This is higher than other estimates and it was suggested that the high, observed growth rate was due to immigration from the growing population of South Georgia, especially in the period between 1966 and 1973, when the observed rate of increase for was as high as 66%. At this time, the Antarctic fur seal at the South Shetlands were near extinction and thus small increase in numbers will give large population growth. Other studies have estimated an intrinsic rate of natural increase for Antarctic and the sub-Antarctic fur seal (*A. tropicalis*) between 7.8% and 16.8% year. Rapid population increases are assumed related to a krill surplus resulting from a reduction in baleen whale numbers as well as an increase in squid stocks following the decline in sperm whales.

Walrus: The intrinsic growth rate of population of Pacific walruses during the late 1950s to mid-1970s was estimated to be 6.7% (Tavrovskii 1971; Sease & Chapman 1988 refered to in Witting & Born 2013). This indicates a finite growth rate of about 7% per year for a population in a phase of growth under favourable environmental conditions with no food limitations (Witting & Born 2013). Witting & Born (2013) reported a growth rate estimate of 7.7% (95% CI: 6.7–8.9%) for the Baffin Bay walrus population. This rate is similar to the estimate by Chivers

(1999; refered to in Witting & Born 2013) who modelled an annual maximum growth rate of 8%. The estimate of Witting & Born (2013) is an increase from previous estimates in 2005 (Witting & Born 2005), where the population growth rate was estimated to 2% (90% CI: 0–7%). The increase in growth rate and precision (smaller uncertainty) is attributed to better data, and the estimate from 2013 is believed to be a more solid estimate of the growth rate.

Sea cows (wildlife group 11) manatees reach sexual maturity between 2.5 and 6 years, however, most females don't breed successfully until they reach 6 to 10 years of age. The dugong matures at greater ages, between 8 to 18 years. The time between births is unclear, with estimates ranging from 2.7 to 5.8 years for dugongs and 2.5 to 3.0 years for manatees. Females produce one calf per season (twins in about 1.4 to 1.8% of births, and possibly as high as 4%). Based on the Florida manatee (*Trichechus manatus latirostris*) life history, the average fecundity (number of female births per female per year) for age classes 4-29 years estimates at 0.127, 0.189 and 0.238. Applying these fecundity numbers in the R-calculator, using a first reproduction equal to 6 years and age at last reproduction equal to 30 years, yields an intrinsic population growth rate of 0.5% (R=1.005), 3.7% (R=1.037) and 5.7% (R=1.058), respectively. This is within the same range as what is estimated from a complete stage-structured population model for the Florida manatee, which estimated growth rates (R) of 1.037 (95% CI: 1.016–1.056) and 1.062 (95% CI: 1.037–1.081) for the Northwest and Upper St. Johns River regions, respectively (Runge et al. 2004).

Aquatic mammals (wildlife group 12) include all other mammalians not fitting into the other wildlife groups. Three important species are polar bear (*Ursus maritimus*), sea otter (*Enhydra lutris*) and the Eurasian otter (*Lutra lutra*).

The Polar bear reaches sexual maturity when they are five years old (males 8-10 years old). Litter size ranges from one to three, but two cubs in a litter is most frequent. Juveniles follow their mother until the age of 2.5 years, at which time the mother is ready to mate again (average reproductive interval 3.68 years). Survival of juveniles is low, with only about one out of three reaching the age of two years. Adults have high survival (97%-99%), and typically live to be 15-25 years old. Amstrup (1995; refered to in Polar Bear: Southern Beaufort Sea Stock) projected an annual intrinsic growth rate (including natural mortality but not human-caused mortality) of 6.03% for the Southern Beaufort Sea stock using a Leslie-type matrix of recapture data. Taylor et al. (2002) estimated the population growth rate without harvest at R= 1.059 (5.73%) for the Viscount Melville Sound (Canada) population.

The sea otter show high plasticity with respect to life history. Typically, there is only one pup per pregnancy. On the rare occasion of twins, the mother can only raise one. Females usually give birth about once a year. Weaning period is between 2-11 months. Females reach sexual maturity at 4 years. Estimates of population growth in five sea otter populations below equilibrium density in the north-east Pacific Ocean was (Estes 1990): 17-20 % for Attu Island, south-east Alaska, British Columbia, Washington State and 5 %-7 % for the central California population. The annual growth rate in Prince William Sound (Gulf of Alaska) was about 10 % following the end of the fur harvest in 1911 (Bodkin et al. 1999; Bodkin et al. 2002).

The Eurasian otter attains sexual maturity at around 18 months (male) and 24 months (female), but in captivity sexual maturation is usually at 3 to 4 years (cf. Chanin 2003 and references therein). The gestation period is approximately 63-65 days, the litter size varies from 1 to 5 (mean 2.3-2.8), and the life expectancy is around 17 years. A long-term monitoring (1977 to 2002) in 3 catchments in western Britain estimated the annual population growth rates at 1-7 %, with the highest rates in the earlier years and in the areas which were uninhabited by otters at the beginning of the study (Mason & Macdonald 2004).

Sea turtles (wildlife group 13) Sea turtle species share a common life cycle, which is composed of a series of stages. Unlike most species of seabird and marine mammal, marine turtles show no parental care of their eggs. Estimates of age at sexual maturity vary among species and populations and is estimated to be 3 years in hawksbills (*Eretmochelys imbricate*), 12 to 30 years in loggerheads (*Caretta caretta*), and 20 to 50 years in green turtles (*Chelonia mydas*). The large variation may reflect difficulties using mark–recapture studies successfully due to

early pelagic life-history stage, small size and low survival probabilities (cf. Scott et al. 2012). Females show variation in both the number of eggs laid per clutch and the number of clutches laid in a season. Most species of sea turtle do not nest annually, but typically deposit two to four clutches of 50–150 eggs every 2 to 4 years (cf. Broderick et al. 2003 and references therein). The exceptions are the Kemp's (*Lepidochelys kempii*) and olive ridley (*L. olivacea*) turtles, which commonly nest each year (Shigenaka & Milton 2010). Several species show increased clutch size with increased body size. Most studies of sea turtle populations show a negative growth rate (e.g. Crouse et al. 1987),. Two exceptions are the study by Dutton et al. (2005) where the leatherback turtle (*Dermochelys coriacea*) population was estimated to be increasing approximately. 13 % pa since the early 1990s (approx.. 18–30 in the 1980s to 186 in 2001), and the study by Chaloupka & Limpus (2001), where the green turtles population in southern Great Barrier Reef increased over 8 years by 11 % pa and comprised of 1300 individuals in 1992. The female nesting population increased more slowly at 3 % pa. DNA fingerprinting of mother-daughter relations suggested that the increase in the size of the nesting leatherback turtle population was due to a more than 20 year-running aggressive program of beach protection and egg (Dutton et al. 2005).

Based on the above review, a look-up table for generic population growth rates is constructed and presented in Table 20. The wildlife groups name and the typical species are intended to help choose a correct value for the biological resource.

Table 20. Wildlife groups with generic population growth rates.

Wildlife group	Typical species	Families	R	r
Albatross and skuas	Albatross (Southern royal, Grey-headed Antipodean, Northern royal), skua (brown, great, subantarctic), Northern fulmar	Diomedeidae, Stercorariidae, Procellariidae	1.05	4.9%
Auks, petrels and shearwaters,	Auks (razorbill, common guillemot, Atlantic puffin), petrels (black, white-chinned, Chatham), shearwaters (Bullers, flesh-footed), Black-legged kittiwake	Alcidae, Procellariidae	1.10	9.5%
Gannets, penguins, gulls and terns	Gannets (northern, masked australasian), penguins (Snares crested, Southern rockhopper, Fiordland crested), Gulls (black-backed, lesser black-backed, little) and terns (common white, common, sandwich, Caspian)	Sulidae, Spheniscidae	1.15	14.0%
Cormorants, shags, divers, ducks and goose	Cormorant (great), shags (European, Campbell Island, spotted, Auckland Island), divers (red throated), ducks (common eider, common scooter) and goose (barnacle, snow, Bewicks swan)	Anatidae, Gaviidae,	1.20	18%
True seals, sea lions and fur seals, baleen whales	Grey seal, harbour seal, ringed seal, Antarctic fur seal, subantarctic fur seal, blue, humpback and southern right whales	Balaenopteridae	1.13	12.2%
Walrus, aquatic mammals	Walrus, polar bear, Eurasia otter, sea otters	-	1.06	6.0%
Toothed whales, sea cows, turtles	Bottlenose dolphin, killer whale, harbour porpoise, Florida manatee, sea turtles	Delphinidae, Phocoenidae, Trichechidae, Dugongidae	1.03	3.0%

T~REC~ AND RIF

6 The total recovery time and the resource impact factor

The final results are the total recovery time and the Resource Impact Factor (RIF). The total recovery time (t_{rec}) is given by the following equation,

$$t_{rec} = t_{imp} + t_{lag} + t_{res}$$ **Eq. 6.1**

where the parameters are the time parameters for impact, lag and restitution, respectively.

The Resource Impact Factor (RIF) is calculated using a more precise method than in EIF-Acute because the population growth is not a linear function of time (cf. Chapter 0). The method is illustrated in Figure 16.

The area of each bar is given by the following equation,

$$Area\ of\ one\ bar = TLR - \left[\left(\frac{N_{t1} + N_{t0}}{2} \right) \times (t_1 - t_0) \right]$$ **Eq. 6.2**

where TLR is the threshold set for recovery and N is the population time or population fraction at time t_1 and t_0 (in the example $t_1 = t_{32}$ and $t_0 = t_{31}$). The RIF is given by summing the areas of all bars,

$$Recovery\ Impact\ Factor\ (RIF) = \sum_{t=0}^{t=t_{res}} TLR - \left[\left(\frac{N_{t1} + N_{t0}}{2} \right) \times (t_1 - t_0) \right]$$ **Eq. 6.3**

where t_{res} is the restitution time as defined above.

The interpretation of the RIF is not straightforward. If the extent of damage (*b*) is given as absolute population loss (i.e. number of individuals), the RIF may possible be interpreted as implicit take into considerations the importance of absolute numbers with respect on various cascading effect on other part of the ecosystem. If the extent of damage (*b*) is given as relative population loss (i.e. percentage population loss), the resource impact factor favours populations with high population growth rates, and should be interpreted with care.

As an example, imagine two populations with equal population size (1000) but different fundamental net population growth rate. Population 1 (R = 1.70) has a population loss of 25% and population 2 has a population loss of 10%. The total recovery time (given that the lag phase is 0) is 10 years for both populations. The RIF based on absolute mortality is 772 for population 1 and 227 for population 2, and the RIF based on population fractions is 0.8 for population 1 and 0.2 for population 2. Thus although the total recovery time is identical, the difference in the two RIFs are on an order of 3.4 and 4.0.
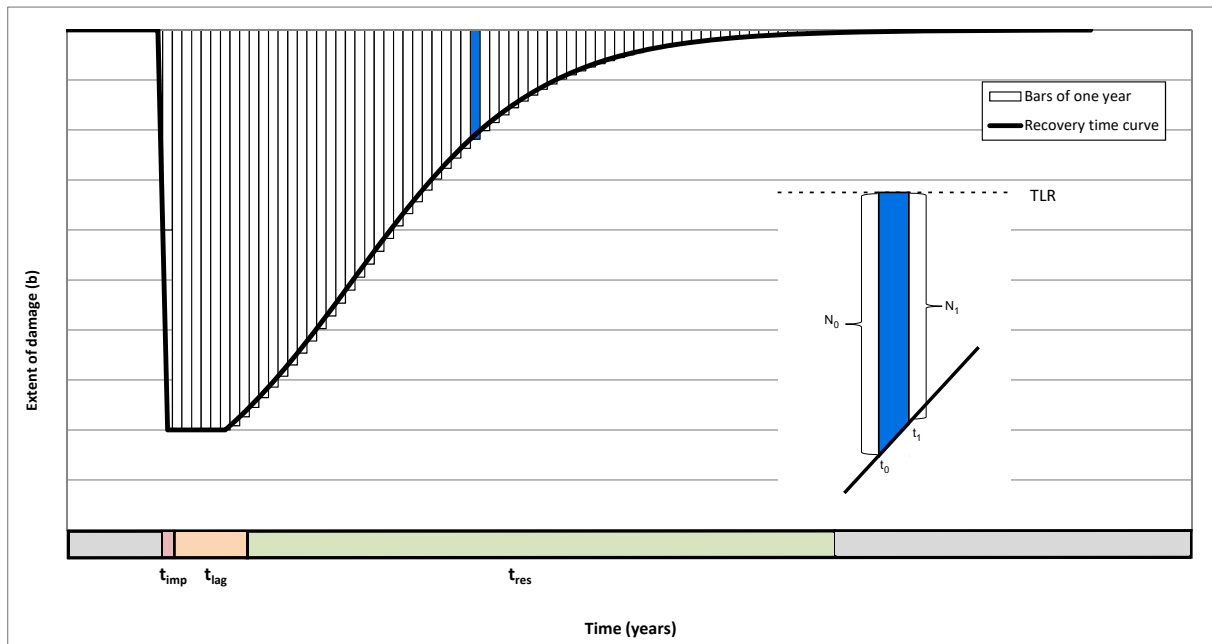
Figure 16. Illustration of calculating RIF based on single bars of one year. t_{imp} is the time period to next breeding season, conservative set equal to 1 year, t_{lag} is the lag-time implicit included in the population model for large extent of damage and t_{res} is the restitution time. The total recovery time (t_{rec}) is equal to $t_{imp} + t_{lag} + t_{res}$.

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Appendix A

A1 Raw data from studies used to review p_{let}

Table 21- Low, high and best guess p_{beh} and p_{phy} values from Ford (1985).

Species		Stadium	p_{beh} (1-Δ)			p_{phy} (Φ)		
			Low	Best	High	Low	Best	High
Cassin's auklet	*Ptychoramphus aleuticus*	All	0.80	0.80	0.90	0.80	0.90	1.00
Xantus's murrelet	*Synthliboramphus scrippsi, S. hypoleucus*	All	0.80	0.80	0.90	0.80	0.90	1.00
Western gull	*Larus occidentalis*	Juvenile	0.50	0.55	1.00	0.20	0.25	0.30
		Adult, immature	0.15	0.40	0.90	0.20	0.25	0.30
Northern fur seal	*Callorhinus ursinus*	Pups	0.90	0.95	1.00	0.60	0.80	1.00
		Female, immature	0.50	0.70	0.90	0.50	0.75	1.00
		Male	0.50	0.70	0.90	0.40	0.60	0.80
California sea lion	*Zalophus californianus*	Pups	0.95	0.98	1.00	0.05	0.10	0.15
		Female, immature	0.60	0.80	1.00	0.00	0.05	0.10
		Male	0.60	0.80	1.00	0.00	0.05	0.10
Northern elephant seal	*Mirounga angustirostris*	Pups[c]	0.95	0.98	1.00	0.00	0.02	0.05
		Female, immature	0.90	0.95	1.00	0.00	0.02	0.05
		Male	0.90	0.95	1.00	0.00	0.02	0.05
Common dolphin	*Delphinus delphis*	All	0.40	0.60	1.00	N.A.	N.A.	N.A.

Table 22. Factor a used to construct the oil vulnerability index (OVI) for seabirds (Williams et al., 1985).

Species		Factor a
Razorbill	*Alca torda*	5.00
Little Auk	*Alle alle*	5.00
Guillemot	*Uria aalge*	5.00
Puffin	*Fratercula arctica*	4.50
Fulmar	*Fulmarus glacialis*	3.00
Manx Shearwater	*Puffinus puffinus*	3.50
Gannet	*Morus bassanus*	3.00
Storm Petrel	*Hydrobates pelagicus*	1.00
Kittiwake	*Rissa tridactyla*	3.00
Lesser Black-backed Gull	*Larus fuscus*	3.00
Great Skua	*Catharacta skua*	3.00
Arctic Skua	*Stercorarius parasiticus*	2.50
Sooty Shearwater	*Puffinus griseus*	3.50
Common eider	*Somateria mollissima*	4.00
Red-necked Grebe	*Podiceps grisegena*	4.50
Long-tailed Duck	*Clangula hyemalis*	4.50
Great Northern Diver	*Gavia immer*	5.00
Goldeneye	*Bucephala clangula*	3.00
Red-breasted Merganser	*Mergus serrator*	3.50
Velvet Scoter	*Melanitta fusca*	4.50
Red-throated Diver	*Gavia steilata*	5.00
Black-throated Diver	*Gavia arctica*	5.00
Great Cormorant	*Phalacrocorax carbo*	2.50
Common Scoter	*Melanitta nigra*	4.50
Black Guillemot	*Cepphus gryile*	5.00
Great Crested Grebe	*Podiceps cristatus*	4.00

Species		Factor *a*
European Shag	*Phalacrocorax aristotelis*	4.00
Little Gull	*Larus minutus*	3.00
Little Tern	*Sterna albifrons*	1.00
Common Gull	*Larus canus*	2.00
Herring Gull	*Larus argentatus*	2.00
Black-headed Gull	*Larus ridibundus*	2.00
Common Tern	*Sterna hirundo*	1.50
Arctic Tern	*Sterna paradisaea*	1.50
Sandwich Tern	*Sterna sandvicensis*	1.50
Great Black-backed Gull	*Larus marinus*	2.50
Scaup	*Aythya marila*	3.00

Table 23. Factor *Be*, *Av*, *Tv* and *Sc* used to construct oil vulnerability index for marine mammals (Isaksen et al., 1989).

Species		Stadium	Be	Av	Tv	Sc
Polar bear	*Ursus maritimus*	Female	3	3	3	3
Polar bear	*Ursus maritimus*	Male	3	3	3	3
Walrus	*Odobenus rosmarus*	Female	2	3	2	2
Walrus	*Odobenus rosmarus*	Male	2	3	2	2
Ringed seal	*Phoca hispida*	All	2	3	2	2
Harbor seal	*Phoca vitulina*	All	3	3	2	2
Harp seal	*Phoca groenlandica*	All	3	3	2	2
Bearded seal	*Erignathus barbatus*	All	3	3	2	2
White whale	Delphinapterus leucas	All	3	3	2	2
Bowhead whale	*Balaena mysticetus*	All	3	3	2	2
Minke whale	*Balaenoptera acutorostrata*	All	2	3	1	1
Fin whale	*Balaenoptera physalus*	All	2	3	1	1
Humpback whale	*Megaptera novaeangliae*	All	2	3	1	1

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Table 24- Low, high and best guess *p_{beh}* and *p_{phy}* values from Ford (1985). The product (P_{let}) are calculated and compared with P_{let} values from French McCay (2009) and EIF and ERA Acute (Spikkerud et al., 2011).

Species		Stadium	p_{beh} (1-Δ)			p_{phy} (Φ)			P_{let} (p_{beh} × p_{phy})			P_w[a]	P_{let}[b]
			Low	Best	High	Low	Best	High	Low	Best	High		
Cassin's auklet	*Ptychoramphus aleuticus*	All	0.80	0.80	0.90	0.80	0.90	1.00	0.64	0.72	0.90	0.99	0.99
Xantus's murrelet	*Synthliboramphus scrippsi, S. hypoleucus*	All	0.80	0.80	0.90	0.80	0.90	1.00	0.64	0.72	0.90	0.99	0.99
	Larus occidentalis	Juvenile	0.50	0.55	1.00	0.20	0.25	0.30	0.10	0.14	0.30	0.35	0.35
		Adult, immature	0.15	0.40	0.90	0.20	0.25	0.30	0.03	0.10	0.27	0.35	0.35
Northern fur seal	*Callorhinus ursinus*	Pups	0.90	0.95	1.00	0.60	0.80	1.00	0.54	0.76	1.00	0.75	0.75
		Female, immature	0.50	0.70	0.90	0.50	0.75	1.00	0.25	0.53	0.90	0.75	0.75
		Male	0.50	0.70	0.90	0.40	0.60	0.80	0.20	0.42	0.72	0.75	0.75
California sea lion	*Zalophus californianus*	Pups	0.95	0.98	1.00	0.05	0.10	0.15	0.05	0.10	0.15	0.75	0.75
		Female, immature	0.60	0.80	1.00	0.00	0.05	0.10	0.00	0.04	0.10	0.75	0.75
		Male	0.60	0.80	1.00	0.00	0.05	0.10	0.00	0.04	0.10	0.75	0.75
Northern elephant seal	*Mirounga angustirostris*	Pups[c]	0.95	0.98	1.00	0.00	0.02	0.05	0.00	0.02	0.05	0.01	0.75[c]
		Female, immature	0.90	0.95	1.00	0.00	0.02	0.05	0.00	0.02	0.05	0.01	0.35[c]
		Male	0.90	0.95	1.00	0.00	0.02	0.05	0.00	0.02	0.05	0.01	0.35[c]
Common dolphin	*Delphinus delphis*	All	0.40	0.60	1.00	N.A.	N.A.	N.A.	-	-	-	0.001	0.001

[a]French McCay, 2009, [b]Spikkerud et al 2006, 2010. [c]Grey seal and harbour seal pups are dependent on fur in the earliest life stages, and P_{let} was therefore set to 0.75 for this part of the population in the breeding period. For pinnipeds such as adult grey seals and harbour seals, P_{let} have been estimated to be 0.01 (French-McCay, 2003), but based on an evaluation of other data available, it was decided to use a P_{let} value of 0.35 for adult seals (Hydro, 2005). However, the resource data include both pups and adults, and therefore the P_{let} is weighted according to the partition between adults and pups in the breeding season. In breeding season months, the P_{let} for pinnipeds is 0.42, in the other months the value is 0.35 (Spikkerud et al., 2010).

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A2   Pivot table

Three tables

- Raw data
- Look-up table for species (green values are values for the wildlife group)
- Look-up table for wildlife groups

Guide

Use the filter buttons or the "slicers" to filter the table (see the about table in the Excel sheet for details)

Appendix B

B1 Review of methods to calculate the fundamental net reproductive rate

In the review we have kept the authors denotation for the population parameters but used the term fundamental net reproductive rate for both *R* and *r*. Since all three parameters express the rate of population growth we replaced the authors different terms for population growth rates with the term growth rate to avoid confusion.

The denotation X_{max}, (where X is *R*, *λ* or *r*) is in the relevant articles in the review referred to as the maximum growth rate that may be realised under ideal conditions (no predation, parasites, excess of food etc.) and without any limits. The correlation coefficients mentioned in the review are comparisons of estimates from their model and with populations growing under optimal conditions, measured either from time periods of large growth from longer time series, reintroduced species or during invasion processes. It is the maximum growth rate.

In practice, the R (or *λ*) or r measures the theoretical rate if the parameters that goes into the equation is based on population living under optimal conditions and the realised rate if it is based on population that are affected by different limiting factors.

Cole's equation and modification of Coles equation

Cole (1954) was one of the first to explore the relative importance of life-history variables on population growth rate. In his widely cited article "*the population consequences of life history phenomena*", Cole (1954) demonstrated that mathematical tools of common demography could be meaningfully applied to ecological questions of describing and predicting population growth, with only limited information on the animals in question (cf. Blomquist 2007).

From the Euler-Lotka equation, Cole (1954) developed the following equation,

$$1 = e^{-r_{max}} + be^{(-r_{max} \times \alpha)} - be^{-r_{max}(\omega+1)}$$ **Eq. 7.1**

which can be solved using numerical methods (e.g. by trial and error using a computer). It considers only the age at first reproduction (α), the annual birth rate of female offspring (*b*), and the age of last reproduction (ω), and assumes that all survival probabilities are equal to 1 prior to the age of last reproduction.

Cole's formula has two advantages for estimating a growth rate; it (1) requires minimal demographic information and (2) involves relatively simple calculations. Because of the unrealistic assumption (survival probabilities equal to 1 prior to the age of last reproduction), the resulting estimates of growth rate tend to be biased by excess (i.e. too high and therefore not conservative). Hone et al. (2010) showed however that predictions of growth rate derived from Cole's equation can provide unbiased estimates of the growth rate estimated from field count data.

To allow for pre-reproductive and adult mortality, Robinson and Redford (1991) multiplied growth rate, defined as λ_c - 1, by a factor (f_{RR}) of 0.6, 0.4, or 0.2, depending on maximum length of life being <5 years, >5 and <10 years, or >10 years, respectively. Their multiplicative factors (f_{RR}), represent implicit survivorship schedules but it is unclear how these schedules relate to actual mortality patterns in natural populations (cf. Slade et al. 2008).

Slade et al. (2008) elaborated Coles (1954) and Robinson & Redford (1991) equations further, by developing a more general model (equation) that is able to incorporate several explicit assumptions or empirical values of age-specific survivorship depending on what data are available. The model is described by the following equation,

$$1 = p\lambda^{-1} + l_{\alpha}b\lambda^{-\alpha} - l_{\alpha}bp^{(\omega-\alpha+1)}\lambda^{-(\omega+1)}$$ **Eq. 7.2**

which can be solved using numerical methods. The *b*, α and ω are as defined previously. The l_{α} is the pre-reproductive survival and the *p* is the adult survival. As noted r_{max} is equal to ln(λ),

thus Cole's equation (Eq. 7.1) is a special case of Eq. 7.2, with l_α and p both equal to 1 (cf. Slade et al. 2008).

Demographic invariant methods

It has been shown that life history and demographic traits co-vary in a predictable way among a wide set of species (cf. Niel & Lebreton 2005 and references therein, but see also Nee et al. 2005). Niel and Lebreton (2005) used this knowledge to develop a method that allow estimates of a growth rate (λ_{max}) and mean optimal generation length (T_{op}) knowing only age at first reproduction (α) and adult survival (s) for bird species. The method assumes constant fecundity and constant adult survival after age of first reproduction.

Two key relationships are used in the calculation by Niel and Lebreton (2005):

$$\lambda_{max} \approx 1 + \frac{1}{\bar{T}_{op}}$$

Eq. 7.3

and

$$\bar{T}_{op} = \alpha + \frac{s}{\lambda_{max} - s}$$

Eq. 7.4

Combining these yields

$$\lambda_{max} = exp\left[\left(\alpha + \frac{s}{\lambda_{max} - s}\right)^{-1}\right]$$

Eq. 7.5

which can be solved using numerical methods. Alternatively, Niel and Lebreton (2005) provided a quadratic solution based on a first-order Taylor series approximation.

$$\lambda_{max} \approx \frac{(s\alpha - s + \alpha + 1) + \sqrt{(s - s\alpha - \alpha - 1)^2 - 4s\alpha^2}}{2\alpha}$$

Eq. 7.6

Niel and Lebreton (2005) showed that the estimates of growth rates from Eq. 7.6 was similar to estimates achieved from Leslie matrix approaches (R^2 = 0.884) of well-studied bird populations with a variety of life history traits, including early (α = 2) to late (α = 12) reproduction, and low (s = 0.73) to high (s = 0.987) survival (cf. Niel & Lebreton 2005 for details about the bird studies used).For the short lived species Eq. 7.6 was less accurate and the growth rates were better estimated by solving Eq. 7.5.

The demographic invariant method have been utilized by in several studies for assessing the potential impact of human-caused mortalities on seabird populations by e.g. commercial fisheries (Richard et al. 2013; Richard & Abraham 2013b), wind farms (Poot et al. 2011) and more generic studies (Dillingham & Fletcher 2008; Richard & Abraham 2013a).

Hone et al. (2010) estimated growth rates of 64 mammal species also based on only age at first reproduction and female age at first reproduction. The estimates correlated positively with growth rates estimated independently from field count data (R^2 = 0.87) but the estimated values had wide confidence intervals. Moreover, the double log term in the equation restricts application of the model for several wildlife groups (pinnipeds, cetacean and several seabirds) in the surface compartment, as it is only valid if b is larger than 1.

B2   R-calculator

Parameters to run the R calculator (the fundamental net reproductive rate)

Column name	Description
α	Age at first reproduction
ω	Age at last reproduction
b	Annual birth rate of female offspring
lα	Pre-reproductive survival probability
p	Adult survival probability

Guide

(orange box)	Fill inn values / choose rule for approximation of the Lotka –Euler equation
(yellow box)	Not required data
(pink box)	Enter a first value (1.5 may be a good starting point); cf. local vs. global solution in the about sheet.

Run Solver (see the about sheet for an explanation)

How to load the Solver Add-in program

1. Click the **File** tab, click **Options**, and then click the **Add-Ins** category.

2. In the **Manage** box, click **Excel Add-ins**, and then click **Go**.

3. In the **Add-ins available** box, select the **Solver Add-in** check box, and then click **OK**.

Table 25. Fundamental net reproductive rate R estimated from complete life history tables.

| Species | | Estimated population growth from life history tables | | | |
Common	Scientific	R	Population, area	Optimal conditions	References
Black-legged kittiwake	*Rissa tridactyla*	0.9465	Norwegian (5 colonies)	No	(Sandvik et al. 2014)
Southern fulmar	*Fulmarus glacialoides*	1.0117	Colony in Great Britain	Yes	(Jenouvrier et al. 2005)
Thick-billed murre	*Uria lomvia*	1.0102, 1.0300	Canadian Arctic	The highest estimate is exclusive hunting	(Wiese et al. 2004)
Great cormorant	*Phalacrocorax carbo*	1.1850	Vorsø, Denmark	Yes-	(Frederiksen et al. 2001)
Glaucous-winged gull	*Larus glaucescens*	1.0608	Protection Island, Washington	Yes-	(Reid 1988)
Right whale[1]	*Eubalaena glacialis*	0.999, 1.010	North Atlantic	Unknown	(Keith 2008; Fujiwara & Caswell 2001)
Humpback whale[1]	*Megaptera novaeangliae*	1.129, 1.065	Gulf of Maine	Unknown	(Barlow & Clapham 1997; Keith 2008)
Hector's dolphin	*Cephalorhynchus hectori*	1.018, 1.050	-	Yes	(Slooten & Lad 1991)
Sperm whale	*Physeter macrocephalus*	1.110	Australian waters	Unknown	(Keith 2008)
Killer whales	*Orcinus orca*	1.0254, 1.0296	Pacific Northwest, British Columbia and Washington State	Yes -	(Brault & Caswell 1993; Bigg et al. 1990)
Harbour porpoise	*Phocoena phocoena*	1.0408	-	Yes	(Härkönen et al. 2013)
Bottlenose dolphin[1]	*Tursiops truncatus*	1.0670, 1.0471	Florida	Unknown	(Stolen & Barlow 2003; Keith 2008)
Harbour seal	*Phoca vitulina*	1.1275	Baltic Proper, Kattegat and North sea	Yes	(Härkönen et al. 2013; Hansen & Harding 2006)
Grey seal	*Halichoerus grypus*	1.1052	Baltic Sea	Yes	(Härkönen et al. 2013)
Ringed seal	*Phoca hispida*	1.1052	Bothnian Bay. Sweden	Yes	(Härkönen et al. 2013)
Northern elephant seal	*Mirounga angustirostris*	0.9315	California	No	(Clinton & Le Boeuf 1993)
Steller sea lion	*Eumetopias jubatus*	0.890	-	No	(Keith 2008)
Florida manatee	*Trichechus manatus latirostris*	0.989, 1.037, 1.062	Florida, 3 areas	No +	(Runge et al. 2004)
Loggerhead sea turtles	*Caretta caretta*	0.9450	Variuos, Little Cumberland Island, USA	No	(Crouse et al. 1987)

[1]Values estimated by Keith (2008) followed by values from the original study.

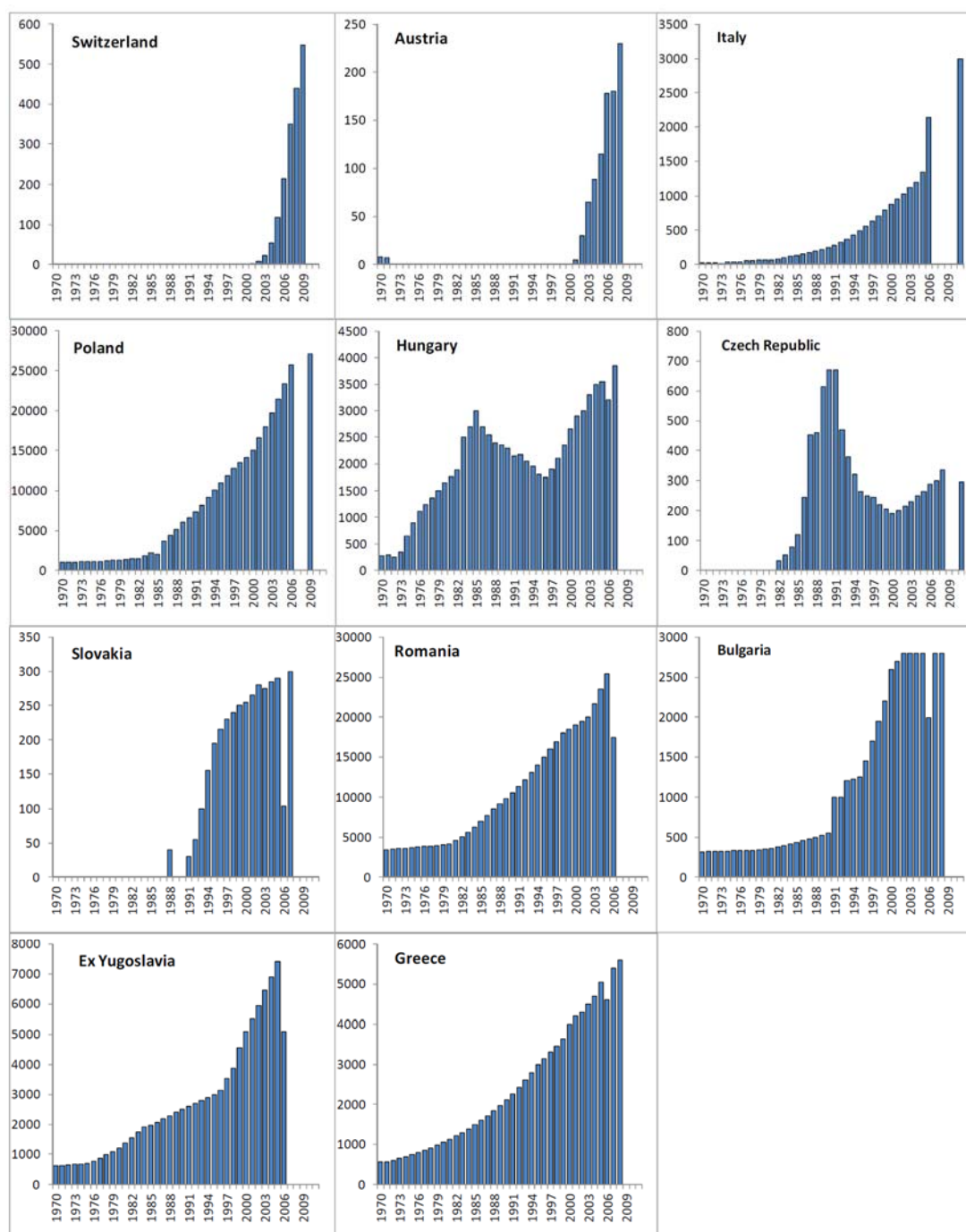# B3   Example of various growth rates in same species
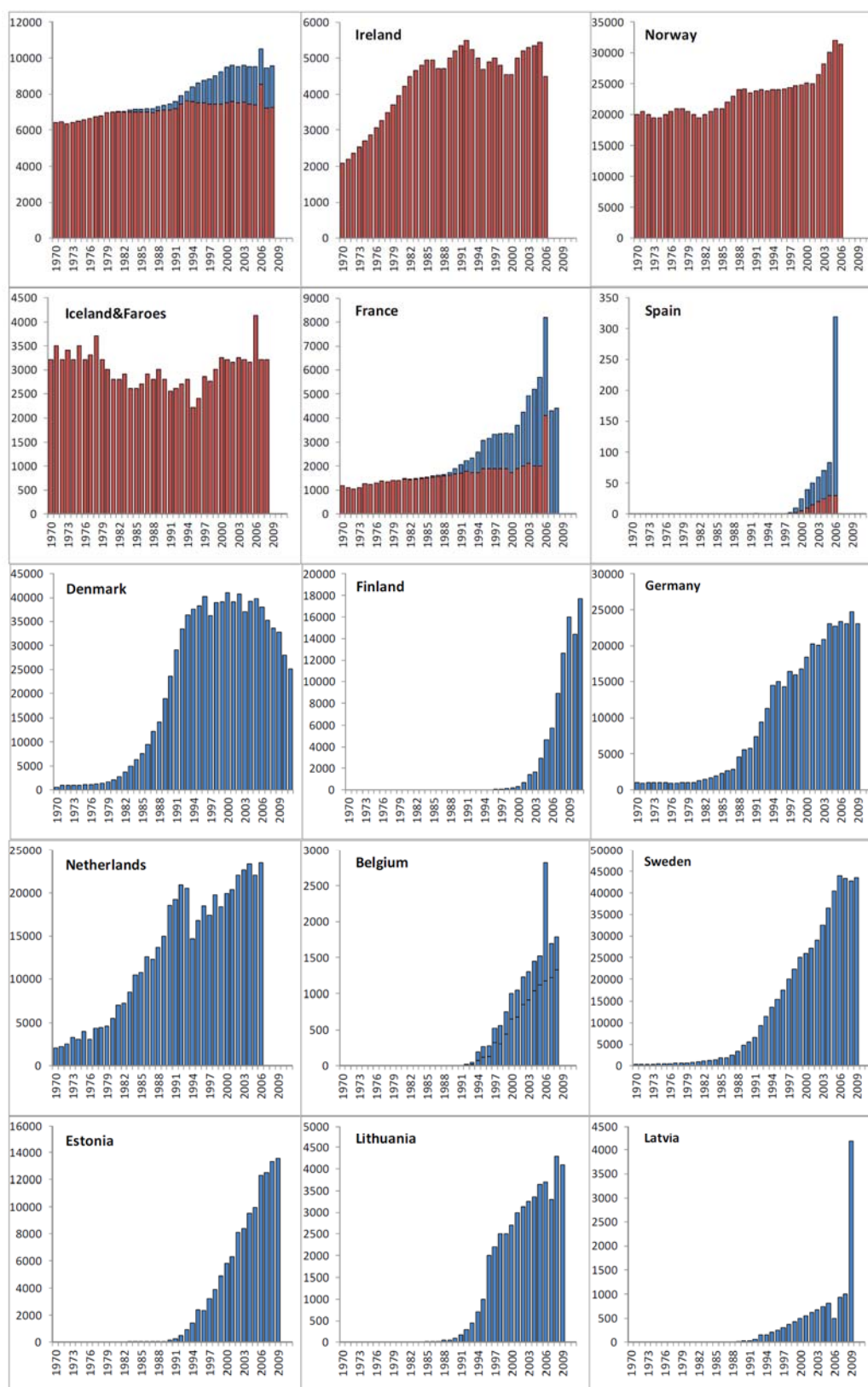
Figure 17. Great cormorant (two sub-species) breeding pair against time for different populations (countries).

B4 Population model, total recovery and resource impact factor

Parameters to run the population model (impact, lag, restitution and resource impact factor)

Column name	Description
N	Pre-spill population size
N'	Post- spill population size
K	The carrying capacity of the population
K	The carrying capacity of the population used in the population model (calculated from pre-spill population size and threshold for recovery)
TLR	Threshold level for restitution
b	Type of density dependence
R	The fundamental net reproductive rate

Guide
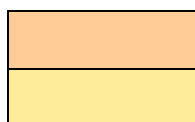
	Fill inn values
	Not required data

Press the button "Get Recoverys and RIFs".